JSCE Guidelines for Concrete
No.17

STANDARD SPECIFICATIONS FOR CONCRETE STRUCTURES – 2007
"Maintenance"

Japan Society of Civil Engineers

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Japan Society of Civil Engineers (JSCE)
Yotsuya 1-chome, Shinjuku-ku, Tokyo 160-0004, JAPAN
FAX +81-3-5379-2769 E-mail pub@jsce.or.jp
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Preface

Concrete structures have supported our society as infrastructures. The society can only preserve itself in wholesome with tough, beautiful and durable concrete structures. Concrete Committee of Japan Society of Civil Engineers (JSCE), leading organization for investigation, research, technological promotion and education of concrete in Japan, considers the issuance and revision of Standard Specifications for Concrete Structures as its most important activity. Standard Specifications for Concrete Structures (JSCE-SSCS), which show the model for plan, design, execution, maintenance and repair of concrete structures, have been highly recognized in practice and contributed to the development of concrete technology in Japan since its first publication as “Standard Specifications for Reinforced Concrete – 1931.”

In order to cope with the development of concrete technology in Japan and the worldwide trend, Concrete Committee converted all Specifications in JSCE-SSCS namely ‘Structural Performance Verification,’ ‘Seismic Performance Verification,’ ‘Materials and Construction,’ ‘Maintenance,’ ‘Dam Concrete’ and ‘Pavement,’ from the “Prescriptive Code” to “Performance-based Code” and completed the work in 2002.

This revised edition adopts the technological development after 2002 and intends to enhance the performance-based nature in Standard Specifications. For practical efficiency, the three Specifications - ‘Design,’ ‘Materials and Construction’ and ‘Dam Concrete’ present not only general provisions for verification of specified performance requirements but also standard methods as simplified methods to achieve the performance requirements under certain conditions. JSCE-SSCS is ready for practical use as it describes the role of each Specification during the plan, design, execution, maintenance and repair phases as well as the relationship among them. And for the first time, it also describes roles of engineers for construction works. This JSCE-SSCS is yet an ultimate one. There are still remaining tasks, such as inclusion of provisions for scenario of concrete structures during service life. What readers can find in this revised edition is rationality with “the performance-based concept” and the applicability for practice, showing the high level of technology in Japan.

This revised JSCE-SSCS consists of five Specifications; ‘Design,’ which combines the previous ‘Structural Performance Verification’ and ‘Seismic Performance Verification’ together, ‘Materials and Construction,’ ‘Maintenance,’ ‘Dam Concrete’ and ‘Test Methods and Specifications.’ Specification of ‘Test Methods and Specifications’ was issued separately in May 2007. Specification of ‘Pavement’ was published as “Standard Specifications for Pavements – 2007” by the Committee on Pavement Engineering of JSCE, which has taken over the issuance and revision works from JSCE-SSCS.

Finally I would like to show my most sincere gratitude to Prof Taketo UOMOTO and Dr Tadayoshi ISHIBASHI, Chairman and Secretary General of Sub-committee on Revision of Standard Specifications for Concrete Structures as well as its Secretaries, Conveners and Members who devoted themselves continuously despite the tight drafting schedule. My gratitude also goes to Advisors, Secretaries, Executive Members and Members of Concrete Committee, who reviewed the draft.

December 2007

Toyo. Miyagawa

Toyoaki MIYAGAWA, Chairman
Concrete Committee of Japan Society of Civil Engineers

Preface to the English Version

The Japan Society of Civil Engineers' (JSCE) Concrete Committee has been publishing the Standard Specifications for Concrete Structures in Japanese since 1931. The English versions were published twice in 1987 and 2005 when the limit state design and the performance-based concept were introduced in the 1986 and 2002 editions of Standard Specifications for Concrete Structures (JSCE-SSCS) for the first time, respectively.

Since 2004 the Concrete Committee has put efforts to enhance information dissemination overseas by presenting various English publications including the series of "JSCE Guidelines for Concrete." Concrete Committee has also decided to prepare the English version of every edition of JSCE-SSCS. This Sub-committee on English Version of Standard Specifications for Concrete Structures was established in 2008.

Our task is to prepare the English version of four Specifications: 'Design,' 'Materials and Construction,' 'Maintenance' and 'Dam Concrete' of the 2007 edition of JSCE-SSCS. Specification of 'Test Methods and Specifications' of JSCE-SSCS is not included in this English version. However, some of these standard test methods and specifications have been translated for publication in a series of "JSCE Guidelines for Concrete." Please visit the website of Concrete Committee at http://www.jsce.or.jp/committee/concrete/e/index.html for the information on the English publications.

This English version includes most of the contents in the original Japanese version. Utmost efforts have been made to ensure that the translation accurately convey the description in the original Japanese version. If there were any discrepancy between the Japanese and English versions, however, reference should be made to the original Japanese version.

Translation of technical work does not only require expertise but a lot of time and dedication. I am grateful to all the members for their tiring efforts. My heartfelt appreciations go to Prof YOKOTA Hiroshi (Secretary General), Dr SHIMOMURA Takumi (Head, WG for Design), Prof SUGIYAMA Takafumi (Head, WG for Materials and Construction), Dr MAEDA Toshiya (Head, WG for Maintenance), Prof AYANO Toshiki (Head, WG for Dam Concrete) and Dr ISHIZUKA Takayuki who proof-read all the translated Specifications. Without them this English version would not have been published.

December 2010

Tamon Ueda

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JSCE Guideline for Concrete No. 17

Standard Specifications for Concrete Structures -2007 "Maintenance"

CONTENTS

PART 1 MAINTENANCE

MAINTENANCE FOR SPECIFIC DETERIORATION MECHANISMS

Application of Standard Specifications for Concrete Structures

Editorial notes for the English Version:

(1) The Standard Specifications for Concrete Structures are a model code which is supposed to be applied in Japan and have no legal bindings.

(2) Therefore, some contents, such as Chapters 2 and 3 of “Application of Standard Specifications for Concrete Structures,” may not fit to practical scheme in construction industry in the other countries.

(3) However, it is hoped that the Standard Specifications for Concrete Structures could be a model code for the other countries after necessary modifications of the contents considering the local conditions.

1. Basic concept concerning the organization of the Standard Specifications for Concrete Structures

The Standard Specifications for Concrete Structures are regularly revised reflecting the state-of-the-art concrete technologies developed in Japan and other countries, and provide standards concerning the technical aspects of concrete structures in a series of phases from planning to design, construction and maintenance.

In this revised edition, the “Standard Specifications for Concrete Structures, Design” is composed of the “Standard Specifications for Concrete Structures, Structural Performance Verification” and “Standard Specifications for Concrete Structures, Seismic Performance Verification” to enhance the convenience of design practice. Durability check and initial cracking check, which should be discussed in the “Standard Specifications for Concrete Structures, Design” have been transferred from the “Standard Specifications for Concrete Structures, Materials and Construction” to “Standard Specifications for Concrete Structures, Design”. The preparation and revision of the “Standard Specifications for Concrete Structures, Pavement” has been handed over to the Committee on Pavement Engineering, JSCE (Japan Society of Civil Engineers). The results are now published separately under the title of the Standard Specifications for Pavement. Thus, the Standard Specifications for Concrete Structures include five components: Design, Materials and Construction, Maintenance, Dam Concrete, and Test Methods and Specifications.

The General Requirements for “Design”, “Materials and Construction” and “Dam Concrete” are described based on the concept of performance-based code. Performance requirements are specified for structures and the methods for checking the compliance with requirements are shown in the General Requirements. In the Standard Methods, standard methods for satisfying the General Requirements under certain conditions are given for more efficient and simpler design and construction. In cases where no conditions specified in the Standard Methods are met, performance verification should be conducted in accordance with the General Requirements. For establishing new standards fitting for structures or regions to which no Standard Methods are applicable, the Standard Methods may be referred to.

Concrete structures are generally constructed for providing services in the phases of planning, design, construction and maintenance in accordance with the respective components of the Standard Specifications. Each type of work is not independent of the others. Data are handed over from an upstream to a downstream phase that are required for carrying out the work downstream to meet the conditions specified upstream. Handing over the data is therefore important to proper implementation of work in respective phases. In the Standard Specifications for Concrete Structures, "Design", "Materials and Construction" and "Maintenance" are closely interrelated to one another. Then, the required data shown in each Specifications should be accurately handed over to the next phase without fail.

Performance requirements for durability, safety, serviceability and restorability that are specified in the "Standard Specifications for Concrete Structures, Design" are determined in the design phase. Construction and maintenance methods are roughly determined in the phase. The data that affect construction and maintenance should therefore be handed over to the next phase without fail in the form of design drawings.

Construction records that are specified in the "Standard Specifications for Concrete Structures, Materials and Construction" provide important data for assessment, deterioration prediction and implementation of remedial measures in the maintenance phase. Accurate construction records should therefore be handed over to maintenance engineers. Construction plans and various inspection reports should also be provided to engineers as required.

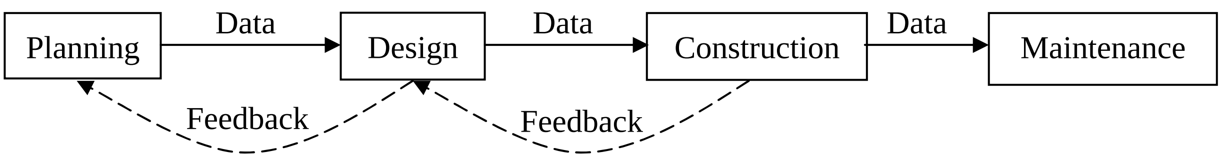


Fig. 1 Flow of work

Figure 1 shows a flow of work from the planning of a concrete structure to service commencement. Data collected in the maintenance phase are not transferred to engineering works in the planning, design or construction phase. It should, however, be taken into consideration that reflecting the data in the maintenance phase in the planning, design and construction of another structure for improvement is important to extend the service life of the structure. The interrelationship is basically the same for design, construction and maintenance described in the "Standard Specifications for Concrete Structures, Dam Concrete."

Each component of the Standard Specifications for Concrete Structures is described below.

The "Standard Specifications for Concrete Structures, Design" shows standard methods for performance verification of concrete structures such as reinforced concrete, prestressed concrete and steel-concrete composite structures, and stipulates the preconditions for checking and structural details. The revised Standard Specifications for Concrete Structures are not applicable to unreinforced concrete structures. Material design values or other applicable items may, however, be applied to unreinforced concrete structures.

The "Standard Specifications for Concrete Structures, Materials and Construction" provides basic general rules concerning the construction of concrete structures. In the construction phase, the construction method and the performance during the construction work are determined based on the design drawings and restrictions on construction. Then, materials are selected and concrete mix proportions are determined, where a concreting plan is developed so as to meet the requirements for water content, cement amount, cement type and other parameters. Whether the concreting plan meets the construction requirements or performance requirements of the structure or not is verified by an appropriate method. If the requirements are not satisfied, the concreting method is re-specified or the mix proportions are modified as long as the conditions handed over from the design phase are met.

The “Standard Specifications for Concrete Structures, Maintenance” provides general basic principles concerning the maintenance of concrete structures. In the maintenance phase, documents such as the design drawings and maintenance plans handed over from the design phase, and the construction plans, as-built drawings, construction records and inspection reports handed over from the construction phase should be fully used for efficient and effective maintenance work. In cases where the use or functions of the structure change due to social changes, performance verification should be made to verify whether the structure meets the resultant performance requirements or not. If designated performance requirements are not ensured, repair, strengthening or other remedial measures should be considered.

The “Standard Specifications for Concrete Structures, Dam Concrete” stipulates performance and quality requirements for dam concrete, and describes the methods for verifying the compliance with the requirements and the basic design and construction principles. The descriptions concerning design, construction and maintenance in the “Standard Specifications for Concrete Structures, Dam Concrete” are different from the contents of the Standard Specifications “Design”, “Materials and Construction” and “Maintenance” with many respects because of the factors unique to dam concrete such as the unreinforced nature and low or zero slump of dam concrete. The “Standard Specifications for Concrete Structures, Dam Concrete” therefore describes the matters concerning the design, construction and maintenance of dam concrete.

The “Standard Specifications for Concrete Structures, Test Methods and Specifications” lists the Japan Industrial Standards, provisions of JSCE and other standards for the methods mentioned in the other four components of the Standard Specifications. Figures 2 through 4 show work steps in respective phases described in the Standard Specifications for Concrete Structures “Design,” “Materials and Construction” and “Maintenance.”

2. Roles and deployment of responsible engineers

To produce and maintain a reliable structure that meets the performance requirements, the engineers involved should have a capacity to carry out the work and a high level of ethics.

In the planning, design, construction and maintenance of a concrete structure, the engineers should make appropriate decisions under varying work conditions. Therefore, the engineers with required technical skills should be deployed according to the level of difficulty of work. In the planning, design, construction and maintenance, therefore, responsible engineers not only with required technical expertise but also with responsibility and authority should be deployed in organizations of the owner, the consultant and the contractor.

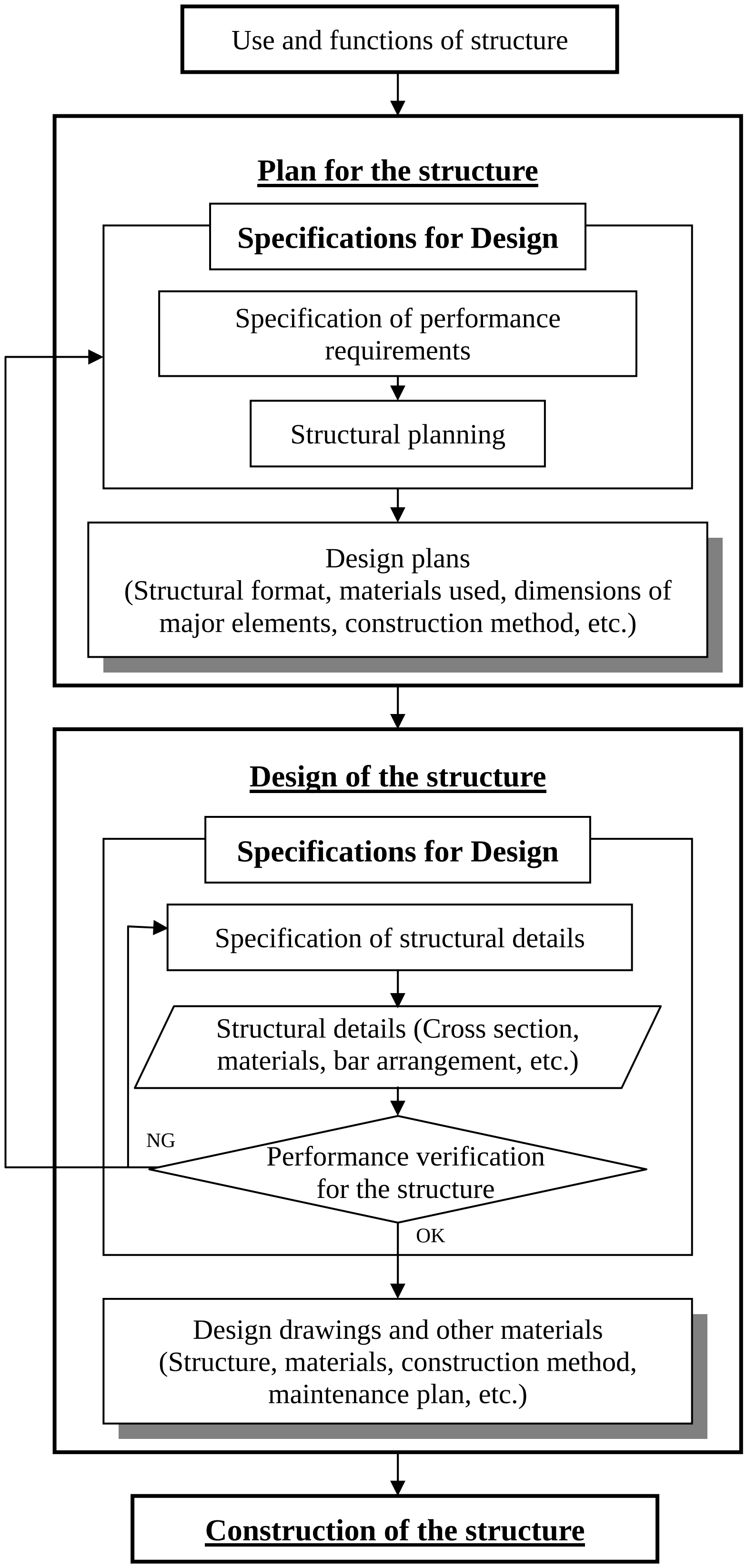


Fig.2 Work steps described in "Specifications for Design"

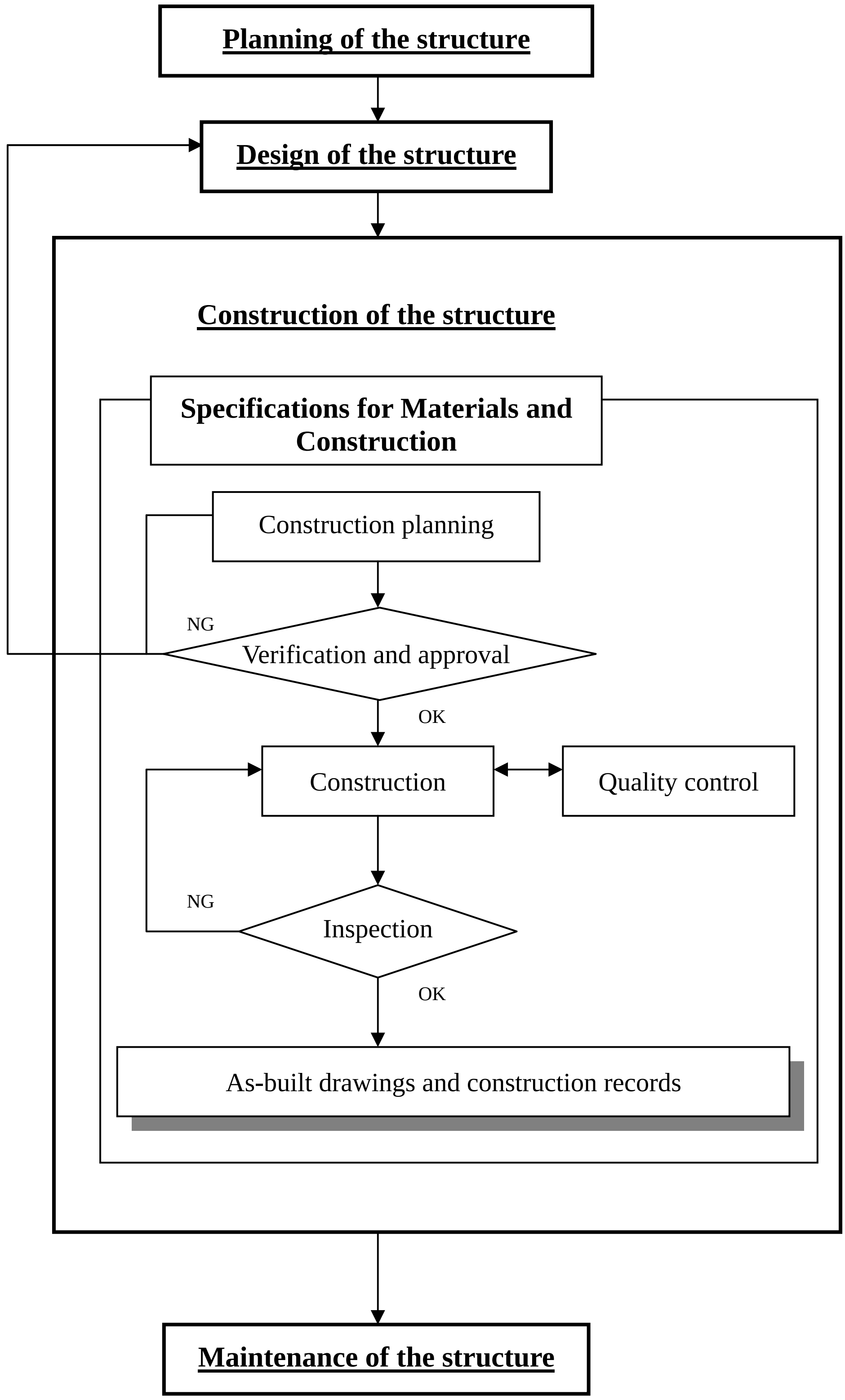


Fig. 3 Work steps described in “Specifications for Materials and Construction”

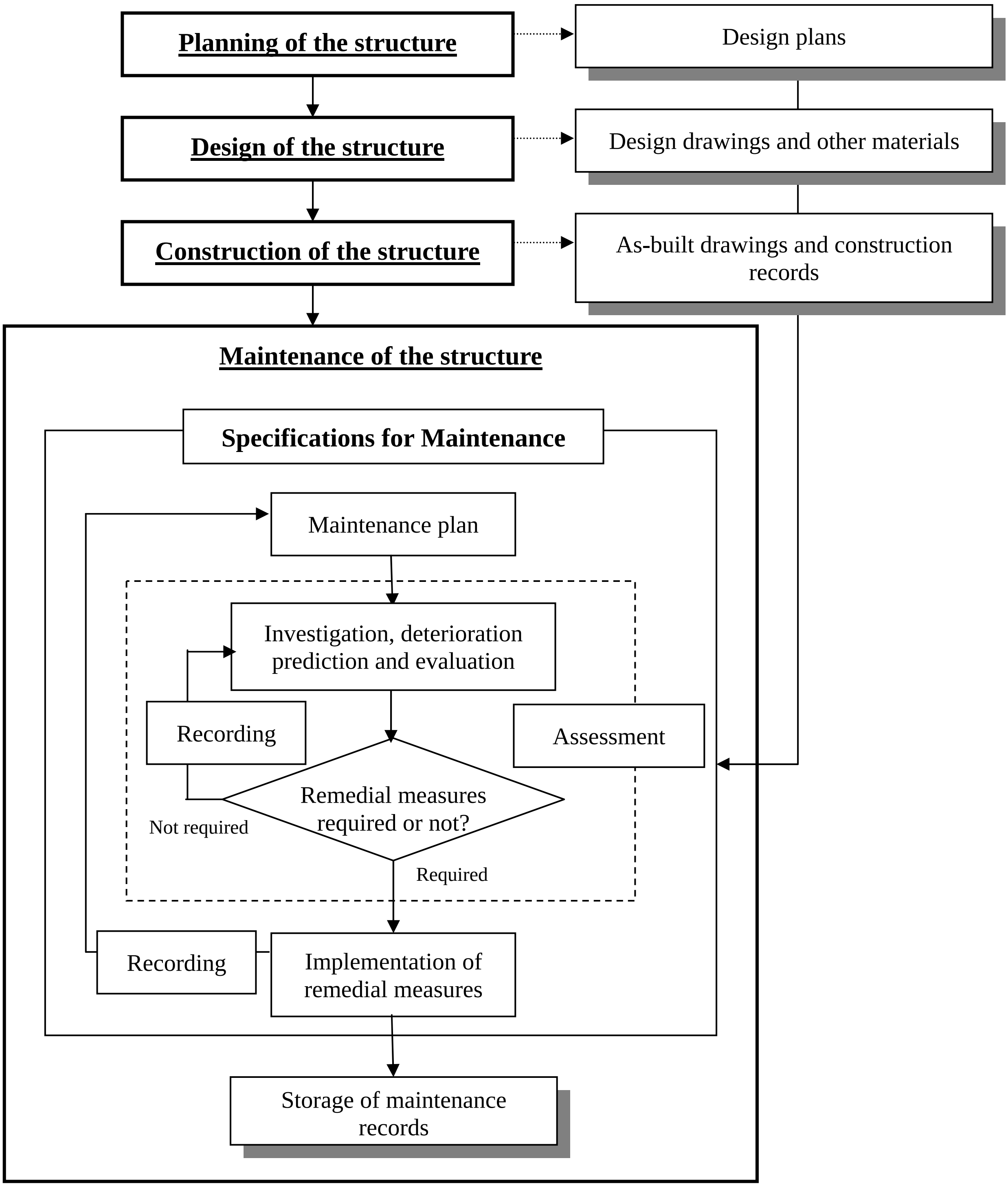


Fig. 4 Work steps described in “Specifications for Maintenance”

The technical skills required for responsible engineers should be defined according to a scale of the work, importance and difficulty of planning, design, construction or maintenance.

As capacity classifications of engineers, engineer qualifications authorized by JSCE are listed in Table 1. The qualifications for the special senior engineers and senior engineers are generally required for responsible engineers.

The JSCE technical qualifications cover several fields. Responsible engineers to be deployed in projects need to have qualifications only for major fields related to the specific project.

Table 1 Engineer qualifications authorized by JSCE

Qualification	Required skills
Executive Professional Civil Engineer	Japan's leading civil engineer with high-level knowledge and experience in his or her field of specialty, or with comprehensive civil engineering expertise
Senior Professional Civil Engineer	Engineer with high-level knowledge and experience in multiple fields or with comprehensive knowledge on civil engineering who can solve key problems as a leader
Professional Civil Engineer	Engineer with knowledge and experience at least in one special field who can carry out task at his or her discretion
Associate Professional Civil Engineer	Civil engineer with required basic knowledge who can carry out assigned task

3. System for ensuring reliability

Many groups are involved in the planning, design, construction and maintenance of a structure. In order to ensure the high reliability of the structure in each work phase, the organizations involved should play their role providing their know-how and assuming due responsibility.

To ensure reliability in the design (and planning) phase, two independent groups should basically check the design. After the design and check by the design company, engineers of the contractor should re-check the design, or request a third party to check the design. Then, fully skilled engineers should be selected for checking so that safety or other reliability parameters may be satisfied. The design drawings serving as a basis for contracting should carry the signatures of responsible engineers of the two groups that assume responsibility.

In the construction phase, reliability is ensured through the quality management by the contractor and the quality verification by the inspector independent of the contractor. Inspections have generally been conducted directly by the Owner and/or Consultant. Completed structures should be inspected wherever possible. If inspecting completed structures is impossible, inspections should be conducted while the structure is being constructed. If the Owner cannot directly inspect the structure under construction, the Owner may request an agent independent of the contractor. Adopting as many highly reliable methods as possible can reduce the labor required for quality management and inspection. In cases where adopting not so reliable methods is inevitable, the level of quality management should be raised or inspections should be conducted more frequently to improve reliability. Inspection items and decision criteria should be specifically presented at the time of contracting because they greatly affect the quality of the structure and the construction cost.

Ensuring safety requires regular investigations. When defects are detected, decision should be made as to remedial measures. For decision making concerning remedial measures for extremely difficult deformation, listening to the opinions of engineers with high skills who have experienced numerous cases is important.

In order for a system for ensuring reliability to work properly, the people or organization with technical skills fit for the specific work should be granted explicit responsibility and authority and assigned to the work. The compensation for the work and time required for the work should also be provided.

Part 1 Maintenance

CHAPTER 1　GENERAL

1.1 Scope

(1) This Specification for "Maintenance” (hereafter, this Specification) describes the maintenance of concrete structures.

(2) Part1: “Maintenance” describes the principles of maintenance of concrete structures.

(3) Part2: “Maintenance for Specific Deterioration Mechanisms” describes the principles and standard methods of maintenance of concrete structures subject to a specific deterioration mechanism.

[Commentary] (1) Maintenance is the act of maintaining the performance of a concrete structure (hereafter referred to as “structure”) within the allowable range during its service period. Maintenance is as important as and is closely related to design and construction. Maintaining a structure within the allowable range generally means to retain it above the required levels.

This Specification is not intended for maintaining structures of a specific structural formalization or those that are built using a specific design or specific construction method. This Specification presents basic ideas concerning the maintenance of all concrete structures, including plain concrete, reinforced concrete, prestressed concrete and steel-concrete composite structures. This Specification can be applied to the structures designed and constructed not in accordance with the “Design” and the “Construction” volumes of the Standard Specifications. The structures that are designed and constructed in accordance with these specifications are based on explicit design and construction ideas and are in accordance with this Specification, which facilitates the maintenance of the structures.

This Specification covers the maintenance of both newly constructed and existing structures. New structures constructed in accordance with specified design and construction standards are unlikely to be subject to outstanding severe deterioration within the design service period. The "Design" and the "Construction" volumes of the Standard Specifications explain that concrete or reinforcing materials of structures built in accordance with the “Design” and the “Construction” volumes of the Standard Specifications are highly unlikely to be subject to outstanding deterioration within the design service period of the structure because the durability of the structure is checked by confirming that the quality of concrete and reinforcing materials and the performance requirements for materials are not reduced within the design service period; and because appropriate remedial measures are taken even in cases where initial defects are detected inacceptance verification of concrete, verification of execution, or verification of the structure. In cases where they are built in accordance with the “Design” and the “Construction” volumes of the Standard Specifications, ordinary structures can be maintained adequately by investigations in routine or regular assessments based mainly on visual observations and require no detailed investigations except for certain key structures. Thus, maintenance can be facilitated.

The durability check specified in the "Design" volumes of Standard Specifications, however, falls short of quantitatively checking all the external forces expected to act on structures. Under the conditions more severe than expected, the reliability of the check is not necessarily high. Climate change or other factors may create conditions more severe than the design conditions. Structures that are constructed carefully using the materials considered appropriate at the time of design may require repair or other remedial measures because of the outstanding deterioration with time. For some structures, the planned service period is set longer than the design service period. Then, maintenance plans should be developed properly considering the possibility of outstanding deterioration after expiring the design service period of the structure.

For existing structures, unsuitable materials may have been adopted or no due consideration may have been given to design or construction because of a lack of understanding of structural durability. Initial defects may sometimes have been overlooked in investigations at the completion of construction or structures may have been used without adequate repair. The performance of structures may have been explicitly reduced below the level at the time of just after construction even under not so severe conditions and repair or other remedial measures may be required. In the case, the defective event should be identified to the maximum extent possible by investigation to determine whether the defective event is ascribable to the initial defects, damage or deterioration and what the main cause is, and necessary remedial measures should be taken. In the case of initial defects or damage, quick and appropriate measures including emergency measures are required. In cases where deterioration is outstanding that affects time-based deterioration of the structure, the deterioration mechanism should be identified to the maximum extent possible and the structure should be maintained adequately based on the prediction of deterioration progress and the evaluation and determination of performance degradation.

Some of the civil engineering structures with a service period of 50 to 100 years may require remedial measures under the conditions where performance requirements vary in changing social situations, e.g. wheel load increases on bridges due to the traffic of larger vehicles and where seismic motions stronger than the design level act on the structure. When design criteria are revised or new criteria are established, the structures and members that have been designed and constructed in accordance with the criteria before the revision or establishment become nonconforming as existing structures and members. The revised or newly established criteria are applicable exclusively to the structures to be designed and constructed after the revision or establishment but do not require the compliance of all structures including those designed and constructed before criteria revision or establishment. Revising criteria or establishing new criteria basically aims at improving the considerations in design and construction of structures to meet the current situations. Civil engineering structures are generally of high public nature. Appropriate measures should therefore be taken for structures in service at the time of revision or establishment of criteria in order to prevent structures from being subject to performance degradation and serious damage, failure and collapse due to nonconformity of existing structures.

This Specification, based on the above discussions, describes all the management actions to maintain the designated performance of existing and newly constructed structures during their service period, and the principles and major methods for appropriate maintenance. Structures are in service for a long time and performance requirements vary greatly. The number of structures in service will be exorbitant if relatively small ones are counted. Carefully maintaining all of the structures is not easy. Under the circumstances, it is important for the engineers involved to maintain structures in ways suitable to actual conditions duly respecting the major points of this Specification and considering not only the defect but also the importance, remaining service life or cost performance of the structure.

(2) and (3) This Specification is composed of two sections. **Part 1** “Maintenance” presents the principles, methods and procedures for effectively maintaining structures comprehensively considering the initial defects, damage and performance degradation. For the deterioration mechanisms affecting the performance degradation of the structure, namely, carbonation, chloride attack, frost attack, chemical erosion, alkali-silica reaction, fatigue (slabs and beams) and abrasion, the basic and specific maintenance methods for each are described in **Part 2** “Maintenance for

specific deterioration mechanisms" in detail based on the description in **Part 1**. Also presented are the basic ideas of seismic retrofitting and required diagnostic methods, which are key maintenance factors.

This specification should be used basically to maintain structures in accordance with **Part 1**, while referring to **Part 2** in necessary in cases where the main deterioration mechanism is clearly identified. In cases where the deterioration mechanism is clearly identified, structures may be maintained in accordance with the descriptions of deterioration mechanisms in **Part 2**. Then, the possibility of composite actions with other types of deterioration should be examined. Maintenance methods should basically be confirmed in accordance with **Part1**.

When adopting special materials, methods and construction not adequately described in this Specification, the major points of this Specification should be duly respected to meet actual situations. For special materials, methods and construction, the Society of Civil Engineers of Japan has prepared recommendations and manuals as listed below.

Recommended Practice for High Strength Concrete, 1980
Recommendations for Design and Construction of Steel Fiber Reinforced Concrete, 1983
Manual of Design and Construction for Lightweight Aggregate Concrete Structures, 1985
Recommendations for Design and Construction of Structures by Prestressed Concrete Panel Composite Slab Method (draft), 1988
Recommendations for Design and Construction of Prestressed Concrete Method, 1991
Recommendations for Design and Construction of Anti-washout Underwater Concrete, 1991Design Code for Steel-Concrete Sandwich Structures (draft), 1992
Recommended Practice for Concrete Containing Air-entraining High range Water-reducing Agents, 1993
Recommended Practice for Expansive Concrete, 1993
Recommendations for Design and Construction of Concrete Structures Using Continuous Fiber Reinforcing Material, 1996
Recommendations for Design and Construction of Composite Structures, 1997
Recommendations for Construction of High-Flowable Concrete, 1998
Guidelines for Retrofit of Concrete Structures, 1999
Recommendations for Design of Reinforced Concrete Columns with Steel Fiber (draft), 1999
Recommendations for Upgrading of Concrete Structures with Use of Continuous Fiber Sheets, 2000
Recommendations for Design and Construction of Structure using Self-compacting, High-strength and Durable Concrete (draft), 2001
Recommendations for Design and Construction of Electrochemical Corrosion Control Methods, 2001
Recommendations for Design and Construction of Concrete Structures Using Epoxy Coated Reinforcing Steel Bars (revised edition), 2003
Recommendations for Design and Construction of Ultra High Strength Fiber Reinforced Concrete Structures, 2004
Recommendations for Concrete Repair and Surface Protection of Concrete Structures, 2005
Recommendations for Shotcreting, 2005
Recommendations for Environmental Performance Verification for Concrete Structures, 2005
Recommendations for Design, Fabrication and Evaluation of Anchorages and Joints in Reinforcing Bars [2007] , 2007

1.2 Principles of Maintenance

The maintenance manager for structures shall develop plans for maintaining the performance of structures within the allowable range during their planned service period, build a system for maintenance and properly maintain structures.

［**Commentary**］ It is necessary to maintain the performance of the structure within the allowable range during its planned service period. To that end, the maintenance manager shall develop maintenance plans in advance; build a system for properly performing a series of maintenance work from assessment that is composed of such specific jobs as investigations, prediction of deterioration progress, evaluation and judgment of necessity for remedial measures and recording; and maintain structures.

The performance of structures deteriorates with time. The degree of deterioration varies according to the quality of concrete and steel that constitute the structure, structural regions or members, and the environmental condition. The maintenance manager should first consider the state of the structure, accurately predict time-based changes of performance requirements in such terms as safety, serviceability, hazards for third party and aesthetic appearance and landscape, prepare a scenario indicating how the structure needs to be, and develop maintenance plans based on the scenario to maintain the designated performance of the structure during its planned service period. Then, the maintenance manager should evaluate the performance of structures in service based on the maintenance plans and maintain the performance of structures at the level designated in the scenario while taking remedial measures as required. More effective maintenance may be possible by enhancing the cost effectiveness through the introduction of life cycle cost evaluation methods and by increasing the reliability of performance evaluation of structures through the adoption of new technologies.

Structures need to be maintained continuously over a long period of time. In the process, social conditions and environment are expected to be subject to greater change than predicted and the use and importance of the structure may vary from those specified in the original scenario. Reviewing the original maintenance plans may become necessary to secure the budget and human resources required for maintenance. The maintenance manager should therefore build a system for adequately and flexibly respond to the above situations.

Fig. C1.2.1 shows an example of maintenance of a civil engineering structure. Adequately maintaining either a newly constructed or existing structure basically requires the development of a system for implementation, definition of responsibilities and assignment of engineers with designated skills. It is, however, generally difficult to cover all the maintenance work including simple daily maintenance works by highly skilled engineers. The level of engineer inevitably varies according to the level of investigation, evaluation or judgment. For example, in investigations in routine assessment can be conducted not only by responsible engineers who can make a high-level comprehensive decision based on the investigation results, or professional engineers who have a specialized knowledge and skills, but also by investigators with no highly specialized knowledge but with basic knowledge in accordance with the manuals that specifically describe the methods of investigations and of evaluation of results. In the maintenance of structures, therefore, it is important to properly assign a responsible engineer who is held responsible for the maintenance and is authorized to perform maintenance work and to have professional engineers and investigators fulfill their respective roles under the control of the responsible engineer.

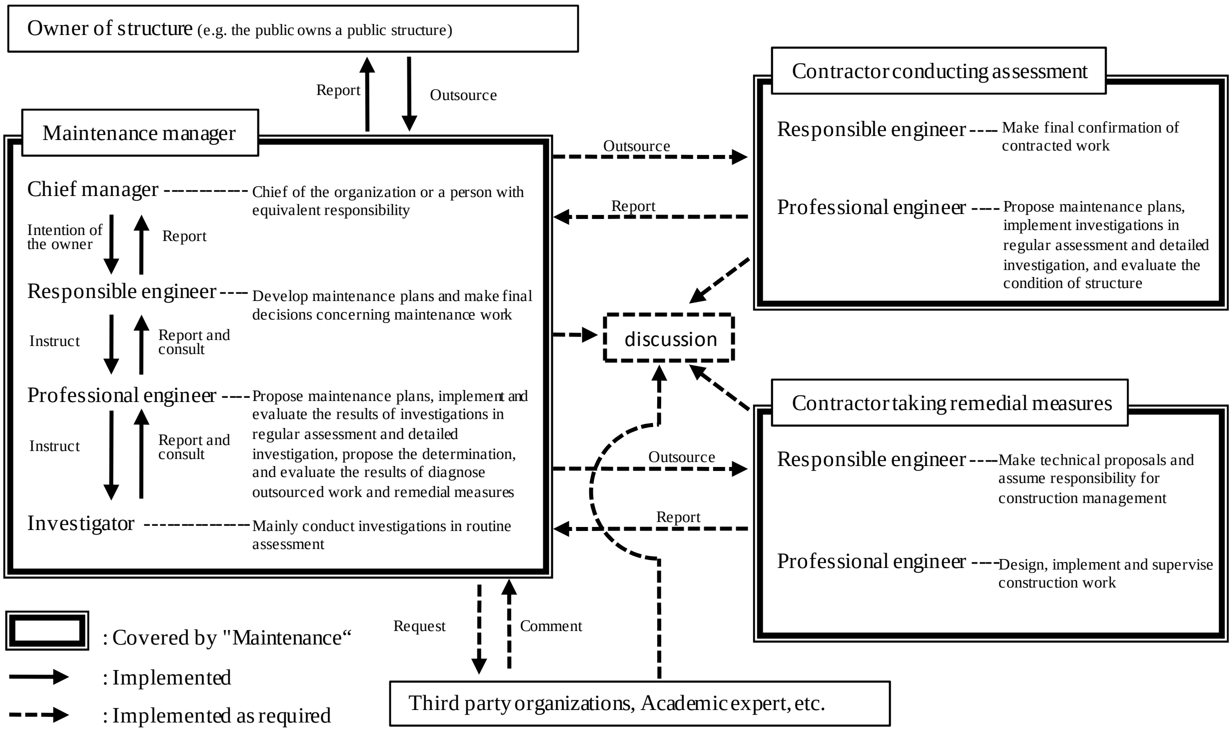


Fig. C1.2.1 Examples of a system for structure maintenance and roles of engineers

The deterioration and damage of structures are never homogeneous. The equipments used in investigations for assessments, and the methods and materials adopted for repair, strengthening and other measures therefore vary greatly. Making highly specialized investigations or implementing special construction methods are sometimes required. Conducting maintenance work exclusively by in-house engineers may be difficult on certain occasions. Then, part of the maintenance work needs to be outsourced to contractors with specialized skills. The maintenance manager should confirm that a responsible engineer capable of and responsible for performing the contracted work is assigned in the contractor and that a system is built under which the maintenance manager can finally evaluate the result of work and make decisions.

The responsible engineer means an Executive professional civil engineer or Senior professional civil engineer authorized by Japan Society of Civil Engineers, a Professional engineer in the field of design, construction or maintenance of concrete structures authorized by The institution of Professional Engineers Japan, or a person with equivalent capacity. The professional engineer means a professional civil engineer authorized by Japan Society of Civil Engineers, concrete diagnosis & maintenance engineer authorized by Japan Concrete Institute, a first-class civil engineering construction management engineer or an engineer with similar capacity.

1.3 Definitions

Terms used in this Specification are defined as follows:

Maintenance: All technical actions for maintaining the performance of the structure above the required level during its service period.

Required performance: The performance required of the structure according to its

purpose and function.

Preventive maintenance: The maintenance for preventing performance degradation of the structure proactively.

Corrective maintenance: The maintenance conducted reactively according to the degree of performance degradation of the structure.

Observational maintenance: The maintenance mainly composed of investigations by visual observation. No direct measures are applied to the structure such as repair and strengthening. The maintenance by indirect observation is included e.g. indirect observation of deformations in the soil and structures in the vicinity in cases where no direct observation is possible for underground members of foundations.

Planned service period: A period during which the structure is scheduled to be in service. It may be modified with a review of maintenance plans.

Design service period: A period during which the structure or member should fully achieve its objective functions as specified in the design phase.

Remaining planned service period: A period between the time of investigation or review and the end of planned service period.

Remaining design service period: A period between the time of investigation or review and the end of design service period.

Function of structure (member): The role that the structure (or its member) depending on the purpose and requirements.

Performance of structure (member): The capacity shown the structure (or its member) depending on the purpose and requirements.

Durability: The resistance of the structure to time-based deterioration of performance due to the degradation of members of the structure under an assumed action.

Safety: The performance of the structure for keeping the life or property of the user or of a person in the vicinity free from any threat.

Serviceability: The performance of the structure for enabling the user of the structure to comfortably use the structure or prevent a person in the vicinity from feeling uncomfortable owing to the structure, and the performance for properly providing other functions required of the structure.

Hazards for third party: Effects of damage to people or property caused by concrete pieces falling off the structure.

Investigation in assessment: Any action in diagnosis for checking for problems with the structure or member.

Investigation in initial assessment: An investigation made at the start of maintenance mainly to identify the initial conditions of the structure.

Investigation in routine assessment: An investigation that is made periodically once in several days through once a week and is composed mainly of simple inspections including visual observation.

Investigation in regular assessment: An investigation made periodically once in several years to identify the conditions of the structure or member that cannot be confirmed by investigations in routine assessment.

Investigation in extraordinary assessment: An investigation made temporarily to identify the conditions of the damage to the structure caused by accidental loads during a great earthquake or typhoon or, by artificial accidental loads at the time of a crash of vehicles or ships or fire.

Investigation in emergency assessment: An investigation made urgently in the event of an accident or damage greatly affecting a structure to verify whether or not similar structures or structures under similar conditions are subject to a similar accident or damage.

Standard investigation: A specified package of investigation items in the maintenance plan.

Detailed investigation: Any investigation to collect detailed data not obtained in standard investigation.

Monitoring: Identifying the conditions of the structure or member using the sensors installed in the structure or member.

Repair: A measure to remove the hazards for third party or restore or improve esthetic appearance and landscape or durability. Included are the measures to restore mechanical performance in terms of safety and serviceability to the level available to the structure at the time of construction.

Strengthening: A measure to raise the mechanical performance in terms of safety and serviceability above the level available to the structure at the time of construction.

Seismic retrofitting: A kind of retrofitting conducted to achieve the seismic performance in accordance with the latest criteria in cases where the seismic performance of an existing structure becomes no longer conforming to new criteria because of the revision of design standards.

[Commentary] Preventive maintenance: The performance of structures generally starts deteriorating as the degradation of members becomes outstanding. Preventive maintenance is a method of maintaining structures by taking appropriate measures to prevent outstanding deterioration from occurring. Preventive maintenance is the most desirable maintenance method because it minimizes the deterioration of the structure or member. Detailed investigations and monitoring are required even before the deterioration becomes outstanding. Predicting deterioration with relatively high precision is also required. Preventive maintenance is effective especially for maintaining important structures and structures with a long planned service period.

Remedial maintenance: This maintenance method is composed of relatively simple investigations mainly based on visual observations before the occurrence of outstanding deterioration, and implementation of appropriate measures to control deterioration after the deterioration is determined outstanding. At present, this category of maintenance is carried out in numerous cases.

Observational maintenance: In cases where a structure has been in service with no special repair or strengthening or where a member that is relatively easy to replace is replaced at the discretion of the persons who perform maintenance work, neither detailed investigations are made nor remedial measures are implemented and the structure or member is maintained through simple visual observations. Observational maintenance is applied to structures or members for which direct investigations are not or cannot be implemented but which are checked for an anomaly indirectly by inspecting the deformations of soils or the structures in the vicinity. Examples include underground structures and foundation structures for which direct investigations are difficult.

Planned service period and design service period: The planned service period is determined as well as the design service period at the time of design. In design, the design service period is generally assumed to be longer than the planned service period (Fig. C1.3.1). Maintenance may be planned on the assumption of the design service period shorter than the planned service period and of repair and strengthening while the structure is in service. The maintenance manager sometimes revises the planned service period based on the social or economic factors such as future changes in type and level of performance requirements for the structure. The planned service period may also be prolonged owing to the revision of maintenance plans with social changes while the structure is in service. Then, the structure will be maintained by repair or strengthening to achieve the performance requirements throughout the revised planned service period.

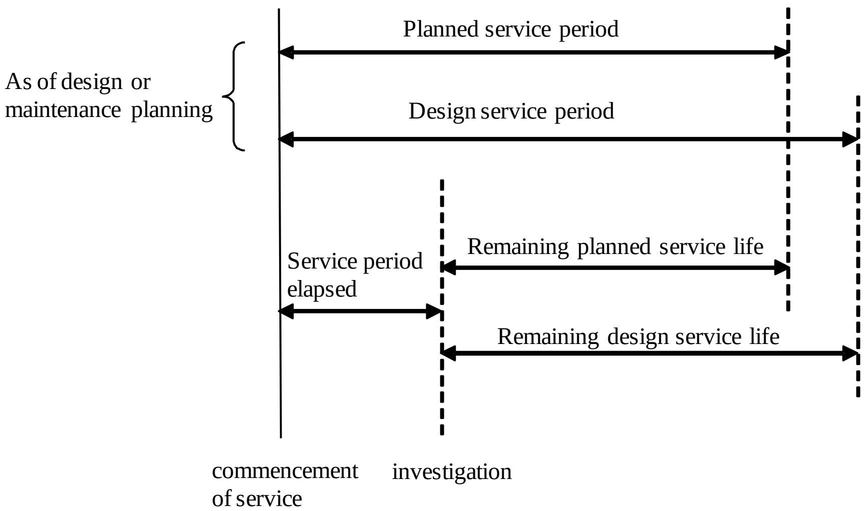


Fig. C1.3.1 Image of useful life and service period
(in the case of design service period longer than planned service period)

Durability, Safety, Serviceability and Hazards for third party: Refer to Chapter 2 Performance Requirements.

Investigation in assessment: The objective of investigation is to identify the performance of the structure and collect data required for maintenance. In this Specification, investigation is defined to include document search, inspection and testing. Assessment refers to any action not only for investigation, or checking for an anomaly in the structure, but also for prediction of deterioration progress based on investigation results, performance evaluation of the structure and judgment of necessity for remedial measures.

Standard investigation and Detailed investigation: The methods should be specified in maintenance plans for making investigation to obtain specific data on the conditions of the structure or member during the investigations in such as routine, regular and extraordinary assessments. In this Specification, the investigation specified in the maintenance plans is defined as the standard investigation and the investigation for obtaining more detailed data not collected in standard investigation is defined as the detailed investigation.

Monitoring: The methods for continuously identifying the progress of deterioration of concrete structures or members include identifying the progress of deterioration by detailed investigations conducted at relatively short intervals before outstanding deterioration occurs, identifying the progress of deterioration by collecting at designated times detailed data including the data obtained in fracture tests using specimens exposed around the structure and grasping the conditions of the structure or member real-time using sensors installed in the structure or member. In this Specification, the method of grasping the conditions of the structure or member using sensors is defined as monitoring.

Repair and Strengthening: Restoring the mechanical performance of the structure or member reduced by deterioration or damage to or above the level available at the time of construction is defined as repair or strengthening respectively. Remedial measures taken when the performance requirements for durability or the hazards for third party are not met are all defined as repair either for restoring performance to or above the level available at the time of construction (Fig. C1.3.2). Repair work is thus carried out generally in cases where mechanical performance higher than at the time of design or construction is required. Repair includes seismic retrofitting for structures determined non-conforming to new criteria because of revision of design standards.

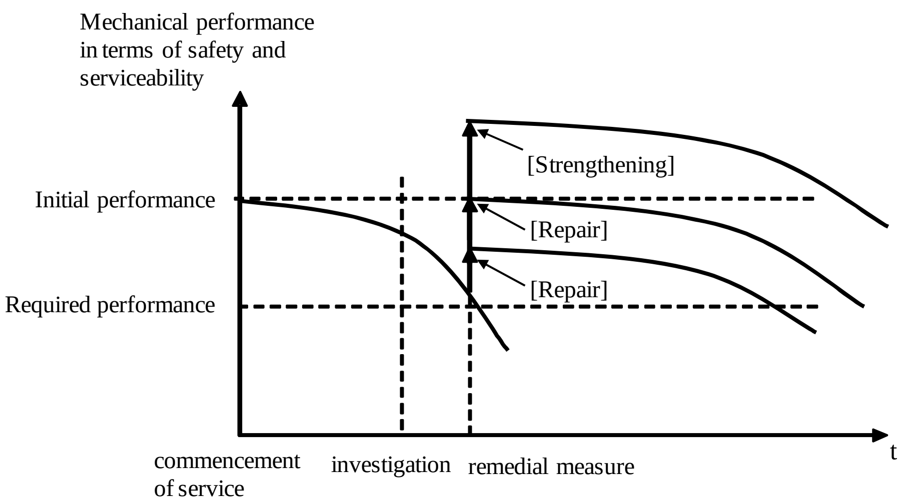


Fig. C1.3.2 Definitions of repair and strengthening

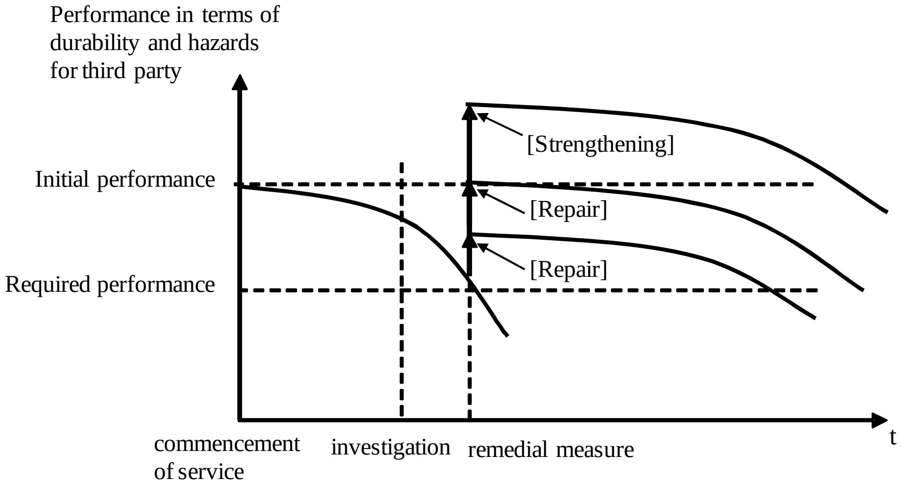


Fig. C1.3.2 Definitions of repair and strengthening

Seismic retrofitting: Seismic retrofitting is a type of repair to help the seismic performance of a structure meet new design standards in cases where the present seismic performance of the structure becomes no longer conforming to new criteria. Seismic retrofitting has been defined separately from other types of repair because it is higher required in Japan, one of the earthquake-prone countries in the world.

CHAPTER 2 PERFORMANCE REQUIREMENTS

2.1 Principle

In the maintenance of a structure, the performance requirements for the structure shall be identified.

[Commentary] In cases where the performance requirements for the structure are not defined explicitly, only inconsistent corrective maintenance is conducted. Then, no structures can be maintained effectively. Identifying the performance requirements of the structure is essential to maintenance. In maintenance, the performance requirements for the structure are checked throughout its planned service period to confirm that the requirements are maintained within the allowable range. When the performance requirements are evaluated and determined to be below the designated level, necessary remedial measures are taken.

The performance requirements are all types of performance required to achieve the purpose for which the structure is used. The performance requirements are generally designated in design. In performance based design, performance requirements are explicitly defined such as safety, serviceability, restorability and other parameters as designated in the "Design" volume of the Standard Specifications. For existing structure, however, performance requirements for the structure in design may be unknown. For maintaining structures, therefore, not only the performance requirements considered in design but also the performance requirements that are not considered in design but are important from the maintenance viewpoint should be identified.

2.2 General

(1) The performance requirements in maintenance for an ordinary structure covers are safety, serviceability, hazards for third party, esthetic appearance and landscape, and durability .

(2) Safety is related to safety against sectional fracture and seismic load, safety against fatigue fracture and safety with respect to the stability of structures.

(3) Serviceability is related to the performance that enables the user of the structure to use the structure comfortably and the functions required of the structure.

(4) Hazards for third party are related to public damage to third parties caused by structures such as the falling of cover concrete lumps and the noise that is caused while the structure is in service.

(5) Esthetic appearance and landscape are related to the harmonization with the surrounding environment including the effects of stain of rust and cracks due to deterioration.

(6) Durability is related to the durability in terms of safety, serviceability, the hazards for third party, and esthetic appearance and landscape.

［**Commentary**］(1) There are wide varieties of structures. The functions required of respective structures also vary greatly. The maintenance of structures is a process in a series from construction, service (maintenance), demolishing and removal or reuse. Maintenance is the act to secure the performance required while the structure is in service based on a comprehensive concept. In this Specification, the basic performance requirements for ordinary structures have been classified into safety, serviceability, hazards for third party, esthetic appearance and landscape or durability (Fig. C2.2.1). The "Design" volume of the Standard Specifications lists safety, serviceability, restorability and other performance requirements as the performance requirements for structures. This Specification basically covers the same performance requirements but additionally describes the hazards for third party, esthetic appearance and landscape, and durability because structures or members are given different performance priorities in design and in maintenance. Details are provided below.

Restorability is defined in the "Design" volume of the Standard Specifications as the performance for restoring the functions of the structure in the designated period of time to make the continuous use of the structure possible. The restorability of the structure after it is put into service can, however, be evaluated by checking safety or serviceability. This Specification therefore provides no description about restorability as a performance requirement.

In relation to other performance requirements, resources should be used effectively and carbon dioxide emissions, energy consumption and environmental impact should be reduced in the process from the demolishing to reuse of structures. This should be fully considered during maintenance. An increasing number of researches have recently been conducted and discussions made concerning the basic concepts and methods related to this issue. This Specification should specifically present evaluation technologies once they have been established. Article concerning this issue can be referred to the Recommendations for Environmental Performance Verification for Concrete Structures.

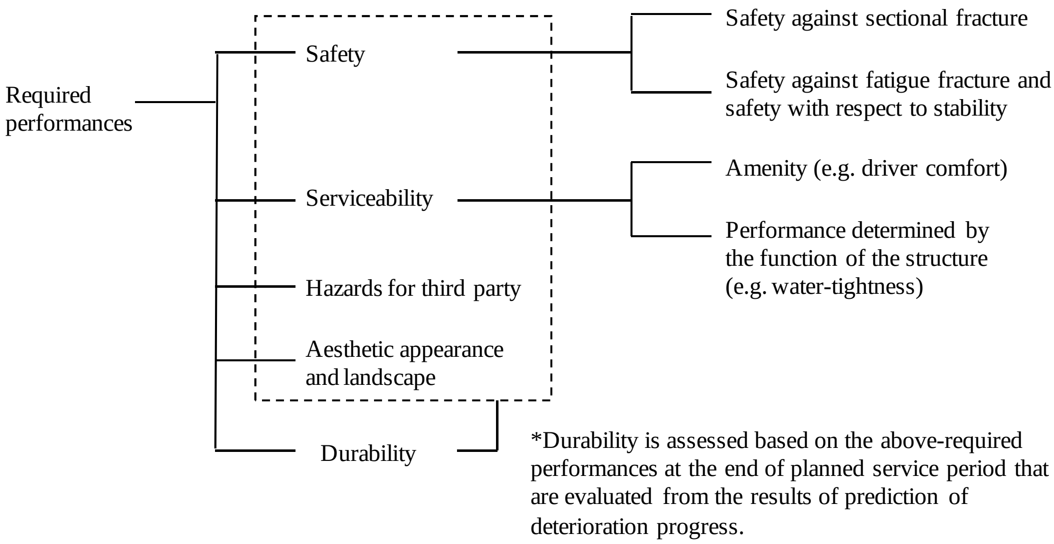


Fig. C2.2.1 Classifications of performance requirements

(2) The performance requirements for safety have been designated like the design-performance requirements in the "Design" volume of the Standard Specifications. The safety

against sectional fracture should be evaluated for all the loads and environmental actions that are likely to be applied while the structure is in service, which include accidental loads such as earthquakes and impact loads due to the collision with vehicles or ships.

Also included in the performance requirements for safety are the safety against fatigue fracture and the safety with respect to the stability of the structure (performance to maintain the stability of the structure against slides or collapses mechanism), and the functional safety to ensure the travel of vehicles and trains.

(3) The performance requirements for serviceability have also been designated like the design-performance requirements in the "Design" volume of the Standard Specifications. Included are the performances for amenity while using the structure and the performance for the functions required of the structure.

The "Design" volume of the Standard Specifications lists the comfort of vehicle occupants and pedestrians, facades, and noise and vibration levels as amenity factors. In maintenance, facades are related to aesthetic appearance and landscape, and noise and vibration levels are related to the hazards for third party. The comfort of vehicle occupants and pedestrians should therefore be evaluated as the performance for serviceability.

As the performance for the functions required of the structure, capacities to intercept or permeate materials such as the water-tightness, permeability, sound proofing, moisture proofing, and protection from cold or heat should be evaluated in maintenance. Many of the performance factors are subject to time-based changes from the initial level. The performance for the functions required of the structure generally varies with the changes of social conditions. For example, highway bridges need to have sufficient lanes to carry actual traffic volumes.

(4) The hazards for third party are specified as one of the safety performances in the "Design" volume of the Standard Specifications such as public damage of the structure to third parties due to the falling of cover concrete lumps. The hazards for third party however are not related to the load bearing capacity of the main body of the structure and require a different performance verification process from that for safety. Addition to that, those are one of the important performance requirements in maintenance. The hazards for third party are therefore treated separate from safety in this Specification. Noise affecting the surrounding area while the structure is in service is included in the hazards for third party.

(5) The "Design" volume of the Standard Specifications stipulates that structures should be designed so as to be provided with aesthetic appearance and landscape that are in good harmony with the surrounding environment. The effects of rust and cracks due to the smudging or deterioration of the structure on aesthetic appearance and landscape may sometimes be important in determining maintenance measures. Aesthetic appearance and landscape have therefore been specified as a performance requirement.

(6) This Specification has designated durability as a performance indicator to comprehensively determine whether safety, serviceability, hazards for third party, and aesthetic appearance and landscape can be maintained within the allowable range over the planned service period as the "Design" volume of the Standard Specifications. While the structure is in service, the performance requirements for safety, serviceability, hazards for third party, and aesthetic appearance and landscape should be achieved from a maintenance viewpoint. If time-based change in these performance factors can be verified with sufficient accuracy, there is no need to consider durability as a performance indicator. The techniques to predict deterioration or evaluate performance have recently been advancing remarkably. However, those techniques are not practically mature at present. In this Specification, therefore, durability, which has been generally used in and out of

Japan, has been designated as a parameter that comprehensively indicates these performance factors during the planned service period. Verifying durability is considered to serve as an alternative to verifying whether performance requirements are met or not in terms of safety, serviceability, hazards for third party, and aesthetic appearance and landscape during the planned service period of the structure.

Considering durability as performance requirements is related to how the planned service period should be specified and what level of performance requirements should be achieved in terms of safety, serviceability, hazards for third party, and aesthetic appearance and landscape during the planned service period of the structure. In this Specification, therefore, the durability of the structure is assumed to be guaranteed during the planned service period of the structure if it can be confirmed that the performance requirements for the structure are achieved in terms of safety, serviceability, hazards for third party, and aesthetic appearance and landscape both at the time of investigation and at the end of the planned service period of the structure. Durability should be examined properly not only by quantitative methods but also semi-quantitative methods (e.g. grading).

CHAPTER 3 METHODS FOR MAINTENANCE

3.1 Principle

The maintenance manager for structures shall develop plans for maintaining the performance of structures within the allowable range during their planned service period. The manager also shall appropriately assess structures, take remedial measures based on the results of assessments and record the results of assessments and remedial measures.

[Commentary] Collectively referred to as the maintenance of structures is the action for maintaining the performance of a structure within the allowable range during its planned service period. The maintenance of structures is composed of assessments consisting of investigations, estimations of deterioration mechanisms, predictions of deterioration, performance evaluation of structures and judgment of necessity for remedial measures; remedial measures taken as required based on the results of assessments; and recording of the results of assessments and remedial measures, as shown in Fig. C3.1.1. In order to carry out all the work properly, the maintenance authority for structures should first develop maintenance plans and maintain structures in accordance with **1.2** "Principles of Maintenance. "

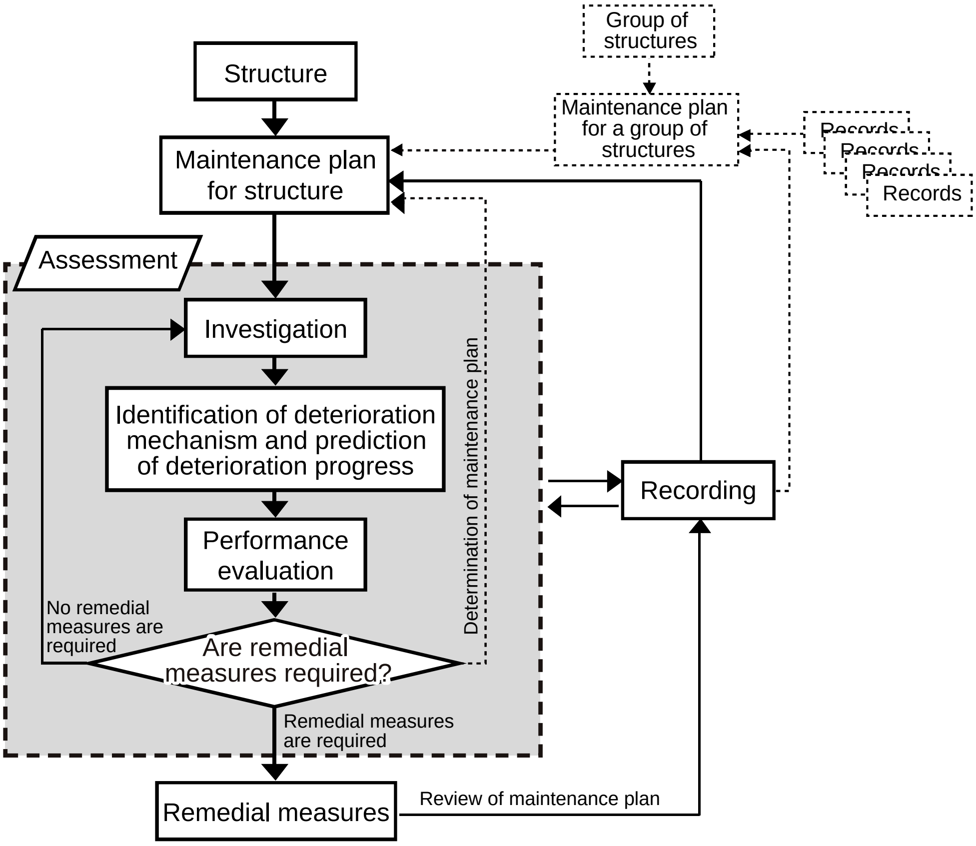


Fig. C3.1.1 Procedure for maintaining a structure

For the maintenance of structures, methods have been studied for developing structure maintenance plans more efficiently while optimizing the budget by regarding multiple social infrastructure systems (a group of structures) including the particular structure as an asset and building an asset management system for the group of structures. In these methods, maintenance plans are first developed for the group of structures, and then for individual structures constituting the group, and the plans are implemented. No satisfying maintenance methods have, however, been established for groups of structures. No maintenance for groups of structures is therefore described in this Specification.

3.2 Maintenance Plans

3.2.1 General

(1) Maintenance plans should select the maintenance categories; and describe the deterioration mechanisms expected during the planned service period; methods of assessments composed of investigation of structures, regions and members, predictions of deterioration, performance evaluation for structures and judgment of necessity for remedial measures; and remedial measures fit for the expected deterioration and methods for selecting remedial measures.

(2) Maintenance plans shall be developed before the performance of maintenance work, modified as required based on the results of initial assessments that are made following the development of the plan, and then finalized. Maintenance plans should be reviewed as required during the maintenance.

(3) Once maintenance plans have been developed, manuals should be prepared that present maintenance procedures based on the maintenance plans.

[Commentary] (1) Maintenance plans comprehensively describe the timing, frequency, methods and systems (organizations, human resources, budgets, etc.) of assessments, remedial measures and recording regarding the condition of the structure.

Fig. C3.2.1 outlines a procedure for developing maintenance plans. For developing maintenance plans for a structure, the period should first be determined for maintaining the structure based on the planned service period of the structure assumed in the design phase. In cases where no planned service period has been specified in the design phase, the design service period may be regarded as the planned service period for developing maintenance plans. The design service period is sometimes determined for a certain structure, region or member based on the assumption of renovating the structure, region or member during its planned service period. Then, the renovation plan should be incorporated into the maintenance plan. When developing a maintenance plan for a structure in service, the remaining planned service period, which is obtained by subtracting the service period elapsed from the planned service period, should be specified as the period of maintenance.

Importance, planned service period and environmental conditions vary from structure to structure. Maintaining structures placed under different conditions in one and the same manner is not rational. It is therefore important to classify maintenance optimally according to the conditions of structures. For specific descriptions of maintenance types, refer to **3.2.2** “Categories and Details of Maintenance.”

The phenomena that deteriorate structures such as carbonation, chloride attack, frost attack and alkali-silica reaction are referred to as deterioration mechanisms. Structures are deteriorated by either external or internal factors. External factors include environmental, meteorological and external force conditions at the location of the structure. Internal factors are related to design parameters such as the dimensions of regions and members, concrete cover, arrangement of steel, design strength, mix proportions and material quality, or to construction parameters such as the condition of fresh concrete, method of placement and method of curing. Deterioration mechanisms vary for structures under the same environmental conditions if the structures are affected by different internal factors. The above points should be taken into consideration when developing maintenance plans to properly estimate deterioration mechanisms that are expected to be found in structures.

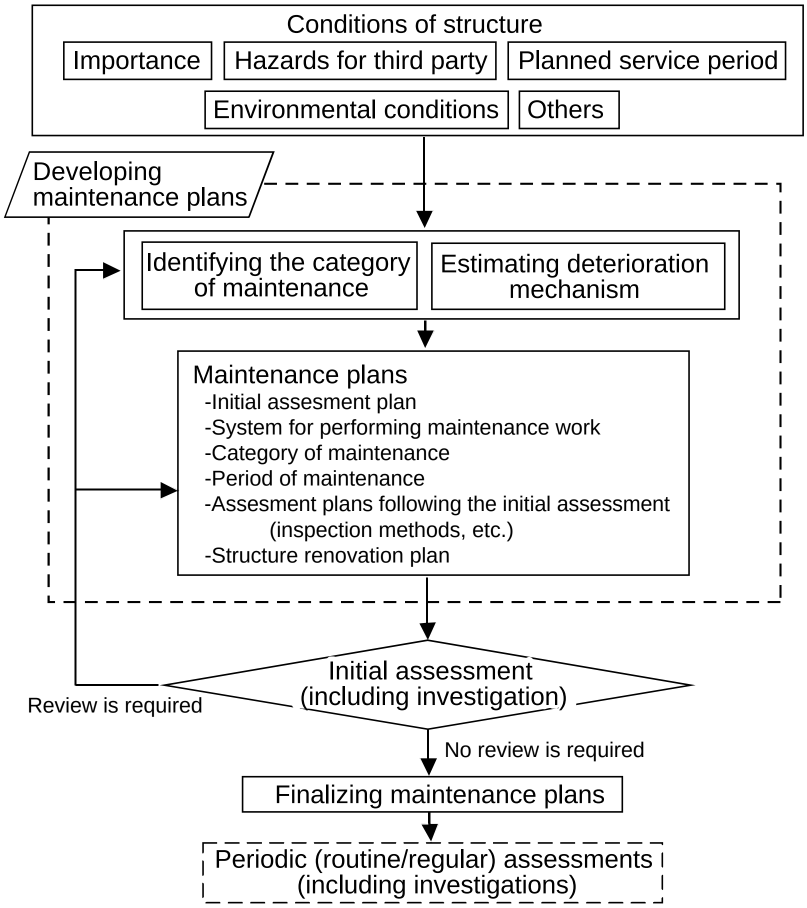


Fig. C3.2.1 Procedure for developing maintenance plans

As described above, maintenance plans are developed after the period and category of maintenance are specified and deterioration mechanism is estimated. Maintenance plans define specific components of assessment such as the details (e.g. method and frequency) of inspections conducted in inspection methods for estimating deterioration, methods for evaluating the performance of the structure, and criteria for determining the need of remedial measures according to the objective of assessment; and present the planned method, scale, time and sequence of implementation of remedial measures fit for the expected deterioration. When developing maintenance plans in the planning and design phases of a new structure, cooperating the design and the development of maintenance plans for the structure may be effective. For example, inspection passages or ladders may be installed to facilitate maintenance work. Studying the cost effectiveness of investigations or remedial measures enables the selection of a more efficient maintenance scenario at optimal life cycle cost. It is also important to develop maintenance plans while anticipating natural disasters such as earthquakes and typhoons and accidents like fire and crashes of ships.

(2) For a new structure, maintenance plan development should be started in the planning and

design phase of the structure. Data should be collected at the initial assessment upon the completion of the construction to verify the need for reviewing the original maintenance plan. Modifications should be made to the maintenance plan as required, and then the maintenance plan should be finalized. When maintaining an existing structure in service in accordance with this Specification, initial assessment should be specified in the maintenance plan, and the adequacy of the maintenance plan should be examined based on the information on the structure obtained in investigations in the initial assessment before finalizing the maintenance plan. After large-scale remedial measures are taken or if the results of prediction of deterioration progress based on the investigation results are different from the initial prediction of deterioration progress, the maintenance plan that is being implemented should be reviewed as required. Structures are in service over a long period of time. The required performances for structures are highly likely to vary during the period because of changes of public life-style or needs, changes in physical distribution or social changes. Reviewing maintenance plans may become necessary to reflect such changes.

(3) Structures in service are not always maintained by the responsible engineer who developed the maintenance plan. Investigation in the routine assessment is not always conducted by a professional engineer. Once the maintenance plan has been developed, therefore, manuals should be prepared and training programs should be implemented for those who are engaged in maintenance work as required so as to carry out maintenance as scheduled.

3.2.2 Categories and details of maintenance

(1) The category of maintenance shall be selected based on the importance, hazards for third party, planned service period and environmental conditions of the structure or member.

(2) The category of maintenance shall be selected from among the following three.
A: Preventive maintenance
B: Corrective maintenance
C: Observational maintenance

[Commentary] Structures should be maintained properly after the category of maintenance is selected considering their importance, hazards for third party, planned service period and environmental conditions. The importance of maintenance varies greatly according to the social and economic importance, hazards for third party and planned service period of the structure or member. The ease of the components of maintenance such as the prediction of deterioration progress, repair and strengthening also varies from structure to structure. Applying any uniform concept of maintenance is therefore not effective. The category of maintenance should be defined that is properly fit for the conditions of the structure or member.

This Specification adopts three types of maintenance: A Preventive maintenance, B Corrective maintenance and C Observational maintenance. A Preventive maintenance and B Corrective maintenance should be treated as standard types of maintenance.

The characteristics of structures that require the respective types of maintenance are described below.

A: Preventive maintenance
(i) No deterioration should occur because outstanding deterioration makes maintenance difficult.
(ii) Deterioration of concrete surface causes failure.

(iii) Safety for third parties is extremely important.
(iv) The design service period is long.

The structures in this category are generally very important, so monitoring is effective in numerous cases. Monitoring means continuous measurement of stress, deformation, corrosion and temperature of members using sensors installed on the surface of or inside the structure.

B: Corrective maintenance
(i) Remedial measures can be taken easily even after the occurrence of outstanding deterioration.
(ii) Outstanding deterioration causes no trouble.

C: Observational maintenance
(i) The structure is used as long as possible with no design service period being specified.
(ii) Evaluation and judgment are conducted by investigating structures indirectly (surveying, soil settlement, leakage, etc.) due to the extreme difficulties in investigating structures directly.

3.3 Assessments

3.3.1 General

(1) In the assessment of structures, investigations shall be carried out following the maintenance plan. Based on the results of the investigation, confirmation of deterioration based on the results of investigations, identification of deterioration mechanisms, prediction of deterioration progress, evaluation of performance of the structure and judgment of necessity for remedial measures shall be done appropriately.

(2) Assessments include initial, periodic and extraordinary assessments. Professional engineers or engineers at a higher position with knowledge and experience shall conduct assessments based on the investigation plan defined during the development of the maintenance plan.

[Commentary] (1) Assessment collectively means a series of actions during maintenance for finding defects in the structure or member. The series is composed of investigation, evaluation of performance of the structure and the judgment of necessity for remedial measures. For properly maintaining structures based on plans, the conditions of the structure should first be identified by investigations, the deterioration mechanisms that occur or are likely to occur in the structure should be estimated, and deterioration should be predicted. Based on the results of investigations and deterioration predictions, whether the required performances for the structure are expected to be achieved or not during its planned service period in terms of safety, serviceability, hazards for third party, and aesthetic appearance and landscape should be determined; and whether the remedial measures are required or not should be determined. The prediction of deterioration progress means predicting the future deterioration of the structure, region or member caused by the deterioration mechanism estimated based on the results of investigations. Examples are predictions of the progress of corrosion of steel in concrete due to carbonation or chloride attack, or concrete surface deterioration due to frost attack.

This Specification defines deterioration as the defect that progresses with time and distinguish deterioration from the initial defects such as crack, honeycombing, formation of cold joints and sand streaking that is generated during construction or the damage that occurs in a short period of time but remains unchanged subsequently such as the crack and peeling due to earthquakes or crashes. This Specification describes the methods of maintenance mainly in the case of performance degradation of structures due to deterioration. In cases where part of the initial defects are left unattended in the structure or where damage is caused by earthquakes or crashes, the effects of the defect should be evaluated by assessment.

In cases where the design loads are changed or the required performances of the structure are changed to comply with new seismic performance criteria during its service period, it becomes necessary to make assessments to evaluate the load bearing capacity or seismic performance of the structure, to review the maintenance plan to maintain the structure in accordance with the new criteria and to take remedial measures including strengthening as required.

(2) The details of investigations required and the levels of prediction of deterioration progress, evaluation of performance of the structure and judgment of necessity for remedial measures vary greatly according to the objective of assessment. Positioning assessments similarly and making assessments at one and the same technical level are not effective. This Specification therefore classifies assessments as the initial assessments conducted initially in maintenance, periodic assessments conducted routinely or periodically during the period of maintenance, or extraordinary assessments conducted in cases where accidental loads act on the structure.

Fig. C3.3.1 shows flowcharts for maintenance and the positioning of assessments. For details of the respective actions in a series of assessment from investigation to the judgment of necessity for remedial measures, refer to the chapters indicated in the figure.

Assessments are very important actions that determine the future of the structure that is being maintained. Professional engineers or engineers at higher positions with adequate knowledge and experience should conduct assessments based on the assessment plan that the maintenance authority defined during the development of the maintenance plan.

Responsible engineers should make the assessments that involve higher level decision-making concerning the future and cost performance of the whole group of structures. Other engineers than professional engineers may be assigned to daily assessments that involve simple decision-making based on the available manuals such as the determination of whether the structure has defect or not that the considerations in inspections are made available to the engineers.

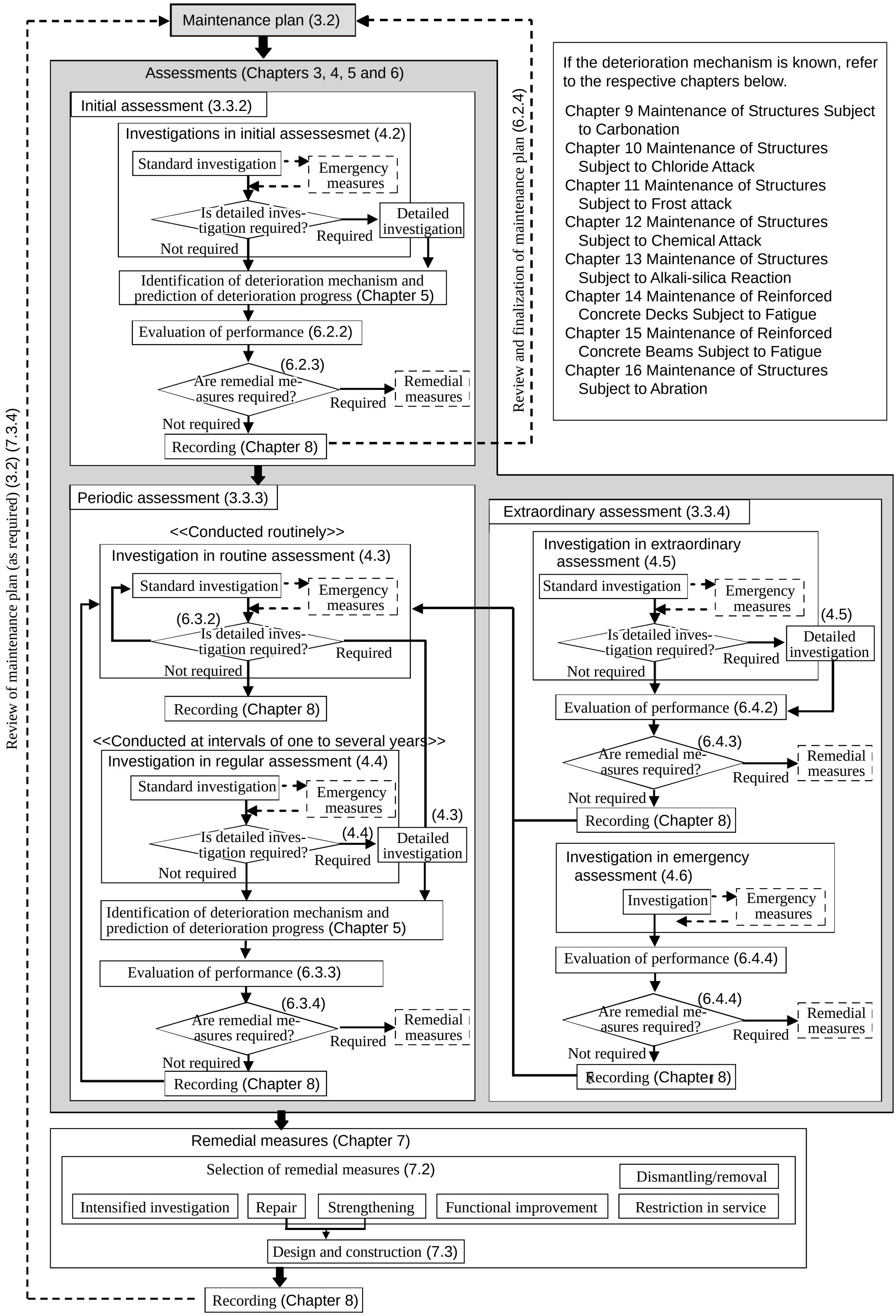
3.3.2 Initial assessments

(1) The initial assessment shall be conducted when identifying the initial conditions of the structure or when reviewing the maintenance plan is required after a large-scale repair or strengthening.

(2) In the initial assessment, it is necessary to estimate the deterioration mechanism, evaluate the performance of the structure, judge the need of remedial measures, and verify the validity of the maintenance plan based on the results of investigation.

(3) In cases where emergency or other measures are found necessary in the initial assessment, appropriate actions shall be taken.

[Commentary] (1) The initial here means the initial stage of maintenance conducted in accordance with this Specification. The initial assessment means the assessment conducted for a new structure for the first time since the commencement of service. The initial assessment also means the first



Maintenance plan (3.2)
Assessments (Chapters 3, 4, 5 and 6)
Initial assessment (3.3.2)
Investigations in initial assessesmet (4.2)
Standard investigation
Emergency measures
Is detailed investigation required?
Required
Not required
Detailed investigation
Identification of deterioration mechanism and prediction of deterioration progress (Chapter 5)
Evaluation of performance (6.2.2)
(6.2.3)
Are remedial measures required?
Remedial measures
Recording (Chapter 8)
Review and finalization of maintenance plan (6.2.4)
Review of maintenance plan (as required) (3.2) (7.3.4)
If the deterioration mechanism is known, refer to the respective chapters below.
Chapter 9 Maintenance of Structures Subject to Carbonation
Chapter 10 Maintenance of Structures Subject to Chloride Attack
Chapter 11 Maintenance of Structures Subject to Frost attack
Chapter 12 Maintenance of Structures Subject to Chemical Attack
Chapter 13 Maintenance of Structures Subject to Alkali-silica Reaction
Chapter 14 Maintenance of Reinforced Concrete Decks Subject to Fatigue
Chapter 15 Maintenance of Reinforced Concrete Beams Subject to Fatigue
Chapter 16 Maintenance of Structures Subject to Abration
Periodic assessment (3.3.3)
<<Conducted routinely>>
Investigation in routine assessment (4.3)
(6.3.2)
<<Conducted at intervals of one to several years>>
Investigation in regular assessment (4.4)
(4.3)
(4.4)
Evaluation of performance (6.3.3)
(6.3.4)
Extraordinary assessment (3.3.4)
Investigation in extraordinary assessment (4.5)
(4.5)
Evaluation of performance (6.4.2)
(6.4.3)
Investigation in emergency assessment (4.6)
Investigation
Evaluation of performance (6.4.4)
(6.4.4)
Remedial measures (Chapter 7)
Selection of remedial measures (7.2)
Dismantling/removal
Intensified investigation
Repair
Strengthening
Functional improvement
Restriction in service
Design and construction (7.3)
Recording (Chapter 8)

Fig. C3.3.1 Flowcharts for maintenance and positioning of assessments

assessment of an existing structure that has not been maintained and for which a new maintenance plan has been developed. The initial assessment also means the assessment conducted for the first time since a review of the maintenance plan was considered necessary because of a large-scale repair or strengthening of an existing structure or for other reasons.

(2) and (3) The initial assessment is conducted to grasp the initial conditions of the structure in terms of various performance parameters to enable the maintenance of the structure in accordance with a designated plan. The initial assessment has three major objectives.

(i) To verify the validity of the maintenance plan developed before the initial assessment and to collect data for finalizing the maintenance plan

(ii) To collect basic data (initial values) for starting the maintenance of the structure

(iii) To discover potential problem areas in future maintenance such as the initial defects, damage or deterioration to take remedial measures in the initial stages

The major objectives of the investigation in the initial assessment are to determine whether a new structure has been constructed properly or not, or whether a large-scale repair or strengthening was carried out properly or not for an existing structure, and to collect data required for starting the maintenance of the structure. The investigation is important to the confirmation of initial defects (e.g. cracks, cold joints and honeycombs) and damage, and to the identification of the initial data for predicting deterioration. Determining the need of emergency measures is also desirable in the investigation. For details of investigations in the initial assessment, refer to **4.2** “Investigations in Initial Assessment.”

In order to properly maintain a structure based on a predetermined plan, predicting how the structure, region or member will change in the planned service period is important. In the initial assessment, therefore, the deterioration mechanism expected to occur in the structure should be estimated based on the results of the investigation, and future deterioration should be predicted for the deterioration mechanism using an appropriate model. For the specific methods for estimating deterioration mechanisms and predicting deterioration, refer to **Chapter 5** “Identification of deterioration mechanisms and Prediction of Deterioration Progress.”

If no initial defects, such as deterioration, damage and initial defect, are found in the structure, region or member in the investigation, it is assumed that the required performances at initial stage of meintanance are achieved. If any defects or damage is outstanding, appropriate measures should be taken. The performance of the structure during or at the end of its planned service period should be evaluated based on the results of deterioration prediction described earlier. The results of performance evaluation should be considered when examining the validity of the maintenance plan developed. The maintenance plan may be reviewed if a review is found necessary as a result of the examination of the validity of the plan. In cases where serious deterioration is found outstanding in the initial assessment and the degradation of performance of the structure is highly likely, appropriate remedial measures should be taken and the investigation should be conducted again. For details of the evaluation of the performance of the structure and judgment of necessity for remedial measures based on the results of the investigation, refer to **6.2** “Evaluation and Judgment in the Initial Assessment.”

Professional engineers with adequate knowledge about the design, construction and maintenance of the concrete structure or engineers with deeper knowledge should conduct the initial assessment.

3.3.3 Periodic assessments

(1) The periodic assessment shall be conducted to evaluate the performance of a structure in service and to judge the need of remedial measures.

(2) The periodic assessment shall consist of routine assessment, in which structures are investigated by routine patrols, and of regular assessment, in which small regions of structures that can hardly been identified by routine patrol are investigated in detail.

(3) In the periodic assessment, whether the initial defects, damage or deterioration is found or not should be determined through investigations. Based on the results of the investigations, the deterioration mechanism should be estimated, deterioration progress should be predicted, the performance of the structure shall be evaluated and the need of remedial measures shall be judged.

[Commentary] (1) Periodically assessing a structure in service to identify the changes of its condition may enable the early detection of defect of the structure and the control of performance degradation. Making preparations for repair or other actions in accordance with a designated plan also becomes possible and an efficient and effective maintenance plan can be implemented. Thus, periodic assessments are the most basic and important action in maintenance.

(2) The performance of the structure is evaluated either directly or indirectly and the need of remedial measures is judged as required, based on the results of investigations in routine assessment conducted at intervals of approximately several days to one month and of investigations in regular assessment conducted at a relatively long intervals, e.g. in several years.

The roles of investigations in the periodic and regular assessment differ to each other. In the investigation in the routine assessment, qualitative identification of the defect of the structure is important. Accurate identification of defect is required. In the investigation in the regular assessment, quantitative identification of the defect of the structure is important. For structures to which maintenance category C is applied, it is sometimes difficult to investigate them directly, as in underground structures. Such structures may be investigated indirectly considering the conditions of the structures in the vicinity as required.

For details of these investigations, refer to **4.3** “Investigations in Routine Assessment” and **4.4** “Investigations in Regular Assessment,” respectively.

(3) Periodic assessments are conducted periodically in maintenance, so the maintenance manager should prepare appropriate assessment manuals when developing the maintenance plan. If no deterioration, damage or initial defects are found in the structure, region or member in the periodic assessment, the structure is assumed to meet the designated required performances at the point of assessment. If the structure is found to maintain its required performances at the end of the planned service period by predicting deterioration progress based on the results of investigations, there is no need to revise the maintenance plan and the structure may be maintained easily. In reality, however, predicting the future of a structure based on the limited investigation results is not easy. Evaluating the performance of the structure or predicting deterioration based only on the investigation results is therefore difficult. In cases without any defect, the structure is assumed to be sound at the time of investigation. In cases where deterioration, damage or initial defects are

detected including the delamination of surface concrete leading to the spalling of concrete covering affecting third parties, emergency measures should be taken immediately.

In cases where defect is found in the structure in standard investigation in routine or regular assessment, detailed examination should be made to identify the defect as deterioration, damage or initial defects. In the case of deterioration, the deterioration mechanism should be identified and deterioration progress should be predicted based on the investigation results. For details of the identification of deterioration mechanisms and the prediction of deterioration progress, refer to **Chapter 5** "Identification of deterioration mechanism and Prediction of Deterioration Progress." After the prediction of deterioration progress, the performance of the structure should be evaluated and the need of remedial measures should be determined based on the results of prediction. The need should be determined in principle in accordance with the criteria pre-designated in the maintenance plan. The criteria should be defined by the maintenance manager for the structure or a responsible engineer who can serve as a representative of their view by comprehensively considering the results of evaluation of the performance of the structure at the time of investigation or during the planned service period, the importance of the structure, and the category of maintenance. For details of performance evaluation and the judgment of necessity for remedial measures, refer to **6.3** "Evaluation of Performance and Judgment of the Need of Remedial Measures in Periodic Assessments."

Periodic assessments should be conducted by professional engineers with adequate knowledge about the design, construction and maintenance of concrete structures. Standard investigations in routine assessment may, however, be conducted by engineers other than professional engineers as long as adequate manuals and the guidance of professional engineers are available.

3.3.4 Extraordinary assessments

(1) The extraordinary assessment shall be conducted in cases where an assessment is urgently required such as in the case where accidental loads act on the structure.

(2) The extraordinary assessment shall be conducted aiming at identifying the degree of defect of the structure due to damage or deterioration, evaluate the performance of the structure and determine the need of remedial measures through investigations.

(3) In cases where any damage to people due to the collapse of the structure or serious social and economic effects are predicted in the extraordinary assessment, appropriate measures should be taken as soon as possible.

[Commentary] (1) Extraordinary assessments are conducted under the following conditions in cases where the structure is subjected to great seismic forces, or to external forces of other natural disaster such as typhoons, fire or accidents.

1. The structure or the member has been damaged and its performance has explicitly been deteriorated.

2. Verifications are made for local problems in performance in terms of safety, serviceability, hazards for third party, and aesthetic appearance and landscape of the structure although the disaster is not so serious.

3. Structures similar to the one that suffered damage are checked for a possibility of similar

deterioration or damage, and preventive measures are planned or the maintenance plan is reviewed.

The cases that require extraordinary assessments are described below.

Extraordinary assessments in the case of a natural disaster: The Specification for "Design" stipulates that the seismic performance of a structure should be checked in the design phase in cases where the structure is expected to be subjected to external forces due to an earthquake. Even the structures designed in that way are likely to be damaged when subjected to large seismic forces. In cases where the structure is subjected to an extremely large seismic forces, it may collapse. In the event of an earthquake sufficiently large to affect the structure, extraordinary assessments should be conducted to verify whether the structure, region or member has been damaged or not.

In the event of a typhoon, large wind loads or wave forces may cause damage to the structure. In the event of the flushing of river water, collision of driftwood is likely to damage the structure or scouring is likely to depress bridge piers. The rising of groundwater levels due to heavy rains may lead to the collapse of earth retaining walls. In the wake of a typhoon of a magnitude that is likely to affect the structure, extraordinary assessments should be conducted to verify whether the structure, region or member has been damaged or not.

In the event of other natural disaster than earthquakes or typhoons, extraordinary assessments are required based on the same idea as described above if the scale is large enough to affect the structure.

Extraordinary assessments in the case of a fire: In cases where a structure, region or member is exposed to considerable heat during a fire, concrete or reinforcement is likely to be changed its properties. In the event of a fire near the structure, the regions and members subjected to the fire and the surrounding areas should be given extraordinary assessment.

Extraordinary assessments in the case of crashes of vehicles or ships: In cases where a vehicle or ship crashed into the structure, the position subjected to the crash or the region or member near the position may be damaged. Extraordinary assessments are therefore required.

Extraordinary assessments with the revision of criteria: In cases where the design loads and seismic performance criteria are changed with the revision of relevant criteria during the service period of a structure, whether the structure constructed in accordance with the older criteria meets the new performance criteria or not should be verified. Then, extraordinary assessments are conducted.

Extraordinary assessments required urgently: In the event of an accident due to the defect of a structure such as the initial defects, damage or deterioration, accidents are likely to occur also in other structures that are similar to the structure subjected to the accident or in a similar condition. In order to prevent similar accidents, therefore, all of these structures should also be given extraordinary assessment. The structures that are constructed at the same time or in the same format as those in which considerable defect has been detected in periodic assessments should also be given extraordinary assessment to verify whether they are likely to be subjected to similar deterioration or damage.

(2) Extraordinary assessments are conducted as the assessment of a structure, region or member after a disaster or accident to provide data for identifying the condition or degree of damage and for evaluating the performance of the structure.

Extraordinary assessments are urgently required in numerous cases. In cases where the structure is subjected to a natural disaster or an accident, it is highly likely to collapse or fail, or see its safety greatly deteriorated. Extraordinary assessments should be conducted as soon as possible after such occurrences. In cases where the structure has collapsed or failed, the area around the structure should be closed to unauthorized people or the use of the area should be restricted even if the structure appears to be intact.

In cases where an accident occurs due to the defect of a structure, all the structures similar to the one affected by the accident may be given extraordinary assessment. Then, assessment is made urgently mainly to prevent similar accidents from occurring. In this Specification, such assessment is referred to as emergency assessment separate from extraordinary assessment. For details of investigations in extraordinary and emergency assessments, refer to **4.5** “Investigations in Extraordinary Assessment” and **4.6** “Investigations in Emergency Assessment,” respectively. For details of the evaluation of the performance of the structure and the judgment of necessity for remedial measures based on the investigation results, refer to **6.4** “Evaluation of Performance and Judgment of the Need of Remedial Measure in Extraordinary Assessments.”

Extraordinary assessments should in principle be conducted by professional engineers with adequate knowledge about the design, construction and maintenance of concrete structures or engineers with deeper knowledge.

(3) A natural disaster or an accident is likely to cause the structure to collapse in the worst case. Preventing secondary disasters is important such as the damage to people and serious social and economic effects causing the malfunction of lifeline systems. In cases where any potential damage to people or property has been confirmed in extraordinary assessment such as the spalling of concrete due to the delamination of surface concrete, measures should be taken immediately.

3.4 Remedial Measures

In cases where it was determined that remedial measures should be taken to control the progress of deterioration or the degradation of performance of a structure, appropriate remedial measures shall be taken so as to maintain the performance of the structure for a designated period considering the importance of the structure, category of maintenance, remaining planned service period, ease of maintenance, hazards for third party and cost performance.

[Commentary] Remedial measures are classified into intensified investigation, repair, strengthening, functional improvement, restriction in service or dismantling/removal. Whether taking remedial measures is beneficial or not should be determined comprehensively based on the category of maintenance, remaining service life, ease of maintenance, hazards for third party and life-cycle cost. Then, appropriate remedial measures should be selected.

For implementing remedial measures, examinations should be made to select a specific method, and an optimal plan should be developed that specifies the budget, organization and human resources in order to take effective measures. An appropriate method should be selected considering various methods, timing of implementation, effects of construction work and life cycle cost. The remedial measures should be properly recorded because the records will serve as the basis for a review of the maintenance plan and future maintenance of the structure.

For details of remedial measures, refer to **Chapter 7** “Remedial measures.”

3.5 Recording

In order to maintain structures properly, the results of investigation, prediction of deterioration progress, evaluation of performance of the structure and judgment of necessity for remedial measures in the process of assessment, and the details and methods of remedial measures shall be recorded and stored.

[Commentary] Recording is an action essential to effective maintenance of structures. Records serve not only as the data for the maintenance of the structure but also for reference when maintaining similar structures. The results of investigation, identification of deterioration mechanisms, prediction of deterioration progress, evaluation of performance of the structure and judgment of necessity for remedial measures conducted in a series in assessment; and the details of remedial measures should be recorded in such a format as facilitates reference and stored in while the structure is in service. When a maintenance authority organises maintenance work simultaneously maintains several structures, recording and storage should be done uniformly.

For details of recording, refer to **Chapter 8** “Recording.”

CHAPTER 4 INVESTIGATIONS IN ASSESSMENT

4.1 Principle

(1) The investigations in assessment of a structure shall be conducted by a method fit for the objective of the assessment.

(2) In the initial assessment at the start of maintenance, the investigation for identifying the initial conditions of the structure from a viewpoint of maintenance shall be conducted.

(3) In the periodic assessment, the investigation in routine assessment and the investigation in regular assessment shall be conducted to identify changes in condition of the structure.

(4) In cases where an extraordinary assessment is required, the investigation in extraordinary assessment or the investigation in emergency assessment shall be conducted according to the objective of the assessment.

(5) In the investigations in assessment, standard investigation should be conducted with the frequency, for the contents and by the method specified in the maintenance plan. In cases where identifying the detailed conditions of the structure is determined necessary based on the results of standard investigations, detailed investigations shall be conducted.

(6) In cases where emergency measures are determined necessary as a result of investigations in assessment, emergency measures shall be taken immediately.

[Commentary] (1) Adequately maintaining concrete structures, either new or existing ones, requires adequate assessments. Adequate assessments are based on the acquisition of data on the safety, serviceability, hazards for third party, aesthetic appearance and landscape, and durability of the structure by investigations fit for the objective of the assessment.

Investigations in assessment are classified according to the objective and frequency of assessment and the details of the investigations to be conducted. In this specification, investigations in assessment are classified according to the objective of assessment into the investigations to be conducted at the initial, periodic and extraordinary assessments (Fig. C4.1.1).

The investigations carried out in periodic assessment have been classified according to the frequency into the investigation in routine assessment and the investigation in regular assessment. The investigations carried out in extraordinary assessment have been classified according to the objective of assessment into the investigation in extraordinary assessment and the investigation in emergency assessment (Fig. C4.1.1). Comparing information obtained in these investigations provides information required for reasonable maintenance of structures (Fig. C4.1.2). Reasonable maintenance here means the changes in condition of the structure from service beginning or the prediction of changes in condition of the structures after investigations in assessment.

For conducting investigations in assessment, the investigation items, structural regions to be investigated, frequency of investigation and investigation method should be specified properly in accordance with purposes.

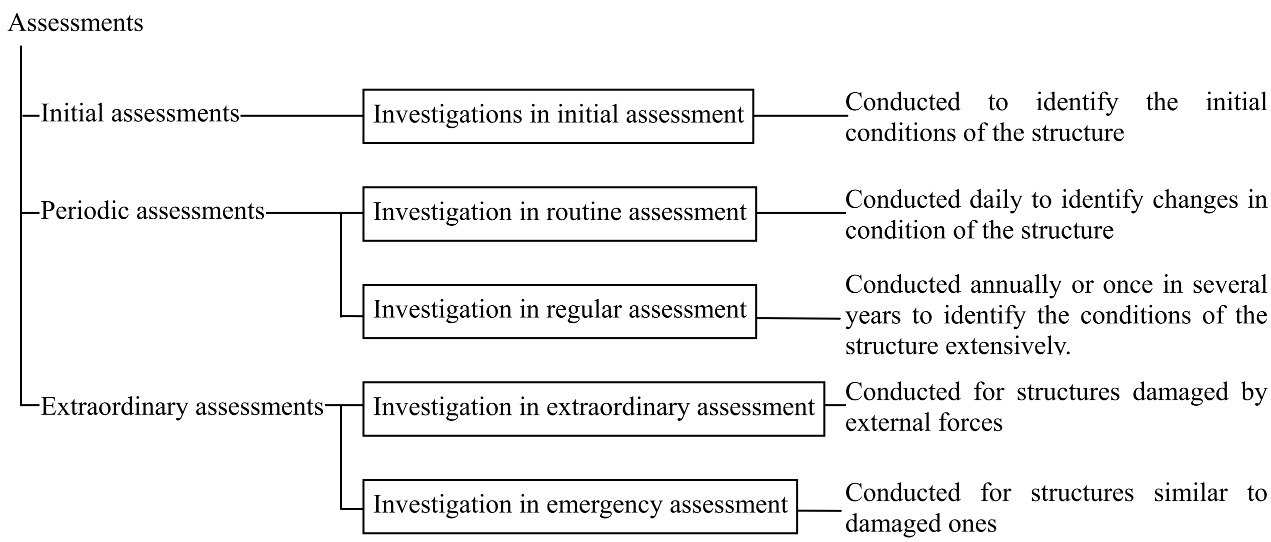


Fig. C4.1.1 Types of investigations in assessment

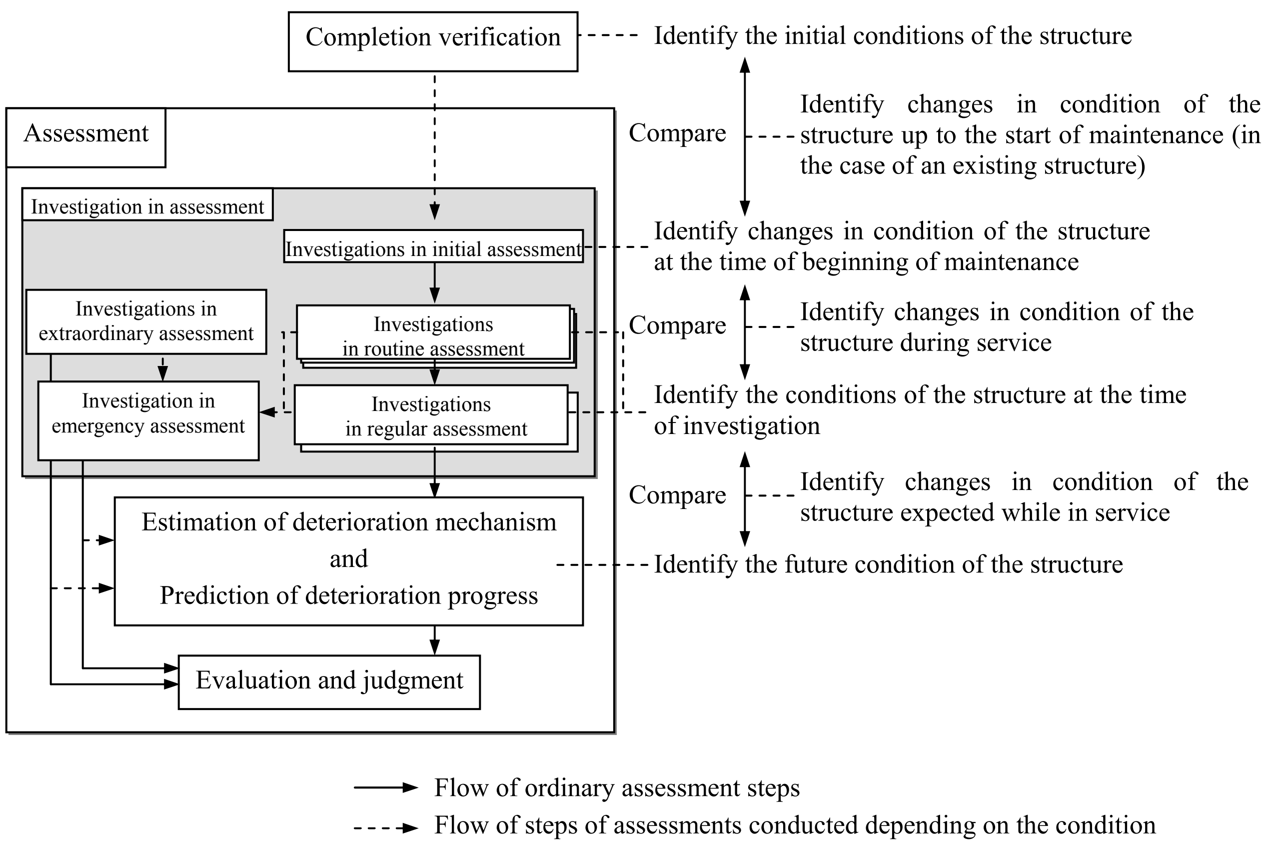


Fig. C4.1.2 Types of investigations in assessment and changes in condition of the structure to be identified

(2) When the initial assessment is carried out, the investigation in initial assessment is conducted to obtain information on the initial conditions of the structure. This information obtained in the investigation in initial assessment is used as the initial value for identifying the condition of the structure. In cases where the results of investigation in initial assessment are different from the

conditions assumed while developing the maintenance plan, the maintenance plan may need to be reviewed. The information obtained in the investigation in initial assessment is very important to subsequent maintenance of the structure. The investigation in initial assessment should therefore be conducted for such investigation items and by such an investigation method that pertinent information may be obtained, and the results obtained should be stored properly.

For newly constructed structures, verifications are generally conducted during or at the end of construction. If these verifications are conducted in consideration of investigation items for which the investigation in initial assessment is to be conducted, the verification results may be used as the result of investigation in initial assessment. For existing structures, no design and construction drawings may be available according to the service period. Even if these drawings are available, the condition of the structure may be different from the condition at the commencement of service. In the investigation in initial assessment, therefore, the structure should be investigated firsthand. In cases where regarding the results of the investigation in initial assessment as the initial condition of the structure is determined inappropriate because of a large-scale repair or strengthening, investigation in initial assessment should be conducted anew. Then, the results should be regarded as the initial conditions of the structure during maintenance.

(3) Changes in condition of the structure can be identified adequately by conducting investigations periodically. A rational approach to periodic assessment is to combine simple investigations such as visual observation while patrolling the structure on a routine basis with intensified investigations of the structure at the closest range possible by visual observations or using instrumentations. In this Specification, the former is referred to as investigation in routine assessment and the latter as investigation in regular assessment.

(4) In cases where a structure is subjected to the actions of external forces due to earthquakes, typhoons or crashes of trains or ships, extraordinary assessments should be conducted quickly. For extraordinary assessments, investigations in extraordinary assessment should be conducted. In cases where design criteria are revised while the structure is in service, assessments should be conducted to verify whether the performance of the structure meets the revised criteria. The investigations for these assessments are also categorized as investigations in extraordinary assessment.

In cases of confirming an accident in the structure due to defects, assessments are conducted urgently and simultaneously for structures similar to the one that suffers the accident or for structures in a similar environment. Such assessments are included in extraordinary assessments. The main objective of such assessments is to prevent similar accidents from occurring. In this Specification, the investigations in such assessment are referred to as investigations in emergency assessment, separate from investigations in extraordinary assessment. For structures that are built in the same period or format as those for which great defects have been confirmed in periodic assessments, investigations are conducted in assessments for verifying whether similar deterioration or damage is likely to occur or not. Such investigations are regarded as investigations in emergency assessment.

(5) In the investigation in assessment of a structure, it is important to identify the condition of the structure in service as adequately as possible according to the designated maintenance plan. The objective is achieved by the most effective method fit for the condition of the structure. Tests and other actions performed to obtain specific information on the conditions of the structure and members are referred to as investigations here.

Defined in this Specification are standard investigations that are normally conducted for the designated items, at the designated time, with the designated frequency based on the maintenance plan; and detailed investigations that are conducted in cases where detailed information is found necessary as a result of standard investigations. The investigations conducted in initial, periodic and extraordinary assessments should be conducted based on the full understanding of the objective and by properly designating the items, method and scope so as to obtain information required for identifying the condition of the structure.

The standard investigations conducted in the investigations in routine or regular assessments aim mainly at determining as soon as possible whether or not the structure, region or member to be investigated is subject to defects, or whether existing defects have progressed or not by continuously conducting the same contents of investigations with an appropriate frequency. For standard investigations therefore, methods should be selected considering efficiency, promptness and cost performance. Investigation methods vary according to the type of investigations. Standard investigations are generally conducted mainly by methods based on visual observations and by hammer tapping or using simple nondestructive testing equipment as required. Making investigations at the same location over a certain period of time enables the identification of the condition of the structure.

In cases where it has been determined as a result of standard investigations that inadequate information is available for evaluating the performance of the structure and for determining the need of remedial measures, more detailed investigations are required. At this point, detailed investigations are conducted. In detailed investigations, acquiring required information without fail is essential rather than efficiency or promptness. The contents of detailed investigations conducted are highly likely to depend on the results of standard investigations. In cases where the deterioration mechanism of the structure can be identified to some extent in the phase of development of the maintenance plan, the specifics and methods of detailed investigations to be applied when the detailed investigations are required should be presented in the maintenance plan based on existing case studies.

(6) In cases where emergency measures are determined necessary for a structure in the course of standard or detailed investigations, such measures should be taken immediately.

4.2 Investigations in Initial Assessment

(1) Investigations in Initial assessment should be conducted for the entire structure.

(2) The method and contents of standard investigations conducted in investigations in initial assessment should involve the investigations of the entire structure by visual observations or hammer tapping and the design and construction document search.

(3) Detailed investigations shall be conducted as required based on the results of standard investigations.

(4) In cases where concrete defects are confirmed that could affect third parties due to the falling of concrete pieces in the investigation in initial assessment, remedial measures shall be taken immediately.

[Commentary] (1) The main objective of investigations in initial assessment is to identify the initial conditions of the structure at the start of maintenance with respect to the performance of the structure. The regions or members where outstanding deterioration or damage occurs are not always uniformly distributed in the structure in service. In investigations in initial assessment, therefore, identifying the initial conditions properly in all the regions and members of the structure is important wherever possible. For the regions for which investigations are difficult after the commencement of service such as the back of a foundation or an underground structure, however, the initial conditions are estimated based on the results of design and construction records search.

(2) The standard investigations in investigation in initial assessment may basically involve the investigations by visual observations and hammer tapping and the document search concerning design and construction records. Nondestructive testing equipment should also be used as required because nondestructive testing can be conducted easily. For the items and methods of standard investigations and the information obtained by respective methods and the precision of the methods, refer to Section **4.7** "Investigation." Investigations in initial assessment should be conducted based on the characteristics decided according to newly constructed structures, existing structures and structures that have undergone large-scale repair or strengthening. These characteristics are described below.

In newly constructed structures and structures that have undergone large-scale repair or strengthening, aging deterioration has rarely occurred. In standard investigations for such structures, document search and confirmations of initial defects and damage by visual observations are generally conducted. For the new structures designed and constructed properly in accordance with the "Design" and "Construction" volumes of the Standard Specifications in particular, design documents or records of verifications conducted during or at the end of construction can be used effectively as information on the initial conditions of the structure. The general information required for identifying the initial conditions of and maintaining newly constructed structures is shown below. The information should be used as a basis for selecting investigation items as required. In cases where deformations have been confirmed by the records of verifications conducted at the end of construction or no deformations have been recognized, the investigations by visual observations or hammer tapping described in 3) below can be eliminated.

1) Information obtained from design documents

- Criteria applied (including the year in which the specifications were established or revised, etc)
- Design service life
- Design values for performances of concrete (e.g. strength)
- Design values for cover depth, reinforcement arrangement (e.g. anchorage positions and joint positions)
- Design values for environmental actions
- Shape and dimensions, etc

2) Information obtained from the records of verifications during and at the end of construction

- Items related to construction outline (e.g. contractor, completion date, construction period and structural type)
- Quality of concrete at major regions (e.g. type of material used, record of verifications of mix proportions, results of verifications of water content per unit volume of concrete, mean and minimum administrative strengths and chloride ion content in fresh concrete)
- Record of verifications of cover depth and reinforcement arrangement, anchorage positions and joint positions at major regions, etc.

- Results of verifications of initial defects or damage including cracks (e.g. locations, lengths, and maximum and mean crack widths) and records of remedial measures taken

3) Information obtained by visual observations, hammer tapping or nondestructive testing method

- Existence of initial defects (e.g. cracks, honeycomb, cold joints and sand streaking)
- Items related to the appearance of the structure at the commencement of maintenance (e.g. outer shape, size, color and defects)
- Existence and degrees of peeling and spalling
- Meteorological and other environmental conditions (e.g. air-borne salt and frost attack in winter)
- Loading conditions for the structure (e.g. live loads)
- Conditions for using the structure (e.g. cyclic wetting and drying, use of deicing agents)

For structures that have just undergone large-scale repair or strengthening, records of the design and construction of the remedial measures taken are also required in addition to the investigations listed above.

Existing structures see their performance changed while they are in service until the point of the investigation of initial assessment from the point of completion owing to the progress of deterioration, occurrence of damage or initial defects left unattended. The information listed below should therefore be obtained by nondestructive testing method in addition to review of design records, record of verifications during construction, and conducting visual observations, hammer tapping tests. In cases where neither design records nor the verification records during construction have been stored, conducting additional investigations should be considered for collecting required data.

- Defect of the appearance of concrete with time (e.g. deformation, scaling, exposure of aggregate and lack of section)
- Measurements of concrete performance (e.g. strength and chloride diffusion coefficient)
- Measurements of cover depth
- Existence of cracks, stain rust, free lime, gel, etc. (in case of existence, condition and period of occurrence, etc.)
- Occurrence of steel corrosion (in case of occurrence, form, degree and range of corrosion, etc.)
- Existence of damage to supplementary equipment (in case of existence, location, degree, etc.)
- Existing assessment records
- Existing records of repair and strengthening

(3) Detailed investigations are conducted in the following cases as required according to the results of standard investigations.

(i) Defect has been confirmed and determined undoubtedly to be deterioration.

(ii) Defect has been confirmed but whether it is deterioration, damage or initial defect is unknown.

(iii) No defect has been confirmed but failures have been found in materials through document search, and conducting more sophisticated investigations and monitoring the progress of defects have become necessary.

In case (i), the deterioration mechanism causing the defect should be identified, and **Part 2** Maintenance for Specific Deterioration Mechanisms should be consulted and investigation items and methods should be selected so as to collect data for identifying the progress of deterioration and for predicting deterioration. Then, detailed investigations should be conducted.

In case (ii), after the occasion of the defect is clarified, investigation methods should be selected for determining whether the defect is ascribable to deterioration, damage or initial defects. Then, detailed investigations should be conducted. In cases where the defect has been determined ascribable to deterioration, further detailed investigations based on the results of the detailed investigations in case (i) are required. In case where the defect of the structure is determined ascribable to damage or initial defects based on the results of detailed investigations, appropriate remedial measures should be taken.

In case (iii), detailed investigations should be conducted in cases where it has been found evident that considerable deformation is highly likely to occur while the structure is in service. The degree and period of expected defect should be verified in advance by conducting detailed investigations properly and the plan for subsequent maintenance should be revised accordingly. Detailed investigations should be conducted as required in cases where it is assumed from the design or construction records that the design cover depth is insufficient or the actual cover depth is considerably smaller than the design level despite the existence of no initial defects, damage or deterioration, or in cases where the quality of concrete or reinforcement is assumed to be poor based on the construction records.

Insufficient grouting in a post-tensioned prestressed concrete structure is one of the construction defects. Confirming this construction defects from construction records is, however, difficult. Insufficient grouting may cause prestressing steel to corrode, leading to the reduction of tensioning force or fracture in the worst case. In the areas with insufficient grouting, cracks along the sheath, free lime or water leakage is found relatively early after construction. In cases where such a defect has been found, detailed investigations should be conducted to verify grouting conditions by partial boring or using nondestructive testing equipment such as X-ray method and ultrasonic methods. Whether cracks exist or not near the anchorage, delamination of backfill concrete and strain of rust should also be investigated.

For items and methods of detailed investigations, refer to Section **4.7** “Investigation.”

(4) In cases where defects are discovered that are likely to cause concrete pieces to fall such as the delamination of cover concrete or cold joints, third parties including people and property are likely to be damaged. Then, emergency measures should be taken immediately. As emergency measures, the area of delaminated concrete is generally chipped and patched. Concrete pieces may fall before emergency measures are taken. In cases where defects are discovered that are likely to cause concrete pieces to fall, the area under the point of defect should be cleared of people or properties, and nets should be put up in the area. Trains and vehicles should be ordered to slow down and the restricted traffic for heavy vehicles should be taken.

4.3 Investigations in Routine Assessment

(1) Investigations in routine assessment should be conducted to determine whether deterioration, damage or initial defects have occurred or not and how serious they are in the coverage where investigations are possible during daily patrol of the structure.

(2) When conducting investigations in routine assessment, the items, methods and frequency of the investigation shall be determined properly considering the objective of the investigation, maintenance category, and importance of the structure and results of deterioration prediction.

(3) Standard investigations in investigations in routine assessment shall be mainly composed of visual observations using the naked eye, photographs and binoculars as well as driving feeling. Hammer tapping and other investigations shall be conducted depending on the situation.

(4) Detailed investigations shall be conducted as required based on the results of standard investigations.

(5) In cases where concrete defects are confirmed in the investigation in routine assessment that could affect third parties due to the falling of concrete pieces, remedial measures shall be taken immediately.

[Commentary] (1) and (2) Investigation items: In investigations in routine assessment, investigations are basically conducted by visual observations and hammer tapping for the damage, defect and deformation of the appearance, the state of service of the structure, the conditions of concrete and steel, the conditions of structure authorship and supplementary equipment, the environmental actions and the existing remedial measures.

Investigation points: Investigations in routine assessment, which are conducted in the coverage where investigations are possible during daily patrol of the structure, should be conducted in the coverage as wide as possible. In locations where investigations are difficult during daily patrol of the structure, investigations in routine assessment can be conducted by installing a permanent scaffold. In case of important structures, members and regions as well as deterioration and damage-sensitive, installation of supplementary equipment such a permanent scaffold should be considered at the stage of design and construction from viewpoints of the importance of structure and the economic efficiency. Then this equipment should be installed if possible.

Investigation frequency: The frequency of investigation should be properly determined considering the staff actually conducting investigations and the budget, the importance of the structure, the hazards for third party and the results of deterioration prediction.

(3) Standard investigations in investigations in routine assessment are classified into some major groups: visual observations using the naked eye, photographs and binoculars, hammer tapping as well as driving feeling. For respective investigation methods, refer to Section **4.7** "Investigation." The investigations by visual observations are conducted for all the regions. The investigation by hammer tapping is conducted only for the regions where hammer tapping is possible. The investigation by driving feeling intends to find malfunctions of expansion joints or to determine whether excessive deflection or vibration exists or not, and is therefore related direct to serviceability.

For investigations in routine assessment, investigation manuals should be prepared based on the characteristics of the structure, and investigations should be conducted in accordance with the manuals. Investigation procedures, methods of recording defects of concrete surface or abnormal sounds and considerations for ensuring safety during investigations should be specified to enable the people with no specialized knowledge about maintenance to conduct investigations.

(4) In cases where defect has been confirmed in standard investigations and (i) the defect is outstanding, (ii) the cause for the defect is unknown, or (iii) the deterioration is much different from the prediction results, a professional engineer should verify the condition and conduct detailed investigations in investigations in routine assessment as required. Detailed investigations in investigations in routine assessment should be conducted like detailed investigations in investigations in regular assessment.

(5) For actions in cases where the delamination of concrete or other problems that are expected to affect third parties have been confirmed in investigations in routine assessment, refer to Commentary (4) in Section **4.2** “Investigations in Initial Assessment.”

4.4 Investigations in Regular Assessment

(1) Investigations in regular assessment should be conducted by the method and with the frequency specified in the maintenance plan to determine whether deterioration, damage or initial defects have occurred or not and how serious they are throughout the structure.

(2) The contents, regions, frequency and investigation methods for investigations in regular assessment shall be selected properly considering the objective of the investigation in regular assessment, maintenance category, importance of the structure, region or member, existing maintenance records and deterioration prediction.

(3) In standard investigations in regular assessment, visual observations and hammer tapping shall be conducted. Investigations using non-destructive test machines or core samples shall be also conducted as required.

(4) Detailed investigations shall be conducted as required based on the results of standard investigations.

(5) In cases where concrete defects are confirmed in an investigation in regular assessment that could affect third parties due to the falling of concrete pieces, remedial measures shall be taken immediately.

[Commentary] (1) Investigations in regular assessment intend to determine by simple methods such as visual observations and hammer tapping whether deterioration, damage or initial defects have occurred or not and how serious they are throughout the structure including the regions and members where determination is difficult in investigations in regular assessment. To determine whether deterioration, damage or initial defects have occurred or not and how serious they are in the regions and members where adequate determination is impossible; installing scaffolds may become necessary.

Investigations in regular assessment should be conducted under the guidance of a professional or responsible engineer, or an engineer whose technical level equal to them with knowledge about the design, construction and maintenance of concrete structures, in accordance with manuals prepared based on the professional knowledge about the design, construction and maintenance of concrete structures.

(2) and (3) Investigation contents: Investigations in regular assessment are basically conducted by visual observations and hammer tapping for the items related to damage, defect and deformation of the appearance of the structure, and to the state of service of the structure. In cases where a scaffold is installed, investigations can be conducted in proximity to concrete. Then, investigations using non-destructive test machines or core samples can also be employed. The width and length of cracks and the area of delaminated concrete should be measured using scales to quantitatively determine the defect on concrete surface. The results of estimation of the deterioration mechanism and the deterioration conditions at an early stage can be verified by properly combining the methods using nondestructive testing equipment concerning the estimated deterioration mechanism. Items for standard investigations in investigations in regular assessment are listed below.

- Cracks (e.g. time of occurrence, width, length and pattern of occurrence)
- Stain of rust, free lime, discoloration, scaling, lack of section and production of gel
- Concrete performance (e.g. strength and chloride diffusion coefficient)
- Measured value of cover depth
- Penetration of deleterious materials (in case of occurrence, types of materials and the degree of penetration, etc.)
- Occurrence of steel corrosion (in case of occurrence, form, degree and range of corrosion, etc.)
- Existence of damage to supplementary equipment (in case of existence, location, degree, etc.)
- Existing records of assessment and remedial measures taken
- Meteorological or other environmental conditions working as deterioration-related environmental action (e.g. air-borne salt, frost attack in winter)
- Service conditions of the structure (e.g. cyclic wetting and drying, use of deicing agents)

Standard investigations should be conducted for selected appropriate items by a relatively simple and economical method. Comparing the results of standard investigations with the previous investigation results obtained in investigations in initial assessment and investigations in regular assessment enables the identification of changes in condition of the structure since the start of maintenance (Fig. C4.1.2). Investigation items may be changed on a timely basis in view of the budgetary restraints or for conducting effective maintenance. For example, relatively simple investigations may be conducted for a limited number of investigation items in limited investigation areas in biennial investigations in regular assessment while more intensified investigations are conducted for more items approximately once in ten years. For the items of standard investigations and corresponding methods, refer to Section **4.7** "Investigation."

Investigation points: Investigations should be conducted throughout the structure in principle. Conducting careful investigations is important at locations where confirmation is difficult in investigation in routine assessment or regions and members that are likely to be subjected to deterioration or damage. In large structures such as viaducts or tunnels, it is difficult to conduct full-coverage investigation for the structure at a time. Then, the area to be investigated may be divided into some sections and consecutive investigations may be conducted at proper intervals. To that end, the area and sequence of investigation should be determined considering the existing maintenance records, importance of regions and members and cost performance.

Frequency of investigation: The frequency of investigations in regular assessment should be properly determined considering the results of deterioration prediction, importance of the structure, region or member, type of structure, design service life, remaining service life, environmental condition, maintenance category, existing maintenance records and cost performance. Investigations in regular assessment are generally conducted once in several years. The interval of investigations in regular assessment has generally been set at one to five years for marine structures, five to ten years for plant structures, five years for road bridges and two years for railroad institutions. Flexibly adjusting the interval is important to effective maintenance. For example, long intervals are set in the initial stages of service with a small likelihood of emergence of deterioration, and shorter intervals are adopted in the stages where deterioration is likely to become outstanding in view of the prediction of deterioration progress.

(4) Detailed investigations in investigations in regular assessment should be conducted when the following conditions are found as a result of standard investigations.

(i) Deterioration has been confirmed and the deterioration mechanism is unknown or different from estimation.

(ii) Deterioration has been confirmed and its progress is far different from the prediction of deterioration progress.

(iii) Defect has been confirmed but its cause is unknown.

(iv) No defect has been confirmed but the service condition of the structure, loading conditions and environmental actions have changed considerably.

Detailed investigations should be conducted at an appropriate time considering the importance of the structure, region or member, maintenance category, degree of defect, remaining service life and deterioration prediction.

In cases where the defect is a deterioration that occurred at the time identified in the deterioration prediction and the degree of deterioration is nearly in agreement with that assumed in the original maintenance plan, or where the deterioration progressed at a lower rate than predicted, no detailed investigations are required and investigations should be continued in accordance with the original maintenance plan. In cases where deterioration progressed at a higher rate than predicted, whether detailed investigations are required or not and when investigations need to be conducted should be considered based on the type of the deterioration mechanism and the rate of progress. In case of deterioration due to frost attack, chemical attack, alkali silica reaction, fatigue and ablation, it is generally known that the defects occur on concrete surface at early stages. No detailed investigations are therefore required immediately even when such defect is discovered. In cases where corrosion cracks or stain of rust due to carbonation or chloride induced deterioration have been detected, the reinforcement in concrete has already been corroded and deterioration stage has already got to propagation stage or acceleration stage. Detailed investigations should therefore be conducted immediately. For specific methods of detailed investigations for these types of deterioration, refer to **Part 2** “Maintenance for Specific Deterioration Mechanisms.”

In cases where it is unknown whether the defect is ascribable to deterioration, damage or initial defects, the cause for the defect should be determined early. Even in cases where the defect is evidently ascribable to damage or initial defects, damage or initial defects may exist that are difficult to identify through the surface, or concurrent deterioration or poor quality of concrete or reinforcement may also exist. To properly evaluate the influences of these conditions on the structural performance, detailed investigations should be conducted.

(5) For actions in cases where the delamination of concrete or other problems that are expected to affect third parties have been confirmed in investigations in regular assessment, refer to Commentary (4) in Section **4.2** "Investigations in Initial Assessment."

4.5 Investigations in Extraordinary Assessment

(1) Investigations in extraordinary assessment shall be conducted for the structure, region or member that may have been damaged in a disaster or accident as quickly as possible while ensuring the safety of the investigator.

(2) Standard investigations in investigations in extraordinary assessment should basically be conducted by visual observation or hammer tapping in principle.

(3) In cases where damage or deformation has been verified by standard investigations, detailed investigations shall be conducted as required.

(4) In cases where a secondary disaster is likely to occur or damage that could affect third parties has been confirmed, remedial measures shall be taken immediately.

[Commentary] (1) In numerous cases, extraordinary assessments are urgently required after a disaster or accident. There are cases where the safety of a damaged structure has been greatly deteriorated due to a disaster or accident although the structure has not collapsed or failed. In the wake of a disaster or accident, therefore, the area around the structure should be declared off-limits or other measures should be taken to prevent secondary disasters. At the same time, investigations in extraordinary assessment should be conducted as quickly as possible while ensuring the safety of the investigator. In cases where investigations in extraordinary assessment are conducted of a structure in the wake of a great earthquake in particular, aftershocks during investigations are highly likely to cause the structure to be subjected to a new defect or damage. Greater safety should therefore be guaranteed. Investigations in extraordinary assessment of a structure after a fire should be conducted only after the confirmation of fire extinguishment or the removal of toxic gases.

Investigations in extraordinary assessment should be conducted for the structure, region or member that may have suffered damage or defect due to a disaster or accident. There may be cases where investigations in extraordinary assessment are required for regions that are likely to be subjected to damage or defect but are difficult to investigate. Then, investigation in extraordinary assessment methods should be examined comprehensively considering the maintenance category, importance of the structure, region or member, type of performance affected, remaining service life and cost performance.

(2) In standard investigations of investigation in extraordinary assessment, visual observations are first conducted from a distance. After the confirmation of no risk of collapse, investigations are conducted through visual observations at close range or hammer tapping. Investigated are cracking, lack of section, delamination, peeling, spalling and water leakage, deformation, supporting conditions, and abnormal sounds and vibrations. Nondestructive testing equipment should be used to meet cost performance and emergency requirements in cases where such testing is considered effective for verifying damage or deformation.

(3) The damage to a structure, region or member due to a disaster or accident is determined by structural factors. Then, in cases where examining remedial measures is determined easily from the

appearance of concrete by standard investigations, remedial measures such as repair and strengthening should be taken without conducting detailed investigations. In cases where no emergency measures are considered necessary from the appearance of the structure despite some damage, crack depth should be investigated and detailed investigations should be conducted for identifying the load bearing capacity and stiffness of the structure at an appropriate point of time when the effects of accidental external forces have disappeared, and data for evaluating the performance of the structure should be collected.

In cases where the structure has been subjected to the effects of a fire, detailed investigations are required for verifying the quality of concrete and reinforcement that have been subjected to high temperature. Tests should therefore be conducted to estimate the temperature of the heat to which concrete samples are exposed and verify the effect of the heat, and to examine the dynamic characteristics of steel. In addition, investigations should be conducted to identify the area where subjected to high temperature, because this area needs repair.

In cases where emergency measures have been taken based on the results of standard investigations, detailed investigations should be conducted at the earliest time possible after the disappearance of influences of external forces to place the structure in service safely and securely.

For conducting detailed investigations, refer to Section **4.7** “Investigation.”

(4) In cases where defects are discovered in investigations that are likely to cause concrete pieces to fall and damage people and property such as the delamination of cover concrete, appropriate measures should be taken immediately. As emergency measures of investigations in extraordinary assessment, the area under the point of defect should be declared off-limits, or netting should be provided immediately in the area to prevent concrete pieces from falling. Trains and vehicles should be ordered to slow down and the weight of vehicles traveling in the area should be restricted. Emergency measures should be taken continuously for a required period of time until the restoration of the structure to its original state.

In cases where emergency measures are taken in investigations in extraordinary assessment, it should be fully understood that they are taken under different conditions from those for ordinary emergency measures and care should be taken to prevent secondary disasters from occurring while installing the emergency measures.

4.6 Investigations in Emergency Assessment

(1) In cases where an accident has occurred due to defect of a structure or considerable defect has been confirmed in a structure although no accident has occurred, investigations in emergency assessment shall be conducted in the region or member of a similar structure that is likely to suffer similar defect.

(2) In investigations in emergency assessment, investigations shall be conducted by using an appropriate method capable of verifying the existence of defect similar to the one causing the accident.

(3) In cases where concrete defect are confirmed in an investigation in emergency assessment that could affect third parties due to the falling of concrete pieces, remedial measures shall be taken immediately.

[Commentary] (1) There is a high possibility that structures of the same type constructed in the same period have been designed and constructed in accordance with the same standard. In cases where an accident has occurred due to defect of a structure or where outstanding defect has been confirmed in the structure in periodic assessment although no accidents were induced, similar problems are highly likely to occur also in similar structures build in the same period. The objective of investigations in emergency assessment is to verify whether defect similar to the one that caused the accident has occurred or not in a structure similar to the one subjected to the accident, and to collect data required for taking remedial measures quickly.

Investigation in emergency assessment should be conducted for the region or member that is determined to be likely to suffer similar defect based on the previous accidents. In investigations, due attention must be given to the safety of the investigator.

(2) By investigations conducted in investigations in emergency assessment, it should be verified whether deformation has occurred or not, data should be collected that is required for identifying the condition of the structure and determining the need of remedial measures. To that end, not only visual observations and hammer tapping but also investigations using non-destructive testing equipment and chipping of concrete for observation should be combined. For structures constructed in accordance with similar design standard or using similar materials, the design standard or existing documents concerning the structure provide useful information. Document search is therefore important. If the structure is exposed to a different environmental action, the action should also be inspected.

(3) For actions in cases where the delamination of concrete or other problems that are expected to affect third parties have been confirmed in investigations in emergency assessment, refer to Commentary (4) in **4.2** “Investigations in Initial Assessment.”

4.7 Investigation

4.7.1 General

Investigations shall be conducted by an appropriate method for appropriate items selected in order to obtain specific data on the conditions of a structure, region or member.

[Commentary] In the investigation conducted during the maintenance of a structure, the condition of the structure should be identified as specifically and quantitatively as possible. To achieve this objective, investigations are conducted.

Selecting more investigation items and investigation methods collecting more data, and setting the investigation point to the more wide-ranging make it possible to obtain more detailed and accurate information on the structure. An increased number of investigation items and more complicated investigation methods, however, increase the time and cost required for investigations. If an excessively high priority is given to the efficiency or simplicity of investigations, identifying the condition and changes in condition of a structure during the maintenance period becomes difficult in cases where inappropriate frequency and coverage of investigation, or inappropriate investigation items and methods are selected.

In investigations conducted in the initial, periodic and extraordinary assessments, fully understanding the objective of investigation, and properly defining the items and methods for efficiently obtaining data required for identifying the condition of the structure are necessary.

4.7.2 Investigation items

Investigation items shall be selected properly considering the type and objective of the investigation, condition of the structure, required information and the cause for deterioration of the structure.

[Commentary] The general investigation items include an outline of the structure, state of service of the structure, defect and deformation of the appearance of the structure, conditions of concrete and steel, structural details, conditions of supplementary equipment, environmental actions and state of existing remedial measures. The information to be obtained on the items and major investigation methods adopted are listed in Table C4.7.1. Investigation items should be selected so that required information may be obtained either in standard or detailed investigations. Items of the standard investigation are basically specified in the maintenance plan. Items of the detailed investigations should be selected properly according to the objective based on the results of standard investigations.

Table C4.7.1 Examples of general investigation items, information to be obtained and major investigation methods

General investigations item	Information to be obtained	Major investigation method
Outline of structure	-Specifications and design standard applied -Design documents -Construction records -Verification records -Maintenance records	-Method based on documents -Method through interviews
State of service of structure	-Conditions while in service (loads, external forces, etc.) -Outline of surrounding environment -Supporting condition -Abnormal sounds and vibrations -Serviceability (ride quality)	-Visual observations (at close range and at a distance) -Driving feeling test -Loading test, vibratory loading test
Defect and deformation of the appearance	-Initial defects (cracks, honeycomb, cold joints, sand streaking, etc.) -Discoloring and staining of concrete -Cracking -Scaling -Delamination, peeling and spalling -Exposure, corrosion and fracture of steel -Deformation -Stain of rust -Water leakage -free lime -Gel	-Visual observations (at close range and at a distance) -Hammer tapping -Surface hardness method
State of concrete	-Materials used and mix proportions -Delamination and internal voids -State of water content -Physical properties (e.g. strength and void structure) -Chemical properties (e.g. hydrates and reaction products) -Degree of penetration of deterioration factors (e.g. depth of carbonation and depth of chloride penetration)	-Method based on surface hardness -Method using elastic waves -Method electromagnetic waves -Local destruction (collection of core samples, chipping of concrete, collection of drilled powder produced while drilling a hole in concrete, etc.)
State of steel	-amount of reinforcing steel -Locations and diameters of reinforcement, and cover depth -Reinforcing bar arrangements -State of steel corrosion -Lack of section	-Chipping -Method using electromagnetic induction -Method using Electromagnetic waves -Measuring directly -Reviews of design documents
Conditions of structural details and supplementary equipment	-Sectional area of the member -Cover depth -Anchorages and joints -Joint of bema and column -State of supplementary equipment	-Method using electromagnetic waves -Measuring directly
Environmental actions and loads	-Meteorological conditions (e.g. temperature, minimum temperature, humidity, precipitation and insulation) -Water supplies (conditions of weathered part of building exterior, conditions of water supplies from the ground, waterproof layers and drain facilities, etc.) -Salt supplies (e.g. amount of air-borne salt, effects of seawater and amount of deicing agents spread) -Wind (direction and velocity) -Carbon dioxide concentration -pH of highly acid river water -Water quality in sewerage facilities -Occurrence of acid precipitation and acid fog -Alkali supplies -Loading conditions (e.g. vehicles, vibrations, water pressure) -External forces related to disasters (e.g. earthquakes and fires)	-Based on existing records -Based on meteorological data (e.g. AMeDAS) -Measuring directly (using sensors, etc.) -Monitoring
Conditions of existing remedial measures	State of Repair and strengthening -State of functionality improvement -State of restriction in service	-Visual observations (at close range and at a distance) -Testing of repair and reinforcing materials

4.7.3 Investigation methods

4.7.3.1 General

The investigation methods described in this section shall be used as standard methods. Appropriate methods shall be selected to obtain information on the items selected.

[Commentary] This Specification describes the basics of general investigation methods: (i) document search, (ii) visual observations, (iii) hammer tapping, (iv) using non-destructive test machines, (v) investigations involving local destruction, (vi) loading and vibratory loading tests of existing structures, (vii) evaluation of environmental actions and (viii) testing of repair and reinforcing materials. Investigations methods used in investigation in initial, routine, regular, extraordinary and emergency assessments should be selected appropriately so that information on investigation items can be collected. Table C4.7.2 shows examples of investigation methods and information obtained. Table C4.7.3 shows examples of deterioration mechanisms and corresponding investigation methods. For the investigation, it is important to select appropriate methods based on these tables and **Part 2** "Maintenance for Specific Deterioration Mechanisms."

When using a method not described in this section, it should be fully examined and its validity should be verified. In cases where the deterioration mechanism is known and more detailed information is required, **Part 2** "Maintenance for Specific Deterioration Mechanisms" should be consulted.

Table C4.7.2a Investigation methods and information obtained

Investigation method		Information obtained
Document search	Collection of documents Interviews	(i) Specifications and design standard used (ii) Design documents (iii) Construction records (iv) Verification records (v) Maintenance records (e.g. investigation records and histories of repair and strengthening)
Visual observations and hammer tapping	Using the naked eye Using binoculars Using cameras Hammer tapping	(i) Initial defects (cracks, honeycomb, cold joints, sand streaking, etc.) (ii) Discoloring and staining of concrete (stain of rust, germination of fungi, precipitation of gel, presence of efflorescence, free lime, discoloring of concrete, water leakage, etc.) (iii) Cracks (directions, patterns, quantity, widths, lengths and stain of rust, etc.) (iv) Scaling (v) Delamination of concrete (presence, number of locations, area, etc.) (vi) Peeling and spalling of concrete (vii) Exposure, corrosion and fracture of steel (viii) Deformation

Table C4.7.2b Investigation methods and information obtained

Investigation method			Information obtained
Using non-destructive test machines	Using a surface hardness	Surface hardness method	(i) Concrete strength
	Using Electromagnetic induction	Using the electrical conductivity and magnetism of steel Using the electromagnetic induction of concrete	(i) Locations and diameters of steel in concrete and cover depth (ii) State of water content
	Using elastic waves	Hammer tapping Ultrasonic testing Impact elastic wave method Acoustic emission testing	(i) Concrete quality, e.g. compressive strength and elastic modulus (ii) Concrete crack depth (iii) Delamination, peeling and void in concrete (iv) Dimensions of members such as the thickness of concrete (v) Grouting in sheath (prestressed concrete structures)
	Using electromagnetic waves	X-ray method Electromagnetic radar method Infra-red devices (thermography method)	(i) Locations and diameters of steel in concrete and concrete cover (ii) Delamination, peeling and void in concrete (iii) Distribution of cracks in concrete (iv) Grouting in sheath (prestressed concrete structures)
	Electrochemical method	Half-cell potential method Polarization resistance method Four electrodes method	(i) Tendency of Corrosion of reinforcement in concrete (ii) Rate of corrosion of reinforcement in concrete (iii) Electric resistance of concrete
	Using optical fiber scope		(i) Internal conditions of concrete (ii) Grouting in sheath (prestressed concrete structures)
Method involving local destruction		Core sampling Chipping Collection of drilled powder produced while drilling a hole in concrete Sampling steel	(i) Crack depth (ii) Compressive strength, tensile strength and elastic modulus of concrete (loading tests) (iii) Carbonation depth of concrete (iv) Analysis of concrete (chemical analysis, fluorescence X-ray analysis, X-ray analysis, thermal analysis, optical microscope, polarization microscope, scanning electron microscope and EPMA) (v) Conditions of chloride ions (concentrations of chloride ions and distribution of concentrations) (vi) Analysis of mix proportions (vii) Released expansion and residual expansion of concrete (viii) Air and water permeability of concrete (ix) Pore size distribution (x) Air void distribution in concrete (xi) State of corrosion of reinforcement (by chipping) (xii) Tensile strength of reinforcement (by sampling reinforcement)
Driving a vehicle		Road alignments, driving feeling test Loading and vibratory loading tests	(i) Section stiffness of member (static and dynamic stiffness) (ii) Vibration characteristics
Investigation for evaluating environmental actions, loads, etc.		Based on existing records Based on meteorological data (e.g. AMeDAS) Measurement directly (using sensors, etc.) Monitoring	(i) Meteorological conditions (e.g. temperature, minimum temperature, humidity, precipitation and insulation) (ii) Water supplies (conditions of weathered part of building exterior, conditions of water supplies from the ground, waterproof layers and drain facilities) (iii) Salt supplies (e.g. amount of air-borne salt, effects of seawater and amount of deicing agents spread) (iv) Wind (direction, velocity and frequency) (v) Carbon dioxide concentration (vi) pH of highly acid river water (vii) Water quality in sewerage facilities (viii) Occurrence of acid precipitation and acid fog (ix) Alkali supplies (x) Loading conditions (vehicles, vibrations, water pressure, etc.) (xi) External forces related to disasters (e.g. earthquakes and fires)

Table C4.7.3a Deterioration mechanisms and corresponding investigation methods

Investigation method	Details		Deterioration mechanism						
			Carbonation*2	Chloride induced deterioration	Frost attack	Chemical attack	Alkali silica reaction	Fatigue	Abraded
Document search	Information on design and construction, information on maintenance and remedial measures		●	●	●	●	●	●	●
Visual investigations*1 Hammer tapping	Using the naked eye, binoculars or cameras		●	●	●	●	●	●	●
	Delamination, peeling and voids		●	●	●	●	●	●	●
	State of corrosion of steel (when steel is exposed)		●	●	●	●	●	●	-
Surface hardness method	Test hammer strength		▲*	▲*	▲	▲	▲*	▲*	▲
Electromagnetic induction	Locations and diameters of steel		▲*	▲*	▲*	▲*	▲*	▲*	▲*
Using elastic waves	Hammer tapping, ultrasonic method, impact elastic wave method, and acoustic emission method		▲*	▲*	▲*	▲*	▲*	▲*	▲*
Using electromagnetic waves	Rader method	Steel arrangement	▲*	▲*	▲*	▲*	▲*	▲*	▲*
		Voids	-	-	-	▲*	-	▲*	▲*
		Cover concrete	▲*	▲*	▲*	▲*	-	▲*	▲*
	Infrared devices (thermography method)	Surface spalling	▲*	▲*	▲*	▲*	▲*	▲*	-
	X-ray method	Steel arrangement, diameter, voids and cracks	▲*	▲*	▲*	▲*	▲*	▲*	-
Electrochemical method	Half-cell potential method and polarization resistance method		▲*	▲*	▲*	▲*	▲*	-	-
	Four electrodes method		▲*	▲*	▲*	▲*	▲*	-	-
Using optical fiber scope	Inside conditions of concrete and grouting in sheath		-	▲*	-	-	▲*	-	-

Legend
●: Items for which standard investigations are conducted.
▲: Items for which standard investigations are conducted as required.
▲*: Items for which detailed investigations are conducted as required.
-: Unknown whether the items is related to the deterioration mechanism or not.
*1: Deformation, discoloring, scaling and cracking are included.
*2: Corrosion of steel owing to the carbonation of concrete.
*3: TG (thermogravimetric) analysis and DTA (differential thermal analysis) make qualitative and quantitative analysis of hydrates and carbonated materials.
*4: Electron probe microanalyzer, which makes qualitative and quantitative analysis of regions in concrete.

Table C4.7.3b Deterioration mechanisms and corresponding investigation methods

Investigation method	Details	Deterioration mechanism						
		Carbonation*2	Chloride induced deterioration	Frost attack	Chemical attack	Alkali silica reaction	Fatigue	Abraded
Method involving local destruction -Collection of core samples -Chipping -Collection of drilled powder produced while drilling a hole in concrete	Appearance and crack depth	▲	▲	▲	▲	▲	▲	▲
	Carbonation depth, uncarbonated depth	▲	▲	▲*	▲	▲*	▲*	-
	Permeation depth of chloride ion	▲*	▲	▲*	▲*	▲*	▲*	-
	Chloride ion content	▲*	▲	▲*	▲*	▲*	-	-
	Compressive strength, tensile strength and elastic modulus	▲*	▲*	▲*	▲*	▲	▲*	▲*
	Analysis of mix proportions	▲*	▲*	▲*	▲*	▲*	-	-
	Amount of alkali	-	-	-	-	▲*	-	-
	Aggregate reaction	-	-	-	-	▲*	-	-
	Released and residual expansion of concrete	-	-	-	-	▲*	-	-
	Pore size distribution	▲*	▲*	▲*	▲*	▲*	-	-
	Air void distribution	-	-	▲*	-	-	-	▲*
	Air and water permeability tests	▲*	▲*	▲*	▲*	-	-	▲*
	Thermal analysis (TG-DTA)*3	▲*	-	-	▲*	-	-	-
	X-ray method (identification of hydrates)	▲*	-	-	▲*	▲*	-	▲*
	EPMA*4	▲*	▲*	-	▲*	▲*	-	-
	Scanning electron microscope	-	-	-	▲*	▲*	-	▲*
Method involving local destruction -Chipping -Sampling steel	State of corrosion of steel	▲*	▲*	▲*	▲*	▲*	▲*	-
	Tensile strength of steel	▲*	▲*	▲*	▲*	▲*	▲*	-
Road alignment and driving feeling test	Road alignment and comfort of vehicle occupants	▲*	▲*	▲*	▲*	▲*	●	▲*
Loading tests (static and dynamic loading)	Crack occurrence and stiffness	▲*	▲*	-	-	▲*	▲*	-
Vibratory loading tests	Natural frequency and vibration mode	▲*	▲*	-	-	▲*	▲*	-
Measurement method of stress	Measurement of strain under loading	▲*	▲*	▲*	▲*	▲*	▲*	-
Measurement method of deformation	Measurement of deformation under loading	▲*	▲*	▲*	▲*	▲*	▲*	-

Legend
●: Items for which standard investigations are conducted.
▲: Items for which standard investigations are conducted as required.
▲*: Items for which detailed investigations are conducted as required.
-: Unknown whether the items is related to the deterioration mechanism or not.
*1: Deformation, discoloring, scaling and cracking are included.
*2: Corrosion of steel owing to the carbonation of concrete.
*3: TG (thermogravimetric) analysis and DTA (differential thermal analysis) make qualitative and quantitative analysis of hydrates and carbonated materials.
*4: Electron probe microanalyzer, which makes qualitative and quantitative analysis of regions in concrete.

4.7.3.2 Document search

Documents concerning the design, construction and maintenance of structures shall be examined.

[Commentary] An outline of a structure can be known by reviewing the specifications, design criteria, design documents, construction records, investigation records, and maintenance records such as the histories of repair and strengthening. Information can also be obtained by interviewing the people who were involved in design, construction and maintenance of the structure to be investigated. Obtaining effective information on the maintenance of the structure by collecting documents may make it possible to omit other investigations. It is important in investigations to take this point into consideration and conduct reviews of document properly.

4.7.3.3 Visual observations and hammer tapping

Visual observations and hammer tapping shall be used to identify the appearance of structure, defects on areas near the surface such as the delamination and peeling of concrete.

[Commentary] With the progress of concrete deterioration, the defect frequently becomes outstanding on concrete surface. In investigations in assessment, therefore, concrete surface should basically be observed visually. In cases where the people engaged in investigation cannot have access to concrete surface, using binoculars may be effective. The items that should be visually monitored and details are described below.

(i) Discoloring and staining of concrete: Area where discoloring or staining occurred, color, presence and area of white gel, efflorescence and free lime, from concrete, occurrence and area of water leakage

(ii) Cracks in concrete: Directions of cracks, patterns of cracks, quantity of cracks, typical widths and lengths of cracks and whether stain of rust from cracks occurred or not

(iii) Scaling: Area of scaling and scaling depth

(iv) Delamination of concrete: Presence, number of locations and area

(v) Peeling and spalling of concrete: Number of locations and area

(vi) Exposure, corrosion and fracture of steel: Concrete cover, number of locations where steel was exposed, length of steel exposed and degree of corrosion

(vii) Displacement and deformation of structures: Deflection, movement and subsidence

For the relationship between the item to be monitored and the characteristics of deterioration mechanism, refer to **Part2** “Maintenance for Specific Deterioration Mechanisms.” When conducting visual testing, refer to NDIS 3418 "Visual testing methods for concrete structures" of the Japanese Society for Non-destructive Investigation. In cases where defect has been detected on the surface of a structure by visual observations, crack widths, and areas and lengths of cracks should be measured using crack scales or measuring tapes. For quantitatively assessing the position and size of defect, analyzing the images recorded by digital cameras is effective. In addition to visual observation, data may be extracted from the intensity of laser beam reflected by the concrete surface.

In visual observations, not only the external defects and deformations of concrete but also the conditions of structures in service including the vehicular traffic can be verified. Exploring the areas around the structure by visual observations also enables the verification of deterioration-related environment actions.

Hammer tapping as well as visual observations enables the identification of internal voids near concrete surface. In hammer tapping, concrete surface is struck with a hammer and the degree of impact and sounds are interpreted to estimate the presence of deterioration in concrete. Hammer tapping is a simple but important method for quickly identifying the presence of deterioration. Accurately determining the presence of deterioration by hammer tapping, however, requires much experience.

4.7.3.4　Methods using nondestructive testing equipment

(1) When conducting investigations using nondestructive testing equipment, the objective, scope and limitations of application and accuracy of measurement required shall be identified, and an appropriate method shall be selected.

(2) Surface hardness methods should be used to estimate concrete strength.

(3) Electromagnetic induction utilizes either the electroconductive or magnetic properties of steel or the dielectric characteristics of concrete, and should be adopted to obtain information mainly on the following items.

(a) Locations and diameters of reinforcing bars, and concrete cover

(b) State of water content

(4) Methods utilizing elastic waves include hammer tapping, ultrasonic testing, impact elastic wave method and acoustic emission method, etc., and should be adopted to obtain information mainly on the following items.

(a) Concrete quality such as compressive strength and elastic modulus

(b) Concrete crack length

(c) Delamination, peeling and voids

(d) Member dimensions including concrete thickness

(e) Grout in the sheath (prestressed concrete structures)

(5) Methods utilizing electromagnetic waves include X-ray method, radar method and infrared devices methods (thermography method), etc. and should be adopted to obtain information mainly on the following items.

(a) Locations and diameters of steel, and concrete cover

(b) Delamination, peeling and voids

(c) Distribution of cracks

(d) Grout in the sheath (prestressed concrete structures)

(6) Electrochemical methods include half-cell potential methods, polarization resistance methods and four electrodes methods, etc. and should be adopted to obtain information mainly on the following items.

(a) Tendency of corrosion of reinforcement

(b) Rate of corrosion of reinforcement

(c) Electric resistance of concrete

(7) Methods utilizing optical fiber scope should be adopted to obtain information mainly on the following items.

(a) Internal conditions of concrete

(b) Grout in the sheath (prestressed concrete structures)

[Commentary] (1) In visual observations and hammer tapping, information can basically be obtained only on the defect on the surface and near the surface layer of a concrete structure. In cases where grasping the internal conditions of concrete is required or where more detailed information is necessary for estimating the deterioration mechanism and determining the degree of deterioration, investigations should be conducted by methods using nondestructive testing equipment.

(2) Collecting core samples for testing strength is a basic and important method of measuring concrete strength in existing structures. Frequently conducting strength tests using core samples is, however, not desirable because the structure may be damaged. Then, surface hardness method is widely used in which concrete strength is estimated based on the results of measurement of surface hardness on concrete surface. Surface hardness method should be conducted in accordance with JIS A 1155 "Method of measurement for rebound number on surface of concrete" and JSCE-G 504-2007 "Test method for concrete strength by test hammer."

The surface hardness of the concrete surface is determined not only by concrete strength but also the state of water content and carbonation of concrete. It is therefore difficult to accurately estimate the compressive strength of concrete at ages greater than a certain level solely based on the measurement of surface hardness. When estimating the strength of concrete of an existing structure, therefore, surface hardness method should be combined with compressive strength tests using core samples.

(3) The methods using electromagnetic induction include the electromagnetic induction method for nondestructive investigation of the locations and diameters of reinforcing bars in concrete and the cover depth, and a method for estimating the water content ratio of concrete based on the relationship between the water content ratio and induction ratio of concrete. When applying these methods, preparations are required such as developing calibration curves. Measuring the diameter of reinforcement or cover depth becomes difficult in cases where reinforcing bars are arranged densely. In addition, the water content ratio of concrete is measured only in surface layers. Then, it should be noted that measurements may sometimes be much different from the internal conditions of concrete.

(4) Investigation methods using elastic waves propagating through concrete include hammer tapping, ultrasonic method, impact elastic wave method and acoustic emission method.

In hammer tapping, the sound waves produced by striking concrete surface with a hammer are detected, and the delamination of concrete and the locations of voids near concrete surface layers are identified based on the distribution and amplitude of the sound waves obtained.

The ultrasonic method is used to identify the quality of concrete and crack depths based on the propagation characteristics of ultrasonic waves through concrete.

In impact elastic wave method, voids in concrete or the thickness of members is assessed based on the elastic waves produced by striking concrete with a hammer. Elastic waves are detected with a vibration sensor installed on concrete surface.

Acoustic emission method is employed to detect acoustic emissions corresponding to cracks or other small failures using an acoustic emission sensor installed on concrete surface, and to monitor the cracking condition based on the frequency of occurrence of acoustic emissions and the characteristics of acoustic emission waveforms.

When taking measurements using elastic waves, the gap between the sensor and the concrete surface on which it has been installed should be minimized by injecting grease into the gap.

(5) Available for obtaining various information using electromagnetic waves that either permeate or are reflected by concrete are X-ray method, electromagnetic radar method and infra-red method (thermography method).

In X-ray method, the locations and diameters of reinforcing bars in concrete, cover depth and voids are detected based on the distribution of X rays that penetrate concrete. X-ray method provides relatively accurate data. The penetration thickness is, however, limited and safety should be ensured during the implementation of the method.

The electromagnetic radar method aims at inspecting the locations of reinforcing bars in concrete and the cover depth based on the reflections of electromagnetic waves (microwaves) at the interface between materials of different relative induction ratio. It should be noted that measurement accuracy may be reduced in cases where concrete contains a large amount of water on its surface or where reinforcing bars are arranged densely because no electromagnetic waves penetrate concrete.

Infra-red method (thermography method) are non-contact methods for inspecting the locations of delamination, peeling, voids, cracks and other defects based on the distribution of concrete surface temperature. The method uses the difference in thermal conductivity between the section of deformation and the sound section. The method involves no contacting and is applicable over a wide area. The exploration depths are, however, limited and the staining of concrete surface, water leakage and the degree of insulation have some influences. The environment for measurement should therefore be duly prepared.

(6) Half-cell potential method, polarization resistance method and four electrodes method are used to obtain information on the state and rate of corrosion of steel based on the fact that the corrosion of steel in concrete is an electrochemical reaction.

Half-cell potential method aims at determining the progress of corrosion of steel by identifying the difference in potential. The potential of internal steel is measured from concrete surface throughout the member. Sections assumed to have been subjected to corrosion can be identified based on the distribution of potentials. Measurement by the half-cell potential method should be conducted in accordance with JSCE-E 601 "Test method for half-cell potentials of uncoated rebars in concrete structures".

Polarization resistance method involves the measurement of the current generated when the potential of steel is slightly polarized (potential is forced to change), and the polarization resistance, which is a parameter of the rate of corrosion, is obtained by dividing the amount of polarization by the measured current. Several methods are available for measuring the polarization resistance. Measuring equipment using the alternating current impedance method has been put to practical use and actually adopted for field measurement at numerous sites.

Four electrodes method directly measures the electric resistivity of concrete. Corrosion currents are generated by electrochemical reaction at the time of corrosion of steel. The lower the electric resistivity of concrete around the steel, the more likely is the corrosion current to flow and the faster the progress of corrosion. Measuring the electric resistivity of concrete enables the acquisition of a guideline for determining the rate of progress of steel corrosion in concrete.

(7) The condition inside the concrete can be monitored by an optical fiber scope put into a small hole created by cracking or a drill hole. In the case of a prestressed concrete beam, the conditions around the beam can be verified via the fiberscope inserted through a gap at the end of the beam. The condition of grouting in the sheath can also be monitored.

4.7.3.5 Investigations involving local destruction

Investigations involving local destruction are conducted mainly by collecting core samples, using the drilled powder produced while drilling a hole in concrete, chipping or sampling steel. Investigations involving local destruction shall be conducted to obtain information on the physical properties and state of deterioration of concrete and steel.

[Commentary] In cases where no adequate information can be obtained by visual observations, hammer tapping or nondestructive testing, or where highly accurate information is required, investigations are sometimes conducted that involve local destruction. Investigations involving local destruction are conducted mainly to identify the physical properties and the condition of deterioration of concrete and to identify the condition of deterioration of reinforcement. To achieve the former objective, core sampling, chipping or using of the drilled powder produced while drilling a hole in concrete is adopted. For the latter objective, observations of the state of steel corrosion after chipping concrete cover are conducted or the steel in the structure is directly collected. When conducting investigations involving local destruction, care should be taken not to damage the performance of the structure.

For details of investigations involving local destruction, refer to Table C4.7.3 that lists examples for respective deterioration mechanisms. In addition to this, investigations should be conducted in accordance with the following standards including JIS standards.

JIS A 1107 Method of sampling and testing for compressive strength of drilled cores of concrete

JIS A 1108 Method of test for compressive strength of concrete

JIS A 1113 Method of test for splitting tensile strength of concrete

JIS A 1152 Method for measuring carbonation depth of concrete

JIS A 1154 Methods of test for chloride ion content in hardened concrete

JIS A 1149 Method of test for static modulus of elasticity of concrete

JSCE-G 573-2007 Measurement method for distribution of total chloride ion in concrete structure

JSCE-G 574-2005 Area analysis method of elements distribution in concrete by using EPMA

NDIS 3419 Method of carbonation test for concrete structures using the drilled powder produced while drilling a hole in concrete

4.7.3.6 Loading and vibratory loading tests of existing structures

Available test method for directly evaluating the mechanical behavior or properties of existing structures are loading and vibratory loading tests. These methods shall be used for obtaining information on the following items.

(a) Stiffness of cross section of the member

(b) Characteristics of vibration

[Commentary] For directly assessing the mechanical behavior or properties of actual structures, loading and vibratory loading tests can be used.

In loading tests, vehicles or trains are generally used as overburdens. The tests under static and varying loading are referred to as the static and dynamic loading tests, respectively. Hydraulic jacks can also be used to apply loads for other members to carry.

In vibratory loading tests, forced vibration is applied to the structure using impact or vibrating machines, or loads are applied using a hydraulic jack for the reaction of supports or other members to carry the load and the load is later released to produce free vibration.

These methods are adopted to verify whether or not the behavior of the structure in the elastic area deviates from prediction. When implementing tests, it is necessary to carefully investigate whether cracks, considerable residual deformation and other defects have occurred or not that may affect the usability and durability of the structure and to verify the validity of the test method as well as the performance of the structure not only in the planning phase but also during and after the loading test.

4.7.3.7 Investigations for evaluating loads and environmental actions

For evaluating loads and environmental actions, investigations shall be conducted by an appropriate method to obtain the environmental and loading conditions to which the structure is subject to.

[Commentary] Concrete structures deteriorate as they are subjected to environmental actions of surrounding environment. Varying environmental actions create varying causes for deterioration. Varying degrees of action cause the rate of deterioration progress to vary. Identifying the characteristics of the environment in which the structure has been placed is therefore very important to appropriate maintenance. Necessary information should be obtained by an appropriate method. For evaluating environmental actions, the following items should be investigated.

(i) Meteorological conditions: Temperature (maximum, minimum and mean temperatures), humidity, precipitation and insulation

(ii) Water supplies: Conditions of weathered part of building exterior, conditions of water supplies from the ground, waterproof layers and drain facilities)

(iii) Salt supplies: Amount of air-borne salt from the sea, effects of seawater and amount of deicing agent spread)

(iv) Loading conditions: Conditions of vehicles and other loads

(v) Other: pH value of highly acid river water, water quality in sewerage facilities handling wastewater with a high sulfate concentration and occurrence of acid precipitation and acid fog

For investigations for evaluating environmental actions, refer to **Chapter 5** "Identification of Deterioration Mechanism and Prediction of Deterioration Progress." Investigations should be conducted for parameters required for estimating the causes for deterioration and predicting deterioration. Investigations are, however, not necessary for all the parameters. For parameters concerning meteorological conditions, the data publicized by the Meteorological Agency of Japan can be used.

4.7.3.8 Tests of materials for repair and strengthening

An appropriate method shall be selected for testing the materials for concrete structures based on the results of full consideration of the required performances for the structure to be repaired.

[Commentary] With the increase of concrete structures requiring repair, opportunities also increase for conducting various tests on repair materials. Only a few methods have, however, been standardized concerning repair materials. Before conducting tests, therefore, testing methods should be fully reviewed. Standards for conducting tests on repair materials are listed below.

JSCE-K 511-2007 Test method for weathering resistance of concrete surface coating materials

JSCE-K 521-1999 Test method for oxygen permeability of concrete surface coating materials

JSCE-K 522-2005 Test method for vapor permeability of concrete surface coating materials

JSCE-K 523-2005 Test method for water permeability of concrete surface coating materials

JSCE-K 524-2005 Test method for chloride ion permeability of concrete surface coating materials

JSCE-K 531-1999 Test method for bond strength of concrete surface coating materials

JSCE-K 532-2007 Test method for elongation performance of concrete surface coating materials over concrete crack

JSCE-K 541-2000 Test methods of organic crack injecting materials for repairing in concrete structures

JSCE-K 542-2000 Test methods of cement crack injecting materials for repairing in concrete structures

JSCE-K 543-2000 Test methods of polymer modified cement crack injecting materials for repairing in concrete structures

JSCE-K 551-2000 Test method of grouting organic materials for repairing and strengthening in concrete structures

JSCE-K 552-2000 Test methods of cement grouting materials for repairing and strengthening in concrete structures

JSCE-K 553-2000 Test methods of polymer modified cement grouting materials for repairing and strengthening in concrete structures

JSCE-K 561-2003 Test method of patching repair materials in concrete structures

JSCE-K 571-2005 Test methods of surface penetrates for concrete structures

JSCE-F 561-2005 Method of making specimens for compressive strength of sprayed concrete (mortar)

JSCE-F 562-2005 Method of making specimens for durability tests of sprayed concrete (mortar)

JSCE-F 563-2005 Test method for rebound percentage of sprayed concrete (mortar)

JSCE-F 564-2005 Test method for dust concentration in air during spraying concrete (mortar)

JSCE-F 565-2005 Test methods for mechanical properties, spraying performance and durability of sprayed concrete (mortar)

JSCE-F 566-2005 Method of making specimens of bond strength of sprayed concrete (mortar) for repairing and strengthening

JSCE-G 564-2005 Test method for length change of sprayed concrete (mortar) for repairing and strengthening

JSCE-G 563-2005 Test method for strength of sprayed concrete (mortar) for repairing and strengthening using prism specimens

4.7.3.9 Monitoring investigations

Monitoring investigations shall be conducted by such a method that can provide information that meets the objective in a designated period of time stably and continuously.

[Commentary] Various monitoring methods have recently been proposed and put to practical uses that enable real-time identification of changes in condition of a structure or member. In monitoring investigations, the displacement or deformation of the structure, strain of concrete or reinforcing steel, penetration of deteriorating regions into concrete, or corrosion of reinforcing steel is identified as required or continuously. Remote control or data collection without field investigations becomes possible by controlling sensors attached to concrete surface or embedded in concrete using computers. Monitoring investigations enable the identification of changes in condition of the structure before the occurrence of external deformation, so they are beneficial in preventive maintenance.

For monitoring investigations, sensors fit for obtaining required information should be used and sensors need to steadily provide information in the place where it is installed during the specified period of time. Unless these requirements are fully achieved, no adequate maintenance can be conducted. In monitoring, information is obtained only indirectly through sensors. In numerous cases, therefore, whether adequate information is obtained or not needs to be verified by checking the structure. Then, it is necessary to fully understand the characteristics of instrumentation and confirm the significance and accuracy of information to be obtained, before conducting investigations by monitoring.

CHAPTER 5 IDENTIFICATION OF DETERIORATION MECHANISM AND PREDICTION OF DETERIORATION PROGRESS

5.1 Principles

(1) Deterioration mechanism shall be identified based on the results of investigations considering the design drawings, materials used, records of construction administration and verifications, environmental conditions and service conditions.

(2) Progress of deterioration shall be predicted based on the results of investigations using an appropriate prediction model for identified deterioration mechanism.

[Commentary] (1) Fig. C5.1.1 shows a basic sequence for identification of deterioration mechanism. If design drawings or construction records are available, specified environmental condition, service condition and estimated deterioration mechanism at the time of design are useful for identification of deterioration mechanism,. Checking the materials used, records of construction administration and verifications can show potential deterioration factors for the structure and identify deterioration mechanism. The actual environmental conditions and service conditions of structure may, however, be different from those assumed in design. Investigations are therefore necessary to confirm the actual conditions. In cases where data relating to the deterioration indexes or distinguishing defects has been obtained by investigations, possible deterioration mechanisms can be narrowed down by consulting **5.2** "Methods for Identification of Deterioration Mechanisms" or **Part 2** "Maintenance for Specific Deterioration Mechanisms."

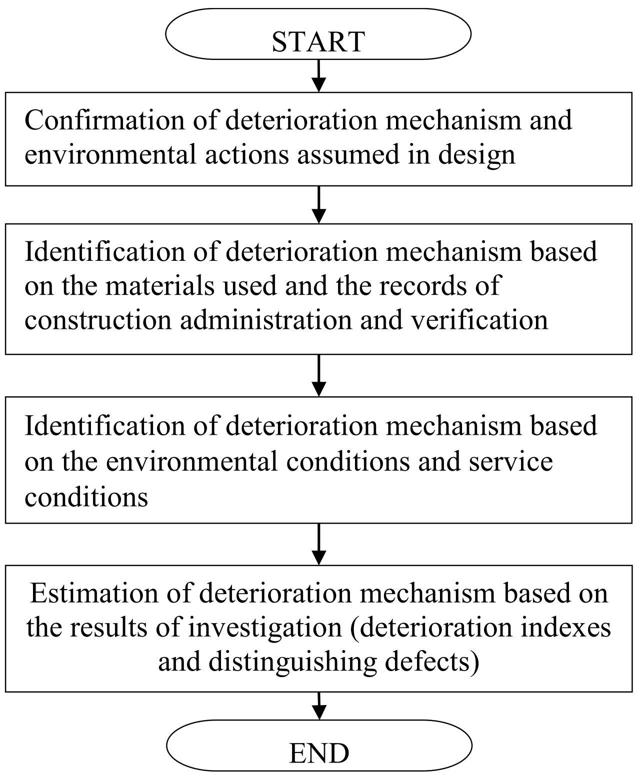


Fig. C5.1.1 Basic sequence for identification of deterioration mechanism

The deterioration index is an index for assessing the progress or degree of deterioration. Deteroration factor, deterioration phenomena and deterioration index of each deterioration mechanism described in **Part 2** “Maintenance for Specific Deterioration Mechanisms” are listed in Table C5.1.1. When iinvestigations are carried out to identify the deterioration mechanism, investigation items should be selected by consulting Table C5.1.1.

Table C5.1.1 Deterioration mechanism, and cause, phenomenon and indexes of deterioration

Deteriora-tion mechanism	Deteriora-tion factor	Phenomenon of deterioration	Examples of deterioration index
Carbonation	Carbon dioxide	Decrease of pH in pore solution due to the chemical reaction between carbon dioxide and cement hydrate induces the corrosion of steel and it causes the cracking or peeling of concrete or reducing the cross section of steel.	Depth of carbonation Amount of steel corrosion Corrosion-crack
Chloride induced deterioration	Chloride ions	Corrosion of steel in concrete is induced by chloride ions and it causes the cracking or peeling of concrete or reducing the cross section of steel.	Concentration of chloride ion Amount of steel corrosion Corrosion-crack
Frost atack	Freezing and thawing	Freezing and thawing of water in concrete causes deterioration of concrete surface e.g., scaling, micro cracking and pop-outs.	Depth of frost deterioration Amount of steel corrosion
Chemical attack	Acidic substances Sulfate ions	Hardened concrete in contact with acidic substances or sulfate ions is dissolved, or concrete deteriorates due to the expansion pressure due to the formation of chemical substances	Depth of penetration of deleterious substances Depth of carbonation Amount of steel corrosion
Alkali-silica reaction	Reactive aggregates	Reactive silicate minerals contained in aggregates or carbonate rocks chemically combines with pore solution whose pH is high and it causes irregular expansion or cracking in concrete.	Degree of expansion (cracking)
Fatigue of deck slab	Volume of traffic of large vehicles	Cyclic wheel loading on highway bridge decks causes cracking or caving-in of reinforced concrete.	Density of cracks Deflection
Fatigue of beam member	Cyclic loading	Cyclic loading on railway bridge causes cracking in tensile steel reinforcements in beams and it leads fracture of steel reinforcement.	Cumulative damage Lengths of cracks in steel

Abrasion	Wearing	Wearing by flowing water or wheel causes the loss of concrete gradually with time.	Amount of abrasion Rate of abrasion

When deterioration mechanism can not be identified by the basic sequence shown in Fig. C5.1.1, for instance the case in which concurrent deterioration should be considered, detailed investigation should be conducted focusiong on the deterioration indexes that are relating to the observed deterioration phenomenon shown in Table C5.1.1. With the results of detailed investigation, each deterioration index should be examined whether or not it can explain the deterioration of the structure refering to **Part 2** “Maintenance for Specific Deterioration Mechanisms”. in order to identify deterioration mechanism.

(2) Prediction of deterioration progress are carried out to estimate future deterioration of the structure caused by identified deterioration mechanism based on the results of investigations. The prediction of deterioration progress is essential to the performance evaluation of the structure during its planned service period and to the judgment of necessity for remedial measures.

Deterioration progress should be predicted quantitatively by using an appropriate model for deterioration progress based on the existing research results and data obtained by investigations, for instance the section of the structure, placement of reinforcing bar, quality of concrete and conditions of steel. For quantitative prediction, the accuracy of the model for deterioration progress appropriate data in quantity and quality are needed.

In actual situations, investigations are frequently conducted mainly by visual observation and investigations are conducted to obtain quantitative data as required. Then, a semi-quantitative prediction model may be used for prediction in which deterioration may be classified into several grades and the periods of respective grades can be predicted.

5.2 Methods for Identification of Deterioration Mechanisms

(1) In cases where deterioration phenomena has not been observed, deterioration mechanism should be identified based on the investigation results relating to the extrinsic deterioration factors of region or member such as the environmental conditions and service conditions, design drawings and records of construction administrations of the structure.

(2) In cases where deterioration phenomenon has been observed, defects caused by deterioration shall be identified and then the deterioration mechanism shall be idenitified from the characteristics of defects and extrinsic deterioration factors of the region or member.

[Commentary] (1) In cases where significant deterioration phenomena has not been observed in the region or member by visual observation or hammer tapping, may be difficult to predict future deterioration phenomena due to the few available information. However, in cases where ezternal factors, such as environmental conditions and conditions for using the structure, are specified by investigations, or where assumed environmental conditions and service conditions in design have been confirmed using design documents, the deterioration mechanism can be estimated to some extent using Table C5.2.1 that lists the relationships between the external factors and deterioration mechanisms. For example, in cases where no initial defects or damage has been detected in investigation in the initial assessment of a newly constructed structure, no detailed investigation is required, and the methods described above may be adopted for estimating the deterioration mechanism for the time being. Then, however, it should be assumed that the modification of the deterioration mechanism may be required during the service period.

Table C5.2.1 Possible deterioration mechanisms relationg to the location, environmental conditions and service conditions of the structure

Extrinsic deterioration factor		Possible deterioration mechanism
Location of the structure	Coastal area	Chloride induced deterioration
	Cold district	Frost attack Chloride induced deterioration
	Spa	Chemical attack
Environmental conditions and service conditions of the structure	Cyclic wetting and drying	Alkali-silica reaction Chloride induced deterioration Frost attack
	Use of de-icing salt	Chemical attack Alkali-silica reaction
	Cyclic loading	Fatigue Abrasion
	Carbon dioxide	Carbonation
	Acidic water	Chemical attack
	Flowing water, vehicles, etc.	Abrasion

It is also important that internal factors of concrete structures are reviewed. Because the structures constructed at the time when there was less awareness of the durability of structures than at the present are likely to deteriorate because of internal factors. For example, in the years when the control of standards concerning the use of alkali-reactive aggregate and the desalination of sea sand were different from today, inappropriate materials may have been used. Existing structures therefore have deteriorated by alkali-silica reaction and chloride attack, etc. because of the use of inappropriate materials in some cases. In cases where the quality of concrete is lower than specified as a design prerequisite because of poor compaction or curing during construction, or where concrete cover of steel is not enough, these internal factors can cause deterioration of structures or accelerate deterioration. Internal factors are closely related to the deteriorations that accelerate the corrosion of steel with thin concrete covering, for instance chloride attack, carbonation and chemical intrusion.

In cases where defects has not been observed in a periodic assessment during the maintenance period and it is in agreement with the initial prediction of deterioration progress, the deterioration mechanism estimated in the initial assessment may basically be considered appropriate. External factors, however, may change with time from those assumed in the initial stage. For structures or members to which maintenance type A has been applied, for example, causes for deterioration should be investigated in each periodic assessment and verified the validity of the estimated deterioration mechanism.

(2) In cases where defects have been confirmed in investigations, the defects caused by deterioration mechanisms should be identified. Then, excluding the types of defects related to the initial defects and damages from the detected defects such as the cracking, swelling, peeling and spalling, staining and discoloring of concrete and exposure of reinforcing bars, by the following procedures, defects related to the deterioration can be extracted.

(i) Initial defects

Cracks, honeycombs, cold joints, sand streaking and others those occur during or shortly after construction are referred to as initial defects. Honeycombs and cold joints can be detected by visual observatio or hammer tapping even long after the structure is in service.

Whether or not cracking is related to initial defects can be detemined by classyfing the major causes of cracking: materials, heat of hydration, drying shrinkage, construction and structure, based on the cracking patterns. For example, as shown in Table C5.2.2, if the cause of cracking can be estimated from the regularity or shape of cracking, the initiation time of cracking can sometimes be estimated.

Table C5.2.2 Relationship between cracking and the causes

		Inappropriate aggregate	Heat of hydration	Shrinkage	Con-struction	Structure
Crack patterns	Irregular cracking	○	—	—	○	—
	Regular cracking	—	○	○	—	○
	Map cracking	○	—	○	○	○
Initiation stage of cracking	Early ages	○	○	○	○	—
	After appropriate aging	○	—	○	—	○

When it is estimated that caracks occurs due to the structural cause by the Table C5.2.2, the load bearing capacity and section force under external forces at the cracked cross section should be calculated by using the design drawings and investigation results. Based on the calculations, the type, magnitude and direction of the force, which generates cracks, should be compared with the actual crack patterns. It is fundamental issue to find the cause of the cracking and to investigate the effects on the safety performance. When the location, width and patter of the cracks are measured, the cause of cracking during construction can be estimated by consulting Figure C5.2.1 and Table C5.2.3.

(ii) Damage

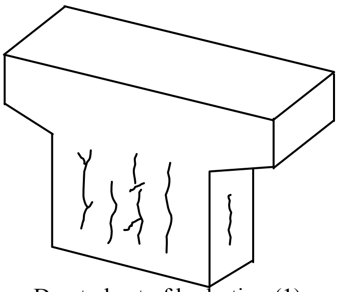
The defective events that leads to cracking and peeling occurring when a structure is subject to excessive forces, such as an earthquake or collision, can be easily distinguished from deterioration phenomena when the cause of such events is known. When the cause is unknown, the involvement of damage can be recognized by inspecting similar structures near the structure to find similar defects in them or by assuming that the defects are kinds of damage and assessing the relevance of the locations and size of defects as damages.

The seismic performance of a structure can generally be evaluated by checking the standards conformed to in the design phase.

After the defects due to deteriorations have been identified from the above procedures, the deterioration mechanism should be estimated based on the relationship between the characteristic of defects obtained in the investigations and distinctive phenomena of deterioration mechanisms listed in Table C51.1.1 considering external factors such as the environmental conditions and service conditions, and internal factors such as the materials used and construction. For details, it should be refered that the "Apparent grades and deterioration state of structures" provided in the relevant maintenance standard in **Part 2** “Maintenance for Specific Deterioration Mechanisms.”

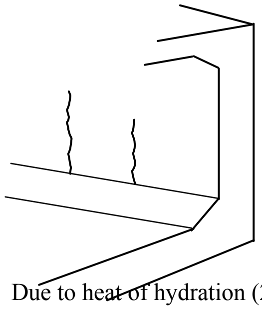
Fatigue occurs on reinforced concrete slabs of highway bridges and on beams of railway bridges only in cases where loading effects are significant. When maintaining such members, fatigue should be first considered as a deterioration mechanism. When adequate consideration have been taken in design or where outstanding deterioration-related environmental action affects, other deterioration mechanism should be considered.

When the degree of deterioration of a structure is in phase to significantly affect the safety performance of the structure, not only physical tests of concrete and analysis of hazardous substances using core samples but also the investigations of steel arrangement and corrosion condition are required. Based on the relationship of the investigation results and the environmental actions, identification of the deterioration mechanism judgment of necessity for remedial measures should be carried out. Since multiple mechanisms are normaly related to deterioration at this phase, all the deteriorationg mechanisms involved should be identified, with their contributions to the performance degradation assessed.



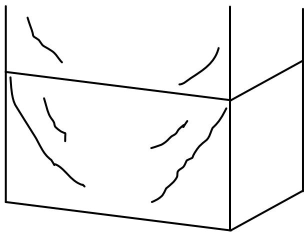
Due to heat of hydration (1)

(Cracks generated by the difference between temperature of inside and that of surface area of the structure, due to cement hydration.)



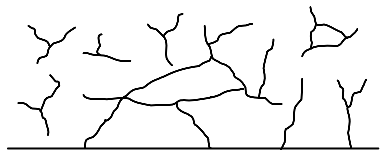
Due to heat of hydration (2)

(Cracks generated due to the restrained thermal deformation of newly placed concrete by existing concrete.)



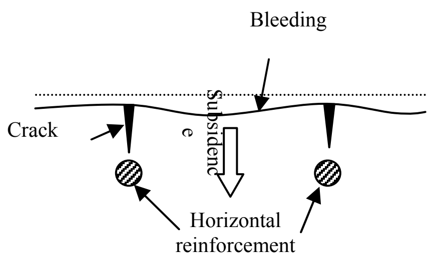
Due to drying shrinkage

(Large diagonal cracks occur at the edge of a large wall structure.)



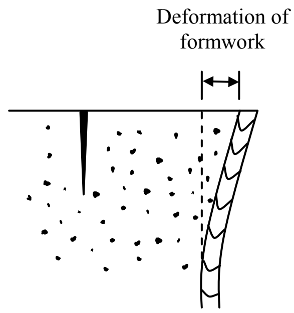
Cracking due to shrinkage caused by inferior materials or poor mixing

(Map cracking occurs due to the delay of concrete placement, the poor quality of cement or aggregate, etc.)



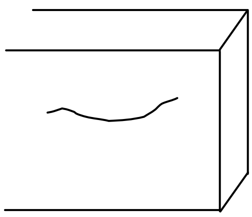
Subsidence cracking

(Cracks generated by the subsidence of concrete around fixed reinforcement during hardening process of concrete.)



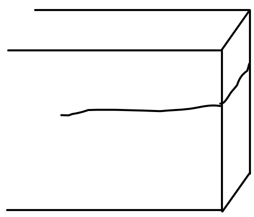
Due to deformation of formwork

(Cracks generated by the deformation and movement of the formwork during hardening process of concrete.)



Due to rapid placement

(Cracks generated by the subsidence of fresh concrete.)



Due to inappropriate placement of layers of concrete

(Cold joints generated by the inappropriate construction.)

Fig. C5.2.1 Examples of initial cracks occurring during construction

Table C5.2.3 Causes of cracking

Major category	Medium category	Minor category	Causes of cracking
Material	Material used	Cement	Abnormal setting of cement Heat of cement hydration Abnormal expansion of cement
		Aggregate	Mud contained in aggregate Low-quality aggregate Reactive aggregate
	Concrete	—	Chloride ions contained in concrete Subsidence and bleeding of concrete Shrinkage of concrete
Construction	Concrete	Bathing	Critical betching error
		Mixing	Heterogeneous dispersion of admixtures Long-time mixing
		Transport	Change in mix proportion during concrete pumping
		Placement	Inappropriate sequence of placement Rapid placement
		Compaction	Insufficient compaction
		Curing	Vibration or loading before hardening Settlement and bleeding of concrete Frost attack at early age of concrete
		Placement of layers of concrete	Inappropriate placement of layers of concrete
	Reinforcing bar	Arrangementof reinforcing bar	Inappropriate arrangement of reinforcing bar Insufficient concrete cover
	Formwork	Formwork	Heaving of formwork Water leakage from formwork to roadbed Early removal of formwork
		Supports	Settlement of supports
Environmental condition	Physical	Temperature and humidity	Difference in temperature and humidity on both sides of the member Cyclic freezing and thawing Fire
		Wearing	Abrasion
	Chemical	Chemical action	Chemical action of acid and chloride Corrosion of internal reinforcement due to carbonation Corrosion of internal reinforcement due to chloride ions
Structure and external forces	Loading	Dead load	Action while concrete strength is still low
		Variable load	Excessive loading in scale and frequency
		Accidental load	Excessive Loading that is not considered as design load
	Structural design	—	Lack of cross sectional area and reinforcing bars
	Support condition	—	Uneven subsidenceDifferential settlement of structure Frost heaving
Other			Other

5.3 Prediction of Deterioration Progress

(1) In the maintenance of a structure, deterioration progress shall be properly predicted to understand the change in structural performance.

(2) Deterioration progress shall be predicted using an appropriate model in accordance with identified deterioration mechanism.

[Commentary] (1) The degradation of performance of a structure or a structural member constituting the structure is caused mainly by deterioration. For properly maintaining structures, therefore, it is important that proper prediction of deterioration progress of the structure, region or member according to the deterioration mechanism under service condition. Reflecting the prediction of deterioration progress in performance evaluation or judgement of the necessity and appropriate time for remedial measures enables effective maintenance.

(2) For predicting deterioration, an appropriate deterioration prediction model should be built based on the existing research results or knowledge. Described below are the basic ideas for building a deterioration prediction model according to each deterioration mechanism, carbonation, chloride attack, frost atack, chemical atack, alkali-silica reaction and fatigue. The structural maintenance methods for respective deterioration mechanisms, and deterioration prediction models are explained more detail in **Part 2** “Maintenance for Specific Deterioration Mechanisms.”

When it is affected by carbonation and chloride attack, the corrosion of steel is a serious issue. For predicting deterioration induced by carbonation or chloride attack, a model has been proposed that can predict relatively accurately the intrusion of steel-corroding factors such as carbon depth and chloride ions ingress. In actual structures, however, the corrosion of steel is frequently accompanied by cracking or peeling of concrete. Predicting the progress of steel corrosion is therefore also important. Prediction models for corrosion rate are, however, generally less accurate than the model for predicting the intrusion of carbon dioxides and chloride ions. In maintenance, data can be obtained on actual steel corrosion by investigations. Then, accuracy of prediction can be improved.

Frost action, chemical intrusion and wear cause deterioration to progress from the surface to the inside of concrete. Though the rate of progress of these deterioration mechanisms has not been fully grasped, deterioration rate in each structure can be predicted based on the relationship between the elapsed service period and the depth of deteriorated area identified by investigation.

When cracking due to alkali-silica reaction has been confirmed, the reaction has already progressed to some extent. It is important to determine whether alkali-silica reaction has nearly ceased at the time of investigation or the reaction will continue. To that end, concrete cores are generally sampled for testing. However, prediction of the deterioration progress of ASR is generally difficult.

In the case of fatigue of a deck slab, cracking on the deck slab increases by the cyclic loading. Deterioration progress can therefore be identified qualitatively based on the relationship between the elapsed service period and the state of cracking.

Predictions vary according to the degree of external forces causing deterioration. Properly specifying the deterioration-causing external force acting on the structure, region or member is important. In actual structures, multiple deterioration mechanisms may sometimes cause a concurrent deterioration. When predicting the progress of the deterioration caused by multiple deterioration mechanisms, it should be noted that the concurrent deterioration is not simply a total of deteriorations caused by individual deterioration mechanisms. It should also be noted that the accuracy of prediction is determined by the deterioration of the structure, region or member or by the performance to be evaluated.

In cases where past maintenance data has been accumulated and adequate information is available on a structure in service under similar conditions as the structure to be examined, deterioration can be predicted relatively easily based on the data. For more efficient and accurate prediction of deterioration progress, sufficient knowledge is required on the deterioration of the structure to be studied. Then, deterioration should be predicted under the supervision of a professional or.

In the initial stages of maintenance, only insufficient data is obtained and the accuracy of prediction is inevitably low. In the prediction of deterioration progress, therefore, prediction should be modified based on the accumulated data obtained in investigations to improve the accuracy of prediction (Fig. C5.3.1).

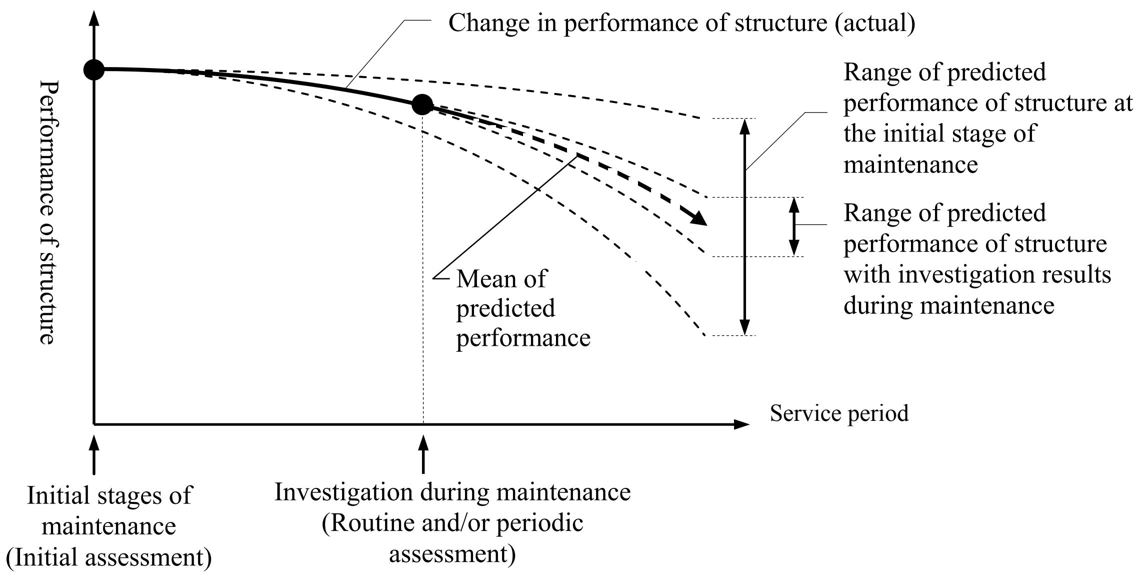


Fig. C5.3.1 Accuracy of deterioration prediction

CHAPTER 6 EVALUATION AND JUDGMENT

6.1 Principles

(1) Performance of the structure shall be evaluated based on the results of investigations. Idendification of deterioration mechanism and prediction of deterioration progress shall be done when they are needed.

(2) Necessity for remedial measures shall be judged based on the evaluation of structural performance considering the remaining planned service period, importance and maintenance category of the structure.

[Commentary] (1) In the maintenance of structures, it should be needed that constant attention to the change in performance of the structure or a region or member that constitutes the structure throughout the service period of the structure. In the assessment of a structure, the present state of deterioration should be identified by standard investigations that are generally conducted in initial, daily, routine or extraordinary assessments, and by detailed investigations that are conducted as required and future deterioration should be predicted. Based on the results, the performance of the structure, region or member at the time of investigation and at the end of planned service period should be evaluated quantitatively, and the necessity for remedial measures should be judged. Evaluation methods, however, vary according to the quality and quantity of data obtained in investigations. It should also be noted when evaluating structural performance that the required performances can vary according to the regions or members that constitute the structure.

No evaluation methods have been established for the hazards for third party, or aesthetic appearance and landscape. For safety and serviceability, equations for evaluation are not fully accurate and quantitative evaluation is frequently difficult. As a more practical method, therefore, condition of a structure at the time of investigations and condition during the remaining service life can be predicted based on the investigation results by comparing them with the grades that have been specified in advance. Poorer grades should be selected when evaluation is difficult.

The performance of a structure should basically be evaluated both at the time of investigation (at present) and at the end of remaining service life. When a long service life is remained, the evaluation of performance can be carried out with a specified evaluation period as tentative target (Fig. C6.1.1). Repeating the process enables performance evaluation during the service period.

In cases where emergency measures are required, performance may be evaluated from investigations without predicting of deterioration progress. There also may be cases where structural performance can not be evaluated properly because of the difficulty in estimating the deterioration mechanism. After remedial measures are taken in these cases, the effect of emergency measures should be identified properly by conducting an increased number of investigations, and data should be collected for evaluating the performance of the structure more properly.

Evaluation of performance of a structure should be done by a professional engineer, responsible engineer or engineer who has equivalents knowledge about the design, construction and maintenance of concrete structures.

(2) Necessity for remedial measures shall be judged based on the performance of the structure, region or member evaluated properly in respective investigations. In cases where the performance

of the structure fails to meet the required performances at the time of investigation, remedial measures are determined to be necessary.

When future performance of a structure will fail to meet the requirements though no remedial measures are needed at the time of investigation, the need of remedial measures should be determined considering the prediction of deterioration progress, remaining planned service life, importance of the structure, maintenance category and higher level maintenance plans for a group of structures or throughout an area. In this case judgment should be done by a responsible engineer.

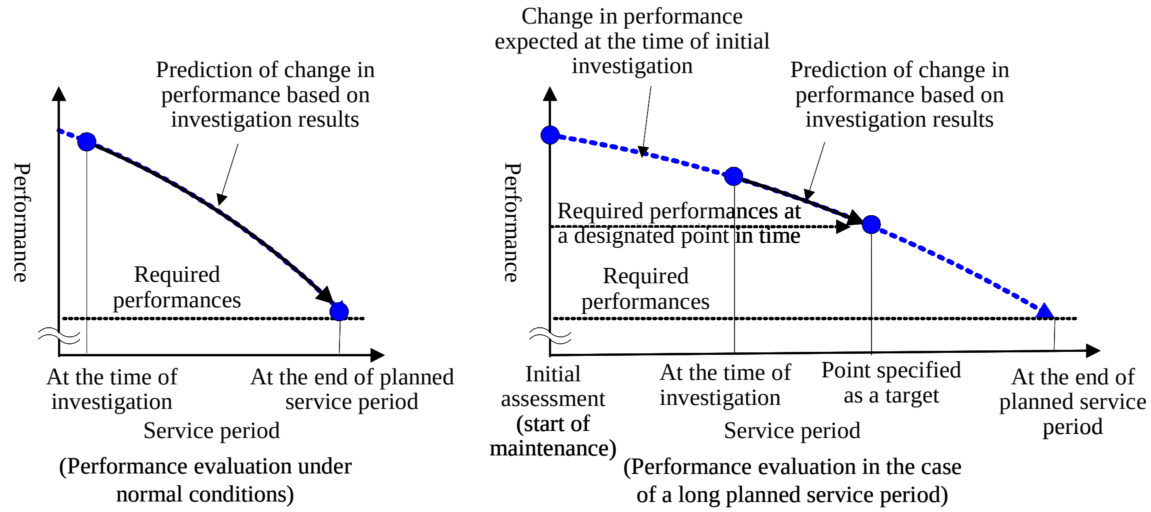


Fig. C6.1.1 Planned service period and performance evaluation (conceptual view)

6.2 Evaluation and Judgment in Initial Assessment

6.2.1 General

In the initial assessment, performance of structure shall be evaluated and necessity for remedial measures shall be judged using appropriate methods in accordance with the objective of the initial assessment.

[Commentary] The initial assessment is the first assessment conducted at the start of maintenance based on an established maintenance plan. The objectives of the initial assessment are not only to identify the condition of the structure before maintenance but also to obtain initial values for evaluating structural performance in subsequent periodic assessments and to verify the validity of the prepared maintenance plan and amend it when it is needed. The results of the evaluation of performance and judgment of the necessity for remedial measures in the initial assessment determine the basic approach to subsequent maintenance of the structure. Performance should be evaluated as quantitatively as possible.

6.2.2 Evaluation based on investigations in initial assessment

Performance of the structure at the start of maintenance and during the remaining

planned service life shall be evaluated based on the condition of the structure confirmed in the initial assessment. Idenitification of deterioration mechanism and prediction of deterioration progress shall be done when they are needed.

[Commentary] Performance has rarely been deteriorated at the time of initial assessment for a newly constructed structure or a structure for which remedial measures have been taken on a large scale. Then, in cases where it has been verified in the initial assessment from records that no initial defects, damage or deterioration was detected or the structure is free from any problem in design and construction owing to appropriate repair, the performance of the structure at the time of investigation, or at the start of maintenance, can be evaluated to be equivalent to the performance assumed in the design phase (or when remedial measures were taken). The performance of a structure up to the end of the planned service period can be evaluated somewhat quantitatively by using a verification method described in design documents and considering the data obtained in standard investigations such as the state of the structure, environmental conditions and service conditions.

For existing structures, it may be evaluated that the required performances have been met at least at the start of maintenance if it has been confirmed that the structure is free from any initial defects, damage or deterioration. There are, however, cases where some defects are observed in an existing structure. In this case, the causes of defects should be identified by investigations. If the defects are ascribed to damage or initial defects, the affects of defects on the required performances of the structure should be examined. If the defects are ascribed to deterioration mechanisms, the deterioration mechanism should be identified and deterioration progress should be predicted, and the performance of the structure, its region or member at the time of investigation and during the remaining planned service life should be evaluated as quantitatively as possible.

For many cases in existing structures, durability performance was not verified in the design phase, and records of design and construction was lost. Then, by the standard investigation in the initial assessment, it is difficult to identify the cause of defects and predict the performance properly at the time of investigation and during the planned service period. In this case, detailed investigations should be conducted as required to evaluate the performance quantitatively. Records of structures with environmental or service conditions similar to those of the structure to be examined may also be considered for reference. For details of performance evaluation in cases where detailed investigations are conducted, refer to **6.5** "Evaluation and judgment based on the detailed investigations."

6.2.3 Judgment based on investigations in initial assessment

(1) In cases where deterioration phenomenon has been observed in the initial assessment, necessity for remedial measures shall be judged considering the evaluated performance of the structure in the period between the initial assessment and the end of the planned service period, and the content of the maintenance planning.

(2) In cases where initial defects or damage has been observed in investigations in the initial assessment, the effect of the defects on the structure shall be reviewed and appropriate actions shall be taken.

[Commentary] (1) In cases where deterioration has been confirmed in the initial assessment, the necessity for remedial measures shall be judged based on the results of performance evaluation at the time of initial assessment and the end of the planned service period of the structure conducted based on **6.2.2** “Evaluation based on the investigations in the initial assessment”, remained planned service period, importance and maintenance category of the structure. When detailed investigations are carried out, the necessity for remedial measures should be judged in accordance with **6.5** “Evaluation and judgment based on the detailed investigations.”

In the initial assessment, the accuracy of performance evaluation at the end of the planned service period is not so high because the remaining service life is long generally. In cases where the performance at the end of the planned service period is lower than the requirement, therefore, no remedial measures need to be taken immediately. Periodic assessments should be conducted in accordance with the maintenance plan that has been reviewed based on the results of investigations in the initial assessment, and actual performance degradation should be confirmed to review the necessity for remedial measures.

(2) In cases where initial defects or damages such as cracks, honeycombs, cold joints and sand streaks have been found in a structure, region or member in investigations in the initial assessment, the effects of the defectsion on the structure should be properly examined. In cases where the initial defect or damage can facilitate deterioration, or exert a bad influence on the performance of the structure, appropriate remedial measures should be taken. The "Design" and "Construction" volumes of the Standard Specifications, and the Practical Guideline for Investigation, Repair and Strengthening of Cracked Concrete Structures prepared by the Japan Concrete Institute. can be refered in the investigations or identification of defects and judgment of the necessity for remedial measures.

When hazard for third party caused by the falling of concrete pieces is concerned, emergency measures should be taken immediately after investigation (**4.2** “Investigations in the Initial Assessment”).

6.2.4 Review of maintenance plan based on results of initial assessment

In cases when performance of the structure can not be evaluated or necessity for remedial measures can not be judge properly based on the results of initial assessment, the maintenance plan shall be reviewed.

[Commentary] If it has been confirmed by the initial assessment that the performance of a structure can properly be evaluated during its planned service period in accordance with the prepared maintenance plan, the structure will be maintained in accordance with this maintenance plan. In cases when it has been found that the condition of the structure is different from that in preparing maintenance plan, regardless of the necessity for remedial measures, the maintenance plan shall be reviewed so that the performance of the structure can be evaluated more properly.

In cases when initial defects and damages have been found in investigations in the initial assessment, raegardless of the remedial measures, review of the maintenance plan will be required depending on the degree of the defects.

6.3 Evaluation and Judgment in Periodic Assessments

6.3.1 General

In periodic assessments, performance of structure shall be evaluated and the necessity for remedial measures shall be judged using appropriate methods in accordance with the objective of periodic assessments.

[Commentary] In periodic assessments, routine and periodic assessments are conducted to verify the change in performance of the structure with time.

In investigations in routine assessments, the effect of defects on the structure is evaluated based on the newly found defects or the change of existing defects observed in routine assessments. Investigations in routine assessments are conducted at short intervals and help finding defects in early stage. Performance may therefore be evaluated qualitatively by a rapid and simple method.

Investigations in regular assessments are conducted at intervals of several months to years as designated in the maintenance plan. Comparing investigation results with the results of preceding investigations enables quantitative evaluation of the performance at the time and the degree of change in performance.

Since periodic assessments are conducted to periodically verify the state of the structure, region or member in accordance with the maintenance plan, results of investigations should be compared with the state assumed in the maintenance plan. If the rate of performance degradation can be confirmed based on the results of investigations at different time, the performance in the remaining service life can be quantitatively evaluated.

6.3.2 Evaluation and judgment based on investigations in routine assessments

(1) Performance of the structure shall be evaluated and the necessity for remedial measures should be judged based on the change in performance of the structure, region and member observed by comparison of results of investigations in routine assessments.

(2) In cases where defects have been observed by investigations in routine assessment, identification of deterioration mechanism, prediction of deterioration progress and judgment of necessity for remedial measures shall be carried out.

[Commentary] The objective of investigations in routine assessments is to find the change of the structure in its early stage by conducting simple tests (e.g. visual observations and hammer tapping) at short intervals. If no change has been found by investigations in routine assessments, the structure can be evaluated as in the assumed condition in the maintenance plan and no remedial measure is needed..

In cases when new deterioration phenomena, damages or initial defects have been found by investigations in routine assessments, the cause should be identified and the degree of defects should be evaluated considering the following.

<u>Identification of causes of deterioration phenomena, damages and initial defects</u>: Defects that occurs on concrete surface as time elapses include cracks, stain of rust, separating out of substances from concrete and deformation that are ascribed to specific deterioration mechanisms, as carbonation, chloride attack, frost attack, chemical attack, alkali-silica reaction, fatigue and wear.

Also included are structural damage due to the action of accidental load or uneven subsidence of foundations, exposed initial defects owing to poor materials or construction, and cracks in repaired sections due to re-deterioration.

Deterioration can occur in all structures due to environmental actions or material properties, and progresses with time. It is important to evaluate the progress of deterioration and maintaining the structure considering the degree of deterioration. On the other hand, neither damages nor initial defects is planned to occur in structures. Once damages and initial defects are found, appropriate remedial measures should be taken corresponding to the degree of its effect on the functions of the structure. In cases when any defects has been confirmed, whether the deformation is deterioration, damage or initial defect should first be identified. Deteriorationg mechanism should be also identified in case of deterioration. Cracks or deformation that has been predicted in design is not included in defects.

Identification of the cause of defects should be carried out in accordance with **5.2** “Methods for identification of deterioration mechanism.” The deterioration mechanism should be estimated considering external and internal factors and based on the condition of defects (pattern and width of cracks, existing of stain of rust, water leakage, calcium carbonate and scaling of concrete, range and tone of discoloration, etc.). The characteristics of defects found in major deterioration mechanisms are shown in **Part 2** “Maintenance for Specific Deterioration Mechanisms.”

<u>Evaluation of the degree of deterioration phenomena, damages and initial defects</u>: Standard investigations in periodic assessments mainly consist of visual observations. The degree of deterioration phenomena, damages and initial defects should therefore be evaluated by those appearances. Then, evaluating the degree of defects according to its grade is useful. The degree of defects identified by investigations in routine assessments can be evaluated by grading of the following characteristic appearances on the structure.

-Location, pattern, quantity, length and width of cracks

-Location and area of delamination, peeling, spalling and a section where abnormal sound is heard

-Location and area of a section subject to scaling or deterioration

-Existence and degree of stain of rust, calcium carbonate and water leakage

It is efficient that the degrees of defects are classified into (i) allowable, (ii) whether allowable or not is uncertain or (iii) not allowable, from the point of veew to ensure the required performances of the structure in the manual for investigations in routine assessments. Criteria should be specified by the authority considering the service conditions and required performances of the structure, region or member.

When detailed investigations are conducted, evaluation of performance and judgment of the necessity for remedial measures should be carried out in accordance with **6.5** “Evaluation and judgment based on the detailed investigations.”

When defects are identified as initial defects or damages, or hazard for third party should be considered, evaluation of performance and judgment of the necessity for remedial measures should be carried out in accordance with **6.2.3** “Judgment based on the investigations in the initial assessment.”

6.3.3 Evaluation of performance based on investigations in regular assessments

In cases where defects have been observed in investigations in regular assessments, the cause of defects shall be identified and the effect of defects shall be evaluated. If the defect is regarded as deterioration, the performance of the structure, region or member shall be evaluated based on the change of condition identified by comparing investigation results with records of past investigation.

[Commentary] The advantage of investigations in regular assessments is more extensive information at the different time of investigations than that of routine assessments. More detailed and quanitative information can be obtained by investigations in regular assessments, because not only visual observations and hammer tapping but also by tests with non-destructive test machines and core samples can be carried out with temporary scaffold. When defects are found in periodic investigations, cause of defects and the degree of defects should be evaluated as quantitatively as possible by the method described in **6.3.2** “Evaluation and judgment based on the investigations in routine assessments.” When deterioration phenomena are found, identification of deterioration mechanism and prediction of deterioration progress should be carried out by comparing investigation results with past results, and the performance of the structure at the time of investigation and during the remaining planned service period should be evaluated as quantitatively as possible.

When detailed investigations are conducted in regular assessments, evaluation of performance should be carried out in accordance with **6.5** “Evaluation and judgment based on the detailed investigations.”

6.3.4 Judgment based on investigations in regular assessments

(1) In cases where deterioration has been observed in investigations in regular assessments, necessity for remedial measures should be judged considering the evaluated performance of the structure, region or member from the time of investigation till the end of the planned service period; and importance, maintenance category and economic efficiency of the structure.

(2) In cases where the initial defects or damage has been observed in investigations in regular assessments, it shall be examined and appropriate measures shall be taken considering the effect of defects or damage on the structure.

[Commentary] (1) Judgment of necessity for remedial measures based on the results of periodic investigations should be carried out based on the results of performance evaluation of the structure, region or member at the time of investigation and at the end of planned service period, and the importance of the structure, maintenance category, higher level maintenance plans for a group of structures or throughout an area, and cost-effectiveness. When detailed investigations are conducted, judgment of necessity for remedial measures should be carried out in accordance with **6.5** “Evaluation and judgment based on the detailed investigations.”

(2) When defects are identified as initial defects or damages, or hazard for third party should be considered in periodic investigations, consideration should be done in accordance with the commentary (1) in **6.2.3** “Judgment based on the investigations in the initial assessment.”

6.4 Evaluation and Judgment in Extraordinary Assessments

6.4.1 General

In extraordinary assessments, performance of structure shall be evaluated and necessity for remedial measures shall be judged immediately using appropriate methods in accordance with the objective of extraordinary assessments.

[Commentary] Investigatons in extraordinary assessments and emergency assessments are conducted in extraordinary assessments. Investigations in extraordinary assessments are conducted mainly in structures that have been subjected to accidental external forces such as natural disasters and fire. Investigations in emergency assessments are conducted in structures that have specific characteristics which cause defects in similar structures and need to be examined. Investigations in extraordinary and emergency assessments are not pre-planned, but they should be implemented quickly in case of necessity. It is important that evaluation of structural performance and the judgment of necessity for remedial measures are carried out immediately using suitable methods for the objective of each assessment. To that end, investigations in estraordinary and emergency assessments should be conducted by a professional engineeror the responsible engineer.

6.4.2 Evaluation based on investigations in extraordinary assessments

Performance of the structure at the time of an extraordinary assessment shall be immediately evaluated properly based on the results of investigations in order to quick implement of remedial measures preventing injury, death, great social and economic impact caused by collaps and destruction.

[Commentary] Structures can collapse in the worst case when extraordinal force affects in a natural disaster or an accident. Though structures can avoide their collapse or fail, safety performance can be lost by a natural disaster or accident. It is difficult to avoid risk in the midst of a natural disaster or an accident, social and economic impacts by secondary disasters or the disruption of lifeline can be prevented with quick countermeasures, designated off limits to the adjacent area to the damaged structure, extraordinary supports for the damaged structure. In order to take appropriate measures for a damaged structure, performance to be restored should be identified as quickly as possible evaluationg the present safety performance, serviceability and hazards for third party of the structure and considering the condition around the structure.

In investigations in the extraordinary assessment conducted due to revision of design standards during the service period of a structure, present compliance of the structure with standards should be evaluated and the performance at the end of the planned service period should also be evaluated.

When detailed investigations are required in extraordinary assessments, the evaluation of structural performance in orde to judge the necessity for remedial measures should be conducted as quickly as possible. When detailed investigations are conducted in a structure for which extraordinary remedial measures have already been taken, to ensure the safety of subsequent services, the performance in service conditions should be evaluated. When detailed investigations are conducted in extraordinally assessments, evaluation of performance should be carried out in accordance with **6.5** “Evaluation and judgment based on the detailed investigations.”

6.4.3 Judgment based on investigations in extraordinary assessments

(1) In cases where defects that can cause hazards for third parties or affect the service of the structure has been observed, remedial measures shall be reviewed immediately.

(2) In cases where no problem has been observed in structural performance at the time of an extraordinary assessment, it may be considered as no immediate remedial measures are needed.

[Commentary] (1) Structures damaged under accidental loading during an earthquake or other natural disaster plaied an important role in the phase of regional restoration in many cases. On the other hand, collapse of structures due to damage can be hazardous to numerous people in the vicinity. The needs of emergency measures to damaged structures are, therefore, eztremely high in stricken areas. When the necessity for remedial measures can be judged solely by visual observations, appropriate repair or strengthening should be applied immediately. Whne no remedial measures can achieve the required performances, service should be restricted immediately or the structure should be removed. It is important to introduce alternative methods quickly that have similar functions.

(2) In extraordinary assessments, top priority is given to prompt action. When structural performance at the time of assessments is sufficient, it can be judged as no remedial measure is necessary. Detailed investigations should, however, be conducted at an appropriate time after extraordinaly situation has finished, to evaluate structural performance in the period between the point of investigation and the end of planned service period and to judge the necessity for remedial measures while the structure is under normal service conditions. When detailed investigations are conducted in extraordinally assessments, the necessity for remedial measures should be judged in accordance with **6.5** “Evaluation and judgment based on the detailed investigations.”

When the performance of an existing structure at the time of investigation or in the period up to the end of the planned service period can not conform to the standards after design standards were revised, appropriate remedial measures should be taken. In case of inadequate seismic resistance, basic idea for maintenance is shown in **Chapter 17** “Basics of Seismic Retrofit.”

6.4.4 Evaluation and judgment based on investigations in emergency assessments

In cases where defects have been observed in a structure similar to the one that was subject to the defects causing an accident in investigations in emergency assessments, remedial measures shall be reviewed immediately. In cases where defects have not been observed, necessity for remedial measures shall be judged considering possibility of occurrence of defects by the end of the planned service period.

[Commentary] Investigations in emergency assessments are conducted when defects of a structure has caused an accident or serious defects has been found in a structure by periodic assessments, to verify whether or not similar defects has occurred in similar structures. When similar defects are found in another structure, remedial measures should be taken immediately. In cases there is a risk of hazard for third parties, emergency measures should be taken.

When no deformation has been confirmed in investigations in emergency assessments, it is determined that no risk is involved at present. Even in such cases, however, data should be collected on the design standards applied to the structure, materials used and construction methods in investigations, the possibility of change in performance in the period up to the end of the planned service period should be evaluated, and the necessity for remedial measures including intensified investigations should be judged.

6.5 Evaluation and Judgment based on Detailed Investigations

(1) Performance of the structure should be evaluated and necessity for remedial measures should be judged based on the quantitative results of detailed investigations.

(2) Performance of the structure at the time of investigations shall be evaluated based on the results of the detailed investigations in order to confirm that the required performance is achieved.

(3) Performance of the structure at the end of its planned service period shall be evaluated using the predicted deterioration progress based on the results of the detailed investigations in order to confirm that the required performance is achieved.

(4) In cases where the required performance is not achieved in the performance evaluation described in (2) and (3), adoption of remedial measures shall be considered.

[Commentary] (1) Detailed investigations conducted in respective assessments provide detailed data on the structure, region or member to be examined. Evaluaton of performance and judgment of the necessity for remedial measures based on the results of detailed investigations should be conducted quantitatively in principle. The obtained data should be first used to identify the cause of defects. If the defects are caused by deterioration, the deterioration mechanism should be identified and deterioration progress should be predicted quantitatively. Then, using the results, the performance of the structure, region or member at the time of investigation and during its planned service period should be evaluated quantitatively. Finally the necessity and timing of remedial measures should be judged.

However, for some attributes of performance, quantitative evaluation can not be applied because of absence or inaccuracyof proposed evaluation equation. Then, the performance of the structure should be evaluated as quantitatively as possible with semi-quantitative evaluation by the grading of the appearance of the structure and other results in detailed investigations.

Evaluation of performance and the judgment of necessity for remedial measures should be conducted by a professional engineer or the responsible engineer because the results may sometimes greatly change the maintenance plan of the structure.

(2) Detailed investigations help identify the condition of a structure, region or member in detail. Then, various performance attributes should be evaluated based on the results of investigations, and whether required performances have been achieved or not should be verified. Described below are the methods for evaluating the structure, region or member at the time of detailed investigation.

<u>Sagety Performance</u>: The load bearing capacity of the region or member should be calculated using appropriate equations for evaluation. Then, whether performance will be evaluated in cross section, member or throughout the structural system should first be estimated. When making evaluations concerning the loss of load bearing capacity due to the corrosion of steel, for example,

the effect of steel corrosion can be evaluated by the loss of cross section of steel. Then, however, evaluation can be made only in extremely local sections of the structure. On the member or structural level, however, evaluation and judgment should be made in close consideration of tthe effects of complicated change s in the bond properties. On the structural level, the condition of deterioration or how loads are carried varies from member to member. The fact that these effects greatly influence the load bearing capacity should be considered when making evaluations. The range of evaluation should be selected properly by considering the degree of deterioration, details of investigations, reliability of evaluation equations, importance of the structure, maintenance category and remaining service life.

Once the range of evaluation has been determined, an equation for evaluating the load bearing capacity should be specified in view of the equation used in design standards, to calculate the load bearing capacity. Whether or not the calculated load bearing capacity sufficiently exceeds the acting loads or stress resultant should be determined to evaluate the load bearing capacity of the structure, region or member. The parameters in the equation for evaluating the load bearing capacity need to express the state of deterioration properly. It should be made possible to specify the loss of effective cross section of concrete as a parameter in cases of frost action or chemical attack, or the loss of steel cross section due to steel corrosion or change in bond characteristics as parameters in cases of carbonation or chloride attack.

The safety factors throughout performance check can be considered to be nearly equivalent to those assumed in design. The values of safety factors should be specified fully considering the volume and accuracy of data collected during detailed investigations, and the degree of deterioration of the structure, region or member, importance of the structure, maintenance category and remaining service life.

Safety performance other than load bearing capacity, such as stability and ductility, should be evaluated and judged based on the same policy as for the load bearing capacity.

<u>Serviceability performance</u>: In regard to the serviceability performance, the required percormance can be verified directly by using indices obtained from investigations, such as deflection, vibration properties, inclination and water leakage. Then, serviceability can be evaluated by determining whether investigation results satisfy the evaluation criteria or not. The stiffness of a member may be evaluated using evaluation equations like the safety of the member.

<u>Hazards for third party and Aesthetic appearance and landscape</u>: The hazards for third party should be evaluated and judged as the risk of delamination, cold joints, etc. of concrete that can couse injury people and/or property by falling concrete fragments. For the safest evaluation and judgment, it may be assumed that cracking can impair the performance related to hazards for third party. When defects have occurred such as concrete swelling and cold joints with people or property located below, the performance requirements related to hazards for third party are as a rule not satisfied, requiring emergency treatment and remedial measures.

Aesthetic appearance and landscape should be evaluated from the aspect of the possibility of cracking, scaling, stain or rust or stain of leakage damages aesthetic appearance of the structure or landscape, or causes discomfort to viewers or make them feel insecure. Aesthetic appearance and landscape are evaluated subjectively. Evaluation is therefore difficult in numerous cases. People engaged in maintenance should evaluate aesthetic appearance and landscape considering the condition of deterioration of the structure, maintenance category, importance and location of the structure and remaining service life.

Grading:

All types of performance to be evaluated should be evaluated quantitatively based on the results of detailed investigations as described above. No evaluation equations may, however, be available for some performance attributes, or evaluation equations may not be sufficiently accurate for other attributes. Then, using highly practical semi-quantitative evaluation methods according to grading instead of methods based on the results of performance check has been considered allowable. Evaluation can be made as described below using a semi-quantitative method.

First, the relationship of the grade of external deformation with the progress of deterioration to the stage of deterioration (initial, progressing, accelerating and deterioration), and the relationship of the grade of deformation to the performance deteriorated at the stage should be identified. For the relationships for respective types of deterioration, refer to **Part 2** “Maintenance for Specific Deterioration mechanisms.” Then, the degree of deterioration of the structure inspected should be evaluated according to the grade based on the results of detailed investigations. The present condition of performance degradation should be evaluated based on the relationship between the grade of deformation and the performance damaged.

(3) Deterioration progress should be predicted based on the quantitative data obtained in detailed investigations. Based on the prediction, safety performance, serviceability, hazards for third party, and aesthetic appearance and landscape at the end of planned service period should be evaluated, and the degradation of performance of the structure should be predicted.

Performance at the end of planned service period may be evaluated by estimating the values of parameters in the evaluation equation at the end of planned service period based on the prediction of deterioration progress if an evaluation equation is available. In reality, however, sufficient knowledge has not yet been accumulated on deterioration prediction and parameters used in evaluation equation can not be estimated with sufficient accuracy. Then, performance may be evaluated according to the grading.

(4) When it is found by performance evaluation conducted as described in (2) and (3) that the required performances will not be achieved at the time of investigation or at the end of planned service period, remedial measures should be considered. When considering the implementation of remedial measures, it is important to comprehensively consider maintenance category, performance attribute to be evaluated and the degree of performance degradation, importance of the structure, importance of the region or member subject to deterioration or damage, cost-effectiveness, and higher level maintenance plans for a group of structures or throughout an area. When taking remedial measures such as repair and strengthening, the appropriate time of implementation should also be examined.

CHAPTER 7 REMEDIAL MEASURES

7.1 Principles

(1) In cases where remedial measures are considered necessary, the performance to be achieved shall be determined considering the importance of the structure, maintenance categories, remaining planned service period, deterioration mechanism and the degree of performance degradation of the structure. Then, appropriate remedial measures shall be taken considering the ease of maintenance and cost performance after the remedial measures.

(2) When taking remedial measures, plans shall be prepared for enforcement and post-implementation maintenance. In cases where the deterioration mechanism has been identified explicitly for the structure, Part 2 should be consulted before taking remedial measures.

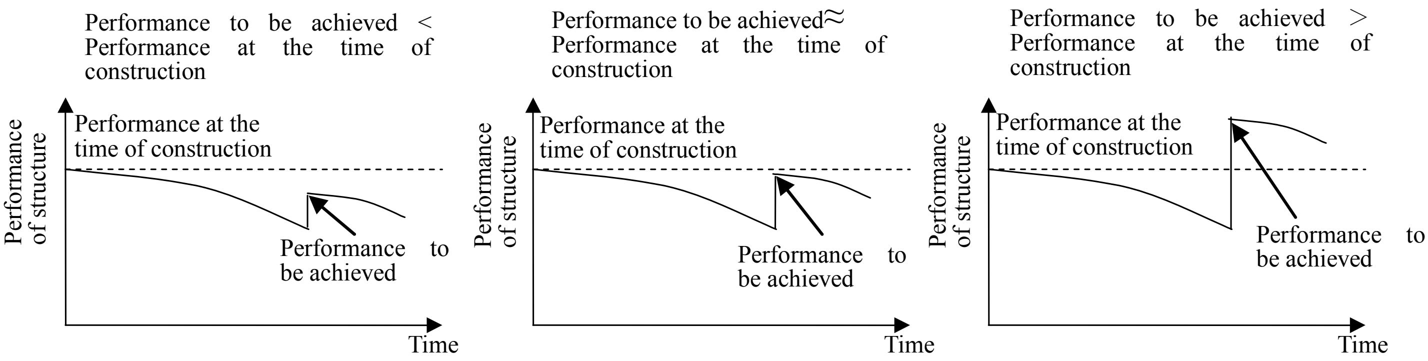
(3) In cases where defect that is likely to cause problems immediately has been recognized such as the hazards for third party, appropriate emergency measures shall be taken promptly.

[Commentary] (1) In cases where remedial measures have been found necessary because the degradation of present or future performance of a structure is an issue, the authority engaged in the maintenance of the structure should determine the performance to be achieved and take appropriate remedial measures. Remedial measures are required in the following cases: (i) cases where the present performance of the structure is below the allowable limit, (ii) cases where the performance of the structure is expected to fall below the allowable limit during the remaining planned service period based on deterioration prediction although the structure is free from any problem at present, and preventive measures are required, and (iii) cases where remedial measures are necessary to meet revised design criteria concerning the loading and seismic resistance.

Remedial measures include the intensified investigation, repair, strengthening, functional improvement, restriction in service, and dismantling/removal (**7.2** “Types and Selection of Remedial Measures”). The performance to be achieved should be determined considering the importance of the structure, maintenance categories, remaining service life, and the condition of deterioration or performance degradation of the structure, and remedial measures should be selected considering the ease of maintenance after the implementation of measures and life-cycle cost.

In cases where the deterioration mechanism has been explicitly identified, appropriate measures should be taken consulting **Part 2**.

Performance should be (i) restored to a level midway between the time of construction and present, or maintained at the present level, (ii) restored to the level at the time of construction or (iii) carried out to a level higher that at the time of construction.



(i)Restoration of performance to a level midway between the time of construction and present, or maintenance of present level of performance

(ii)Restoration of performance to the level at the time of construction

(iii)Carring out to a level higher that at the time of construction

Fig. C7.1.1 Levels of performance to be achieved

(2) When taking remedial measures, the deterioration mechanism or the degree of performance degradation of the structure should first be identified, and plans for enforcing remedial measures and for maintaining the structure after remedial measures are taken should be prepared.

Approaches to the enforcement of remedial measures according to the type of remedial measure are described below. For intensified investigation or restriction in service, the maintenance plan should be reviewed and the reviewed plan should be used for enforcing remedial measures. For repair, strengthening, functional improvement or the dismantling/removal of the structure, the design and construction plans for the remedial measure should be used for enforcement.

Approaches to the preparation of a maintenance plan after the enforcement of remedial measures are described below. For intensified investigation or restriction in service, the plan for enforcement the remedial measure is the same as the maintenance plan after the enforcement of the measure. In cases of repair, strengthening or functional improvement, a maintenance plan should be prepared that explicitly shows the frequency of investigation, items and methods of investigation and remedial measures to be taken in cases where performance is deteriorated to a level below the requirements, to ensure that the required performances may be maintained during the remaining planned service period. If only a short remaining service life has been left, materials and methods can be selected from among numerous types, and a maintenance plan can be prepared relatively easily after the enforcement of remedial measures. If a long remaining service life is available, however, a maintenance plan should be prepared considering the life-cycle cost because remedial measures are taken several times. In cases where the structure is demolished or removed, no maintenance plan is required.

The plans for enforcement remedial measures and for maintaining the structure after the enforcement of remedial measures vary according to the deterioration mechanism even where the degree of performance degradation is the same. In cases where the deterioration mechanism has been explicitly identified, plans for enforcement remedial measures and for maintaining the structure after the enforcement of remedial measures should be prepared consulting **Part 2**.

(3) Selecting remedial measures, preparing plans for enforcement remedial measures and for maintaining the structure after the enforcement of remedial measures, and enforcement remedial measures require certain time. In cases where adverse hazards for third party are expected due to the falling of concrete pieces, for example, appropriate emergency measures should be taken quickly such as the restriction in service, placement of the affected area off limits and application of spalling-proof netting.

7.2 Types and Selection of Remedial Measures

7.2.1 General

Remedial measures shall be selected properly from the intensified investigation, repair, strengthening, functional improvement, restriction in service and dismantling/removal of the structure.

[Commentary] This Specification classifies remedial measures during the period of maintenance into six categories. The types of remedial measures that are selected based on the performance of the structure and the level of performance to be achieved after the enforcement of remedial measures are listed in Table C7.2.1. Table C7.2.2 shows examples of relationships between the result of structural evaluation and the remedial measure that can be selected. The table shows that the intensified investigation, repair, strengthening, restriction in service, or dismantling/removal of the structure is selected as a remedial measure in cases where safety is an issue, and that the intensified investigation, repair, functional improvement, restriction in service, or dismantling/removal of the structure is selected as a remedial measure in cases where serviceability is an issue. In cases where traffic lanes are increased as a result of an increase of traffic volume or where the function of the structure is carried out by installing sound proofing walls, strengthening is likely to be selected.

In cases where a problem has an adverse effect on pedestrians or vehicles like the falling of concrete pieces, repair is generally selected as a remedial measure. In cases where the aesthetic effect of the structure has been deteriorated by cracking or peeling, rust stain or staining, the appearance is restored or improved by repair. Maintenance category C is applicable to structures that need to be maintained only through indirect observation because direct investigation are difficult. For these structures, repair or strengthening should be carried out according to the condition of the structure.

Table C7.2.1 Types of remedial measures according to performance

Structural performance	Level of performance to be achieved and type of remedial measure		
	(i)Level midway between the time of construction and present, or present level of performance	(ii) Level at the time of construction	(iii) Level higher than at the time of construction
Safety	Intensified investigation, repair or restriction in service	Repair	Strengthening
Serviceability	Intensified investigation, repair or restriction in service	Repair	Functional improvement or strengthening
Hazards for third party	Intensified investigation, repair or restriction in service	Repair	—
Aesthetic appearance and landscape	Intensified investigation or repair	Repair	Repair
Durability	Intensified investigation, repair or restriction in service	Repair	Repair

Table C7.2.2 Examples of remedial measures selected based on the results of evaluation

Structural performance	Result of evaluation	Remedial measure																	
		Intensified investigation			Repair			Strengthening			Functional improvement			Restriction in service			Dismantling/removal of structure		
		Maintenance categories			Maintenance categories			Maintenance categories			Maintenance categories			Maintenance categories			Maintenance categories		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Safety	I	O						O											
	II		O	O	O[3]	O[3]	O[1,3]	O	O	O[1]					O	O	O	O	O
Serviceability	I	O			O			O[2]			O								
	II		O	O	O	O	O[1]	O[2]	O[2]		O	O	O[1]		O	O	O	O	O
Hazards for third party	I	O	O	O	O										O	O			
	II				O	O	O								O	O			
Aesthetic appearance and landscape	I				O														
	II		O	O	O	O													
Durability	I	O			O														
	II		O	O	O	O									O	O			

O:Remedial measure that can be selected Result of evaluation I:Likely to cause a problem, II:A problem is involved

Notes 1:Classified as C because no direct investigation is possible, 2:In cases where the objective is to improve functions

3:In cases where safety is increased to the level at the time of construction

7.2.2 Intensified investigation

Intensified investigation shall be carried out by reviewing the maintenance plan considering the results of evaluation and judgment of the necessity for remedial measures, remaining planned service period and specifying the appropriate frequency and items of investigation.

[Commentary] Intensified investigation involves the increase of investigation frequency and of investigation items in cases where repair or strengthening has been considered necessary but cannot be enforced immediately or where the present state is observed without enforcement any measures. When intensified investigation, the maintenance plan should be reviewed considering the results of evaluation and judgment of the necessity for remedial measures or the remaining planned service period, and appropriate investigation frequency and items should be determined.

7.2.3 Repair

Repair shall be carried out so that the designated performance can be achieved, based on the appropriate implementation plan for repair and the post-repair maintenance plan. For details, refer to 7.3 Repair and Strengthening.

[Commentary] The objectives of repair in this Specification are to remove the hazards for third party, restore or improve aesthetic appearance or landscape or durability, and restore the mechanical performance related to safety or serviceability to the level at the time of construction.

The objectives of repair are described below.

(i) To restore concrete structures deformed by cracking or peeling

(ii) To remove concrete that has incorporated deterioration factors due to chloride ion permeation or carbonation

(iii) To prevent the permeation of hazardous substances by surface coating or to prevent damage to third parties due to the falling of concrete pieces

(iv) To guarantee the aesthetic appearance or landscape of the structure

(v) To restore the serviceability of structures requiring watertightness by preventing leakage or taking other measures

Repairing the structure to intercept deterioration factors or control the progress of deterioration while the deterioration is still hidden reduces the burden of maintenance after the repair.

When repairing a structure, preparing plans for enforcement and post-repair maintenance is important. Then, materials and methods should be selected considering the durability of the structure after the repair.

7.2.4 Strengthening

Appropriate plans shall be prepared for strengthening and post-strengthening maintenance. For details, refer to 7.3 "Repair and Strengthening."

[Commentary] In this Specification, the objective of strengthening is to improve the mechanical performance related to safety or serviceability above the level at the time of construction.

Methods of strengthening are described below.

(i) Replacing concrete members

(ii) Increasing the sectional area of concrete

(iii) Adding members

(iv) Increasing support points

(v) Adding reinforcing materials

(vi) Applying prestress

Appropriate plans should be prepared for strengthening the structure and maintaining the structure after the strengthening in accordance with the "Design" volumes of the Standard Specifications and "Guidelines for Strengthening of Concrete Structures (draft)," or based on other standards carried out to the design of the structure, so as to meet the designated mechanical required performances. Then, materials and methods should be selected considering the durability of the structure after the strengthening.

7.2.5 Functional improvement

When improving the functions of the structure, the required functions shall be determined, and appropriate implementation plans and maintenance plans after the functional improvement shall be prepared.

[Commentary] Functions of a structure are carried out by adding new functions by increasing traffic lanes to carry increased traffic volume or by installing sound proofing walls. Functional improvement may sometimes involve strengthening. For functional improvement, appropriate plans for enforcement and for maintenance after the functional improvement should be prepared in accordance with the standards carried out to the design of the structure or other standards so as to meet the designated required performances. Then, materials and methods should be selected considering the durability of the structure after the functional improvement.

7.2.6 Restriction in service

When restricting the service of a structure, the degree and method of restricting loads shall be determined based on the results of evaluation and judgment of the necessity for remedial measures. Appropriate implementation plans and maintenance plans after the implementation shall be prepared and executed.

[Commentary] Restriction in service involves restricting loads or vehicle velocity without repairing or strengthening the structure. Service is generally restricted simultaneously with the intensified investigation until the change of use (e.g. from a pedestrian sidewalk to a roadway), repair, strengthening or dismantling/removal of the structure.

When restriction in service, it is important to determine the load or speed limits according to the deterioration mechanism of the structure or the degree of performance degradation. To that end, loading tests or vibratory loading tests should be conducted. When restriction in service as well as when intensified investigation, the maintenance plan should be reviewed based on the results of structural evaluation and judgment of the necessity for remedial measures, and the remaining planned service period, and the frequency and items of investigation should be specified properly.

7.2.7 Dismantling/removal of structure

Structures shall be demolished or removed in accordance with appropriate enforcement plans considering the effects on the surrounding environment, work safety, disposal of waster after dismantling, team of construction and cost performance.

[Commentary] Structures are demolished or removed in cases of obsolescence due to deterioration, removal or renovation as a result of functional loss, river improvement, improvement of highway or railway alignment, enforcement of redevelopment projects, etc.

For dismantling or removing a structure, a method fit for the structure should be selected. The method should be selected fully considering the effects on the surrounding environment, work safety, waste recycling or reusing methods, construction period and cost performance.

When dismantling/removal, it is desirable to investigation in detail by loading tests or other means the relationship of structural performance degradation and material deterioration for the purpose of improvement of engineering level of maintenance.

7.3 Repair and Strengthening

7.3.1 Principles

(1) When repairing or strengthening a structure, design shall be performed for repair or strengthening based on the results of assessments and preliminary investigation, and appropriate plans should be prepared for proper enforcement and for maintenance after

the repair or strengthening.

(2) Structures shall be repaired or strengthened in accordance with an enforcement plan, and shall be managed and verified properly during and after the repair or strengthening.

(3) When repairing or strengthening a structure, region or member for which the deterioration mechanism has been explicitly identified, Part2 should be consulted.

[Commentary] (1) When repairing or strengthening a structure, the state of the structure should be verified by investigation. Design and construction, and post-enforcement maintenance plans should be prepared. Construction, administration and verification should be carried out in accordance with the plans.

In preliminary investigation, it is important not only to check design documents, construction reports or maintenance records but also to verify design conditions, state of construction, defect of the structure and environmental actions and loading by directly investigating the structure, and to identify the restrictions and problems during construction.

In the design of repair or strengthening, the performance to be achieved and the area of repair or strengthening should be determined, and the method, materials and specifications that satisfy the required performances should be selected. The enforcement plan should specify the area, procedure and method of construction fully considering the objective of design and field enforcement conditions in order to implement the repair or strengthening measure properly.

In repair or strengthening, the state of the structure may sometimes change because additional materials are carried out to an existing structure. Installing additional monitoring equipment may become necessary to identify the progress of defect. The above points should be taken into consideration when a plan for maintenance after repair or strengthening is prepared.

(2) Structures should be repaired or strengthened properly in accordance with an enforcement plan. Materials and the construction method should be managed and verified during construction. At the completion of repair or strengthening, verifications should be conducted to check the results of administrative testing for materials and construction method and to confirm whether repair or strengthening has been completed as planned or not.

7.3.2 Design of repair or strengthening

(1) In the design of repair or strengthening, principles of repair or strengthening to meet designated required performances shall be defined, and appropriate materials and method should be selected.

(2) In the design of repair or strengthening, whether or not the structure, region or member repaired or strengthened meets the designated required performances shall be verified by an appropriate method.

[Commentary] (1) When repairing or strengthening a structure, the principle, area, method and material should be selected, and the structure should be repaired or strengthened considering the following points.

(i) Present condition of the structure to be repaired or strengthened: Dimensions, arrangement and diameter of steel, etc.

(ii) Results of evaluation of the structure and judgment of the necessity for remedial measures in assessments

(iii) Deterioration mechanism

(iv) Importance of the structure: E.g. a bridge on a route important for living

(v) Environmental condition: Meteorological condition and the location of the structure, e.g. in a mountainous or coastal area

(vi) Load condition: E.g. cyclic traffic load is predominant on bridge deck slabs and seismic load is predominant on bridge piers

(vii) Restrictions on construction: Time of construction, period, time available for construction and construction environment (securing work space at the site, noise, vibration, odor, etc.)

(viii) Combinations of repair or reinforcing materials, thickness of surface coating, cross sectional area after repair or strengthening, construction method, etc.

(ix) Maintenance: Ease of maintenance after repair or strengthening

(x) Remaining planned service period

Table C7.3.1 lists principles of repair or strengthening, components of repair or strengthening work and factors to be considered for meeting required performances for respective deterioration mechanisms.

In the design of repair or strengthening to restore or improve the mechanical performance such as safety and serviceability, it is important to ensure that the required performances for the structure are met throughout the remaining service life in accordance with “Design” volumes of the Standard Specifications, “Guidelines for Strengthening of Concrete Structures (draft)” and design standards for the structure. The design for repair or strengthening is different from the design of a new structure. Considerations for construction unique to the design for repair or strengthening should therefore be identified in advance. The method and materials should be selected also considering maintenance after the repair or strengthening.

Table C7.3.2 lists major methods for restoring or improving the mechanical performance of structures in accordance with “Guidelines for Strengthening of Concrete Structures (draft).”

Various researches are now being conducted and case studies of applications are now being accumulated. No techniques may therefore be yet available that fully satisfy designated required performances. Then, the methods or materials should be selected on the assumption of re-repair or re-strengthening. The characteristics of methods or materials should be identified in detail, and methods or materials should be selected based on test results or records of applications.

Major repair or strengthening methods currently put into practice are listed in Fig. C7.3.1.

Table C7.3.1 Principles and methods of repair according to deterioration mechanism

Deterioration mechanism	Principle of repair	Components of repair method	Factors to be considered for meeting required performances
Carbonation	-Remove concrete in which carbonation occurred -Control the infiltration of CO2 and water after repair	-Patching -Surface treatment -Re-alkalization	-Degree of removal of sections of concrete in which carbonation occurred -Prevention of corrosion of reinforcing bars -Quality of materials for patching -Quality and thickness of materials for surface treatment -Alkali amount in concrete
Chloride attack	-Remove Cl- that intruded -Control the permeation of Cl-, water and oxygen after repair	-Patching -Surface treatment -Desalination	-Degree of removal of sections subjected to permeation -Prevention of corrosion of reinforcing bars -Quality of materials for patching -Quality and thickness of materials for surface treatment
	Potential control for reinforcing bars	-Anode materials -Electric power unit	-Quality of anode materials -Amount of polarization
Frost attack	-Remove deteriorated concrete -Control water infiltration after repair -Improve the resistance of concrete to freezing and thawing	-Patching -Crack injection -Surface treatment	-Resistance of patching materials to freezing and thawing -Prevention of corrosion of reinforcing bars -Materials and method for crack injection -Quality and thickness of materials for surface treatment
Chemical attack	-Remove deteriorated concrete -Control the permeation of hazardous substances	-Patching -Surface treatment	-Quality of materials for patching -Quality and thickness of materials for surface treatment -Degree of removal of deteriorated concrete
Alkali-silica reaction	-Control water supplies -Accelerating the diffusion of internal water -Control alkali supplies -Control expansion -Restore member stiffness	-Water treatment (starling and drainage) -Crack injection -Surface treatment -Jacketing	-Materials and method for crack injection -Quality and thickness of materials for surface treatment
Fatigue (concrete deck slabs on highway bridges)	-Control the progress of cracking -Restore member stiffness -Restore shearing load bearing capacity	-Water treatment (drainage) -Waterproofing of deck slabs -Adhesion -Increase of thickness	-Integration with existing concrete members
Abrasion	-Restore lost cross section -Restore or improve roughness coefficient	-Patching -Surface treatment	-Quality of materials for patching -Bond -Resistance to abrasion -Roughness coefficient

Table C7.3.2 Examples of methods for restoring or improving mechanical performance

Carried out to	Method	Major method*1	Applicable member					
			General	Beam	Column	Slab	Wall*2	Bearing
Concrete member	Adhesion	Adhesion		OO	O	OO	O	
	Jacketing	Jacketing			OO		O	
	Prestressing	External cable		OO	O	O		
	Increase of sectional thickness	Increase of thickness		O		OO		
	Replacement of members	Replacing		O	O	OO	OO	
Structure	Addition of beams	Additional installation		OO		OO		
	Addition of walls	Additional installation					OO	
	Addition of support points	Additional installation		OO		OO		
	Seismic isolation	Seismic isolation	OO					OO

OO:Put to practical use in numerous cases, O: Considered applicable

*1: Adhesion: Steel plate adhesion and FRP (fiber reinforced plastic) adhesion (continuous fiber reinforced sheet adhesion and continuous fiber reinforced plate adhesion)

Jacketing: Steel plate jacketing, FRP jacketing (continuous fiber reinforced sheet jacketing and continuous fiber reinforced plate jacketing), reinforced concrete jacketing, mortar shotcrete and precast panel jacketing

Prestressing: External cable and internal cable

Increase of thickness: Increase of top surface thickness, increase of bottom surface thickness and bottom surface shotcrete

Additional installation: Addition installation of beams, earthquake-resistant walls and support points

*2:Wall-type bridge piers are included

(2) In the design for repair or strengthening, the performance of the repaired or strengthened structure should be checked using an appropriate method and whether the performance can be achieved or not should be verified.

In the inspection of the design for repair for restoring or improving durability, numerically identifying the performance to be achieved is difficult at the present technological level unlike for the load bearing capacity or stiffness. Then, the period of guarantee of durability determined by the repair method, material configuration, specifications and other parameters may be categorized into (i) long period equivalent to the remaining service life of the structure, (ii) intermediate period or (iii) short period, for the purpose of inspecting the design for repair.

Post-repair or -strengthening mechanical performance of the structure should basically be inspected in accordance with “Design” volumes of the Standard Specifications using the loading conditions, material properties and structural specifications related to the performance to be checked. Then, the state and area of defect, and structural specifications should be fully identified by conducting investigation in advance, and the effective section or area to be repaired or strengthened should be specified properly. The loads to be carried out should be properly selected considering investigation results and the performance to be inspected.

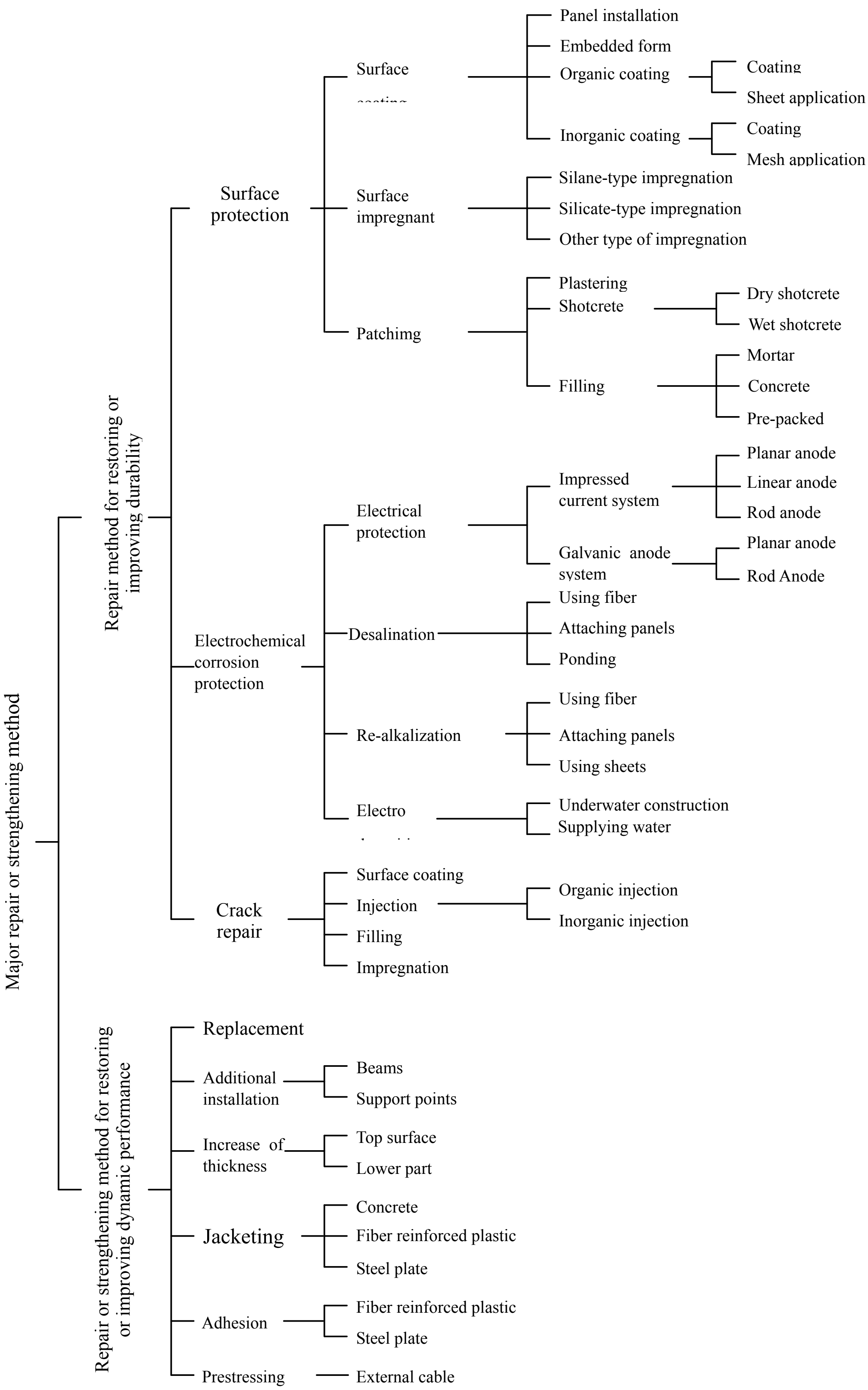

Major repair or strengthening method
Repair method for restoring or improving durability
Surface protection
Surface
Panel installation
Embedded form
Organic coating
Coating
Sheet application
Inorganic coating
Coating
Mesh application
Surface impregnant
Silane-type impregnation
Silicate-type impregnation
Other type of impregnation
Patchimg
Plastering
Shotcrete
Dry shotcrete
Wet shotcrete
Filling
Mortar
Concrete
Pre-packed
Electrochemical corrosion protection
Electrical protection
Impressed current system
Planar anode
Linear anode
Rod anode
Galvanic anode system
Planar anode
Rod Anode
Desalination
Using fiber
Attaching panels
Ponding
Re-alkalization
Using fiber
Attaching panels
Using sheets
Electro
Underwater construction
Supplying water
Crack repair
Surface coating
Injection
Organic injection
Inorganic injection
Filling
Impregnation
Repair or strengthening method for restoring or improving dynamic performance
Replacement
Additional installation
Beams
Support points
Increase of thickness
Top surface
Lower part
Jacketing
Concrete
Fiber reinforced plastic
Steel plate
Adhesion
Fiber reinforced plastic
Steel plate
Prestressing
External cable

Fig. C7.3.1 Major repair or strengthening methods applied for concrete structures

The performance of a repaired or strengthened structure becomes effective through the integration of the repair or reinforcing material and the existing structure. The degree of integration should therefore be inspected properly. The performance not only of the repaired or strengthened region or member but also of the structure system should be inspected. This is because repairing or strengthening the region or member is likely to cause the behavior of the structure system to change considerably from that before the repair or strengthening.

7.3.3 Execution of repair or strengthening

(1) The execution plan for repair or strengthening shall be prepared based on the design fully considering construction restrictions.

(2) Repair or strengthening shall be carried out carefully in accordance with the execution plan considering the characteristics of the method and materials to be adopted, specifications and considerations.

(3) When carrying out repair or strengthening, the items and methods for effective and economical construction management or verification during construction or at the completion of work shall be specified to verify whether the designated required performances have been met or not.

[Commentary] (1) When carrying out repair or strengthening, an appropriate execution plan should be prepared in accordance with **7.3.2** “Design of Repair or Strengthening” fully considering construction restrictions. In cases where repair or strengthening has not been carried out in accordance with the execution plan, not only the designated required performances may not be met but also maintenance after the completion of work is likely to be greatly affected. The purpose of design should therefore be fully understood and an appropriate execution plan should be prepared.

Typical jobs included in the execution plan for repair or strengthening are listed in Fig. C7.3.2.

(2) Repair or strengthening should be carried out carefully by professional engineers with adequate construction technical expertise in accordance with the execution plan. When carrying out repair or strengthening, understanding the characteristics of the method and materials used and the points to remember is necessary because the preparation work and construction method vary according to the method, material or specification of repair or strengthening.

(3) When carrying out repair or strengthening, the items and methods for effective and economical construction management or verification fit for the method, material and specification should be defined. In cases where verifications have found that no required performances have been met, appropriate measures should be taken to achieve the objective.

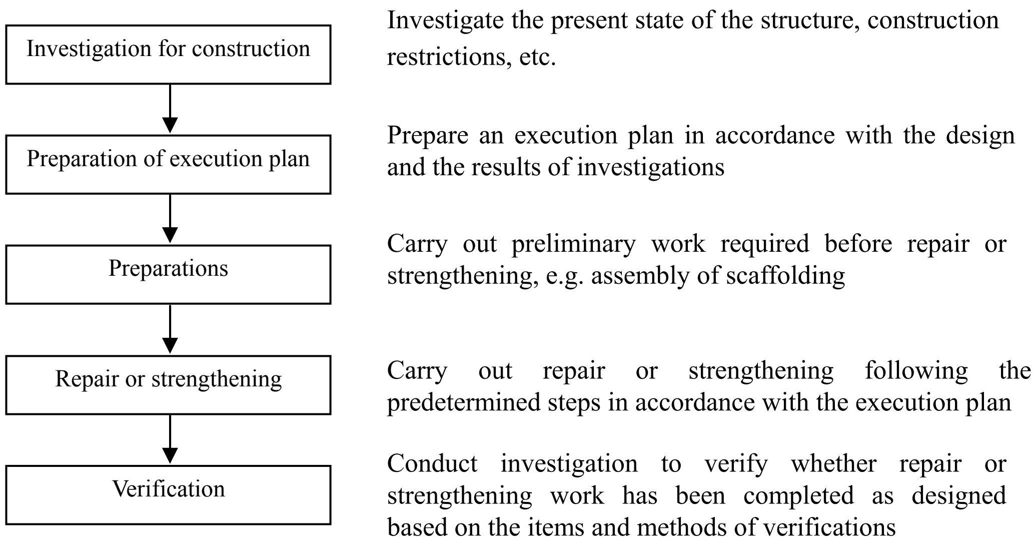


Fig. C7.3.2 Typical jobs included in execution plan for repair or strengthening

7.3.4 Maintenance after repair or strengthening

(1) After repair or strengthening, the structure shall be maintained properly so that it can maintain the designated performance throughout the remaining planned service period.

(2) Even in cases where a region or member of the structure has been repaired or strengthened, the entire structure shall be maintained properly.

[Commentary] (1) After repair or strengthening, the designated required performances of the structure should be satisfied during the remaining planned service period or during the service period specified in the design for repair or strengthening. The continuity of the effect of the repair or strengthening needs to be verified. To that end, the maintenance of the repaired or strengthened structure is important. The maintenance plan before remedial measures are taken should be reviewed and a new maintenance plan should be prepared also considering the repair or strengthening that has been performed. Then, the new maintenance plan should be used as a basis for diagnosing the structure using an appropriate method (investigation deterioration prediction, evaluation of structural performance and judgment of the necessity for remedial measures), records the results of assessments and taking new remedial measures as required.

After repair or strengthening, visual observations of an existing structure may sometimes become impossible in cases where a certain method, e.g. surface treatment, adhesion or jacket, has been enforced. Methods should therefore be considered that enable direct or indirect investigation of existing structures. Installing monitoring equipment may sometimes be effective.

Deterioration after repair or strengthening should be predicted comprehensively based on the investigation results considering the process of deterioration after repair or strengthening including the deterioration of the materials constituting existing structures, and of the deterioration of the integration of the materials used for repair or strengthening and the existing structure. In cases where the structure has been deformed again during the remaining planned service period or during the service period specified in the design for repair or strengthening, and it has been determined that the designated performance requirement would not be met and that taking additional remedial measures would be required, the design and construction method for repair or strengthening that has been carried out should be reviewed (area, method, materials and specifications), and appropriate remedial measures should be taken to maintain the designated required performances.

(2) Repairing or strengthening some members or a limited number of regions may partly change the environmental or loading actions on the structure. As a result, stress distribution, water distribution in concrete, objects transfer characteristics and electrochemical balance may change and defect is likely to occur that is different from that in cases where no repair or strengthening has been carried out. There is also a possibility that new defect may occur in a member or region that has not been repaired or strengthened and that the progress of defect may become a major cause of performance degradation for the structure system. In cases where a member or region has been repaired or strengthened, not only the repaired or strengthened member or region but also the structure system should be maintained properly.

CHAPTER 8 RECORDING

8.1 Principle

In the maintenance of a structure, the results of assessments and the remedial measures taken shall be appropriately recorded and stored in accordance with the maintenance plan.

[Commentary] In order to maintain a structure efficiently and rationally, necessary information should be made accessible as reference data for future use. Such information should contain basic data of structures, standards and specifications applied to design and construction of structure, the results of a series of assessments conducted while the structure is in service such as investigations, prediction of deterioration progress, evaluation and judgment,; or the results of remedial measures taken such as repair and strengthening.

The maintenance records can be used for verifying the validity of the maintenance plan or maintenance technology adopted. Moreover, analysis of the records by clarifying problems and required improvements in design and construction from a viewpoint of maintenance, can contribute to progress in technology which can be reflected in design, construction and maintenance plans for similar structure in future. Records constitute a database on the condition of structures. Structures should be diagnosed and remedial measures should be taken after studying the past records in detail. After completing such a task, the results should additionally be incorporated into the records to keep them up to date.

8.2 Method of Recording

Recording shall be preserved using appropriate method(s) in a fixed format such that they can be easily referred to.

［**Commentary**］Structures are in service for a long period of time. It should therefore be noted that the change of maintenance organization or replacement of person in charge during the period. Then, records should be kept in such a format as to facilitate the understanding of the history of maintenance. Consequently, the records should provide as accurate and objective data as possible. The results of a series of assessments from investigation to prediction of deterioration progress, evaluation of structural performance and judgment of necessity of remedial measures should be recorded using a certain method. To that end, a method fit for the structure should be designated in advance.

For recording, an intelligible format should be used according to the maintenance category, the kind and detail of maintenance and the kind of the structure. Records on the maintenance of a structure may sometimes constitute a large volume of data. In cases where numerous structures are maintained collectively, even larger volumes of data may be managed. Building an efficient database system and keeping it in a digital format for easy access are desirable. Records need to be kept for a long time, during which the system may be modified. It should be made sure that records can be used even in case of system modification. Writing the history of maintenance directly on the structure may be effective.

8.3 Items to be Recorded

(1) The items to be recorded during the assessment of a structure should include the names of persons maintaining the structure and of those conducting the assessment on a contractual basis, basic data of the structure, loading and other environmental conditions, category of maintenance, method and results of investigations in the assessment, method and results of deterioration prediction, the results of evaluation of structural performance and judgment of necessity of remedial measures.

(2) In cases where remedial measures have been taken such as repair and strengthening, the details of design and construction for repair or strengthening, and the names of persons maintaining the structure and of those conducting assessment on a contractual basis shall be recorded.

[Commentary] (1) Examples of typical items to be recorded during maintenance are listed in Table C8.3.1. Points to remember in respective types of investigations are described below.

Recording in initial assessment: In the investigations in initial assessment, in case initial defects are found, the location and state of an initial defect, contents of evaluation and judgment (identified deterioration mechanism, condition of segments, members and structure, judgment of necessity for detailed investigation) should be recorded in addition to the items given in Table C8.3.1. In cases where a detailed investigation has been conducted, the items, method, scope and results of the investigation; and the results of evaluation and judgment of necessity for remedial measures should be recorded.

Recording in periodic assessment: In investigations in routine assessment, the date of investigation, name of investigator and whether there is any defect or not generally need to be recorded. In cases where defect has been recognized, the type, location and condition, and the results of evaluation and judgment of necessity for detailed investigation should be recorded. In investigations in regular assessment, in case any defect is found, the type and location of defect, whether it is in progress or not, contents of evaluation and judgment (identified deterioration mechanism, condition of segments, members and structure, judgment of necessity for detailed investigation) should be recorded in addition to the items given in Table C8.3.1.

In cases where the detailed investigation has been conducted in routine or regular assessment, the methods of investigation (e.g. method and location of collecting samples, equipment used and analysis method and the location and method of nondestructive testing), and the type, location and condition of detect should be recorded as in as much detail as possible. The prediction of the deterioration progress basing on the investigation (discussions on the variance from the predicted deterioration progress in the initial assessment), results of evaluation and judgment (conditions of the region or member and results of examination of remedial measures), names of the maintenance engineers (chief manager, responsible engineers, professional engineers and investigators) and of the people conducting assessment on a contractual basis, if any, should be recorded.

Recording in extraordinary assessment: Investigations in extraordinary or emergency assessment are conducted in case of an accidental event such as earthquake, fire and collision. The items to be recorded in standard investigations in extraordinary or emergency assessment are the details of the accidental phenomenon, objective of investigation, location and condition of damage, results of evaluation and judgment (condition of segments, members and structure, judgment of necessity for detailed investigation) in addition to the items given in Table C8.3.1. In cases where detailed investigations have been conducted, the same items should be recorded as those in detailed investigations in regular assessment.

(2) In cases where repair, strengthening or other remedial measure has been taken, the deterioration of the structure before the measure was taken, timing of implementation, weather, air temperature, method and region of construction, kinds and specifications of materials used, curing methods, quality management methods, and inspection methods and results should be recorded. The names of maintenance engineers (chief manager, responsible engineers and professional engineers) and people conducting assessments on a contractual basis (responsible engineers and professional engineers) should also be recorded.

8.4 Storage of Records

Records should be stored during the service period of the structure.

[Commentary] The maintenance records of a structure should be stored while it is in service because the records serve as a basis for efficient and rational maintenance. Records should desirably be stored beyond the service period of the structure inasmuch as possible because they may be useful for maintenance of maintaining other similar structures.

Table C8.3.1 Examples of typical items to be recorded during assessment and application of remedial measures

		Item to be recorded		People held responsible
Assessment	General	Name of people in charge	Maintenance manager (e.g., chief manager, responsible engineers, professional engineers and investigators)	-Maintenance manager Chief manager Responsible engineers Professional engineers Investigators -Contractor conducting Assessment Responsible engineers Professional engineers
		Specifications for structure	Name, loads, surrounding environmental conditions, planned service period, maintenance type and maintenance records for the structure	
	Investigation	Type	In initial, routine, regular, extraordinary or emergency assessment	
		Timing	Timing of conducting investigation	
		Location	Detailed location of the structure or member to be investigated	
		Item	Items to be investigated	
		Method	For respective items (detailed descriptions are required for non-standard methods)	
		Result	For respective items, testing and judgment	
	prediction	Method	Model, equations or parameters used	
		Result	Initial, progressing, accelerating and deterioration periods	
	evaluation and Judgment	Method	Calculating methods, standard and criterion used	
		Grading	Grading of the appearance of the structure	
		Result	Results of evaluation and judgment for region, member or structure	
Remedial measure		Name of people in charge	Maintenance manager (e.g., chief manager, responsible engineers, professional engineers and investigators) Contractor taking remedial measure (e.g. responsible engineers and professional engineers)	-Maintenance manager Chief manager Responsible engineers Professional engineers Investigators -Contractor taking remedial measures Responsible engineers Professional engineers
		Type	Enhancement of investigations, repair, strengthening, restrictions on service and demolition or removal	
		Method	Construction plan documents and drawings	
		Record	Timing, drawings, execution reports and history	

Part 2

Maintenance for Specific Deterioration Mechanisms

CHAPTER 9 MAINTENANCE OF STRUCTURES SUBJECT TO CARBONATION

9.1 General

(1) This chapter provides standard methods for the maintenance planning, assessment, remedial measures and recording for structures that have been or are highly likely to be subject to performance degradation due to carbonation. The items common to all deterioration mechanisms are shown in Part 1.

(2) This chapter shall be applied to structures of the maintenance categories A (preventive maintenance) and B (corrective maintenance).

[Commentary] (1) Carbonation in concrete structures means the carbonation reaction of the carbon dioxide and cement hydrate as a result of the penetration of the carbon dioxide of the air into concrete, which causes the pH value in voids of concrete to fall. Carbonation destroys the passivation film on the steel surface in concrete, and corrosion progresses with supplies of oxygen and moisture. The corrosion of steel then induces cracking, peeling of concrete cover and reduction of the load bearing capacity. Carbonation transforms all types of hydrates including calcium silicate hydrate. It has also been known that the change of the structure of voids in hardened cement causes the change in strength and shrinkage due to carbonation.

This chapter discusses only carbonation attributable to carbon dioxide. Carbonation caused by other acidic substances is discussed in "Chemical Attack."

This chapter refers to reinforced concrete, prestressed concrete and steel-concrete composite structures subject to carbonation and the description focuses on carbonation mainly related to reinforced concrete. Structures with protective layers on concrete surface such as mortar and surface coatings or structures used in formwork are also intended. The deterioration of the protective layer itself is not included. It should, however, be noted that such performance attributes as aesthetic appearance and landscape, and hazards for third party of the entire structure including the protective layer may be considerably degraded due to the deterioration of protective layers.

Deterioration due to carbonation and steel corrosion progresses during the initiation stage, propagation stage, acceleration stage and deterioration stage (Fig. C9.1.1 and Table C9.1.1). In each stage, deterioration has varying influences on the structure. The degree of performance degradation with the progress of deterioration also varies according to the performance attribute. The methods of assessment (investigation, deterioration prediction, evaluation or determination), remedial measures implementation and recording vary in respective deterioration stages.

A standard maintenance procedure against carbonation is shown in Fig. C9.1.2.

In composite deterioration due to carbonation and chloride attack, the deterioration due to chloride attack is accelerated by carbonation. For the maintenance against the composite deterioration, refer to **Part2, Chapter 2** "Maintenance of Structures Subject to Chloride Attack."

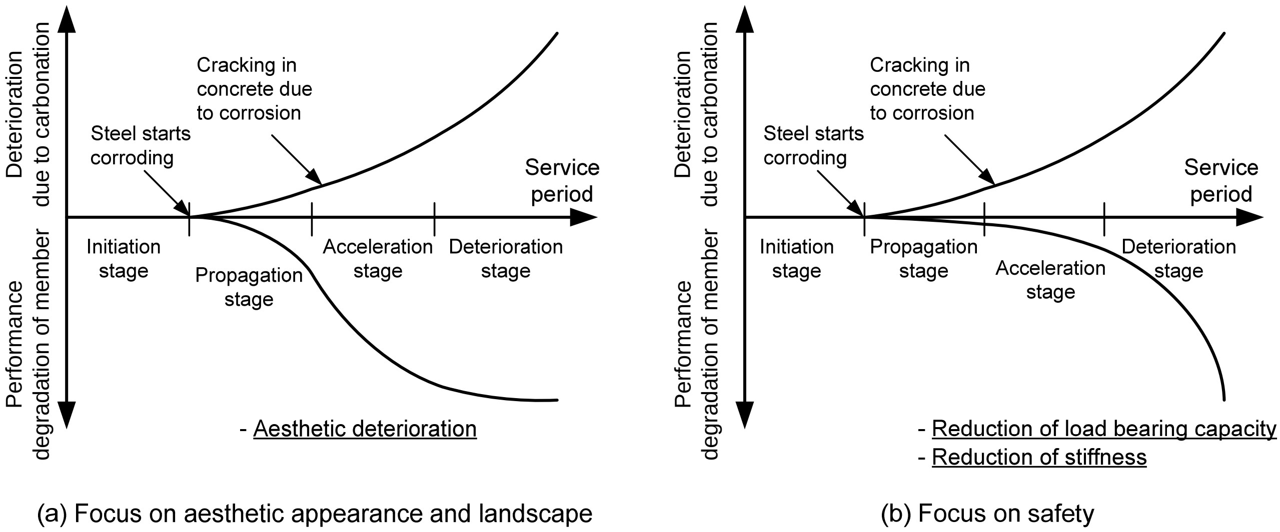


Fig. C9.1.1 Conceptual view of deterioration progress due to carbonation

Table C9.1.1 Definition of deterioration stages

Stage of deterioration	Definition	Factor determining the stage
Initiation stage	Until the depth of carbonation reaches the limit state for the occurrence of corrosion	Rate of carbonation
Propagation stage	From the initiation of corrosion of steel until cracking due to corrosion	Rate of steel corrosion
Acceleration stage	Stage in which steel corrodes at a high rate due to cracking due to corrosion	Rate of corrosion of steel with cracks
Deterioration stage	Stage in which load bearing capacity is reduced considerably due to increased steel corrosion	

(2) Maintenance category B (corrective maintenance) has been designated for numerous existing structures. In the future, maintenance category A (preventive maintenance) is expected to be designated for more structures. In maintenance category A, remedial measures are taken early before performance degradation due to deterioration in view of the life-cycle cost. This chapter therefore mainly discusses structures to which maintenance category A or B is applied. Structures to which maintenance category C (observation-based maintenance) is applied should also be maintained by a basic method described in this chapter wherever possible.

For the matters that should be considered when determining the maintenance category for structures that have been or are expected to be subject to deterioration due to carbonation, refer to **9.2.2** "Maintenance Category." Special matters to be considered for respective maintenance categories are also described in this chapter.

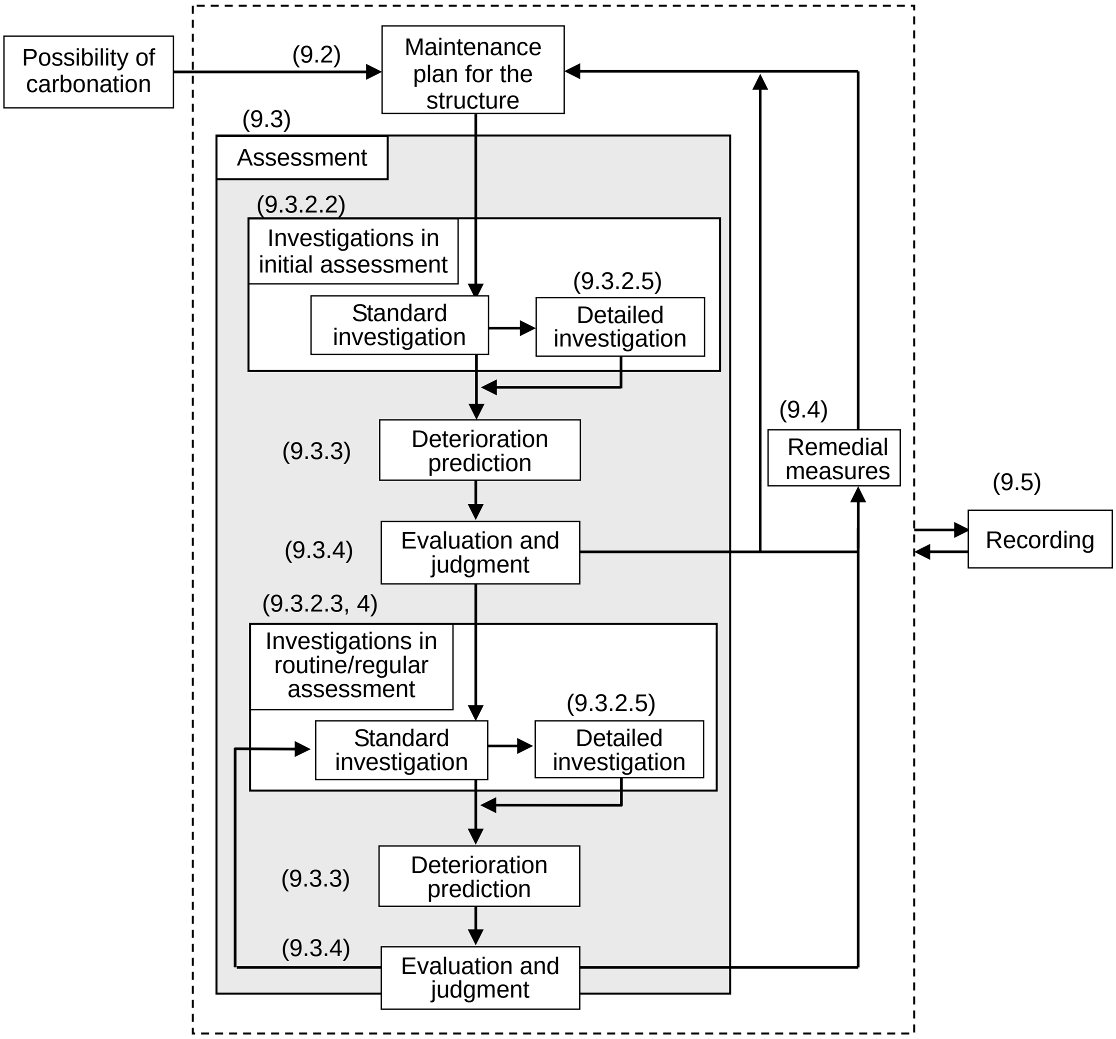


Fig. C9.1.2 Standard maintenance procedure against carbonation

9.2 Maintenance Planning

9.2.1 Basis of planning

In order to maintain a structure subject to carbonation, the category of maintenance shall be selected, the service period planned, and a maintenance planning for activities including assessment, remedial measures and recording drawn up in advance in view of the service and environmental conditions such as the concrete drying conditions and water supplies.

[Commentary] When drawing up a maintenance planning, it is necessary to cover such details as check items and procedures for initial assessment and check items, procedures, timing and frequency for the investigations in routine and regular assessment, evaluation and judgment methods, actions to be taken in the event of deterioration, and recording methods, taking into consideration the type, degree of importance and planned service period of the structure, category of maintenance, and the quality of materials.

The type of structure, size and environmental conditions of concrete structures vary from structure to structure. A maintenance planning must be optimized for each structure. The progress of deterioration of structures subject to carbonation in particular is greatly affected by the depth of carbonation in concrete cover, and humidity and oxygen supplies that cause steel to corrode. An appropriate maintenance planning needs to be drawn up, therefore, in view of these factors.

It is usually difficult, at the stage of maintenance planning, to accurately predict the state of a structure during its service period. It is therefore good practice to draw up a maintenance planning with reference to the deterioration of a similar structure or a structure in a similar environment.

9.2.2 Determination of maintenance category

The category of maintenance of a structure subject to carbonation shall be selected in view of the degree of importance of the structure, the type of structure, hazards for third party, the planned service period and the characteristics of deterioration due to carbonation.

[Commentary] The determination of the category of maintenance is very important because maintenance planning varies widely depending on the category of maintenance. The progress of deterioration and performance degradation due to carbonation is conceptually illustrated in Fig. C9.1.1.

Structures to which maintenance category A (preventive maintenance) is applied should be maintained so that they might be placed under the condition during the initiation stage with no steel corrosion, to prevent performance degradation. The state of the structure should therefore be identified as accurately as possible. Requirements include the following.

(i) Quantitative identification and prediction of the depth of carbonation

(ii) Quantitative identification and prediction of the corrosion of reinforcing bars in concrete

For structures with maintenance category A, remedial measures are taken before reinforcing bars corrode due to deterioration. Thus, large-scale repair or strengthening can be eliminated and the maintenance cost can be reduced accordingly in numerous cases.

Structures to which maintenance category B (corrective maintenance) is applied should be maintained so as to prevent the performance of the structure from failing to meet the requirements. Structures should be maintained to prevent deterioration from reaching the stage of deterioration to ensure safety, the latter half of the acceleration stage to achieve serviceability or the former half of the acceleration stage to keep aesthetic appearance and landscape. Certain actions should be taken when any of the following types of deterioration has been detected.

(i) The corrosion of reinforcing bars in concrete

(ii) The leaching of corrosion rust on concrete surface

(iii) Cracking in the direction of axis of reinforcement on concrete surface

(iv) The spalling of concrete cover

For structures to which maintenance category B is applied, remedial measures should be taken in phase (i) or (ii) above because it is extremely difficult to stop the progress of corrosion of reinforcing bars in concrete once started. It should be noted that large-scale measures will be required if deterioration reaches phase (iii) or (iv).

There have been few cases in which steel corrosion due to carbonation affected performance attributes in short time of occurrence. For ordinary structures that are expected to be subject to carbonation, therefore, maintenance category B (corrective maintenance) may be designated in most cases. Once steel has started corroding, however, investigations are conducted more frequently and remedial measures of larger scale and more costly than before corrosion are needed. For structures of great importance, with a long planned service period, or with high required performances in terms of hazards for third party or aesthetic appearance, therefore, maintenance category A (preventive maintenance) should preferably be selected.

One maintenance category is generally applied to one structure. In cases where the environmental conditions vary from region to region or from member to member, however, applying different maintenance categories to different regions or members may sometimes be effective.

9.2.3 Preparation of maintenance manuals

A maintenance manual describing methods, procedures and frequency requirements should be prepared for each structure in accordance with the maintenance planning, taking the structure-specific conditions into consideration.

[Commentary] The service period of civil engineering structures is long, and maintenance of those structures is performed over a long period of time. It is recommended, therefore, that in order to inform investigators of maintenance concepts and policies, a maintenance manual be prepared so that detailed procedures and methods can be communicated accurately even to newly assigned responsible engineers.

Under certain circumstances such as in cases where the original maintenance planning is altered because the actual progress of deterioration turned out to differ from that assumed in the original maintenance planning, it is necessary to modify the maintenance manual and take appropriate maintenance measures accordingly.

When preparing maintenance manuals, "The Maintenance Manual for Structures Subjected to Carbonation Prepared in Accordance with the Standard Specifications for Design and Construction of Concrete Structures: Maintenance (draft) " may be consulted.

9.3 Assessment

9.3.1 General

In the assessment of a structure whose performance has declined or is highly likely to decline because of carbonation, investigation, evaluation of the present state, prediction of deterioration and judgment of the necessity for remedial measures shall be appropriately conducted in accordance with the maintenance planning.

[Commentary] In order to maintain concrete structures appropriately, this specification requires three types of assessment: initial assessment, periodic assessment and extraordinary assessment. Because the initial and periodic assessments are essential for the maintenance of structures subject to carbonation, this chapter stipulates that those assessments must be conducted. Extraordinary assessments are regarded as assessments to be conducted on an as-needed basis and are therefore not dealt with in this chapter. By conducting periodic assessments during the maintenance period, defect in appearance of structures can be discovered before they occur or in early stages, and remedial measures including preventive measures and repairs can be taken systematically.

9.3.2 Investigation in assessment

9.3.2.1 General

Investigations in initial, routine and regular assessment of a structure subject to carbonation shall be conducted appropriately according to the category of maintenance required for the structure. Prior to investigation, check items, methods, frequency and scope of standard investigation shall be determined appropriately. For each type of assessment, detailed investigation shall also be conducted on an as-needed basis.

[Commentary] It is important to select check items, methods, frequency and scope of investigation appropriately according to the purpose of investigation in accordance with the maintenance planning.

The major parameters that should be identified in investigations of structures subject to carbonation are the depth of carbonation and the corrosion of internal steel. In cases where deterioration has progressed considerably, investigations should be conducted to directly evaluate performance.

The items to be examined in investigations vary according to the degree of deterioration. In cases where it has been determined or assumed that the deterioration was in the initiation stage, investigations should be conducted mainly to identify the progress of carbonation. In cases where it has been determined or assumed that the deterioration was in or beyond the propagation stage, investigations should be conducted mainly to identify the progress of steel corrosion. Table C9.3.1 shows major items to be examined in the respective stages. Data on the items related to deterioration prediction such as the environmental action, depth of carbonation, steel corrosion and location of steel should be collected in as early a stage as possible. Monitoring may be conducted for continuously identifying the depth of carbonation or corrosion of internal steel for structures to which maintenance category A (protective maintenance) is applied.

Carbonation progresses quickly where concrete is dry, and steel corrodes where concrete is wet. Thus, the rate of deterioration may vary from region to region of a structure. The efficiency of subsequent maintenance may be improved by confirming in the initial stages the locations where deterioration is likely to progress.

The frequency and range of investigation should be determined considering the maintenance category, environmental conditions, structural format and the state of deterioration for the structure. Deterioration due to carbonation is likely to occur at locations e.g. overhanging slabs, railings, intermediate slabs and cracking-prone places on bridges. Carbonation is generally likely to progress on the southern rather than northern face. These points should be taken into consideration when selecting the location of examinations.

Regardless of the category of maintenance, it is important to go through the design drawings and specifications, construction records, investigation results and the repair history prior to the investigation of a structure.

If the state of a structure cannot be judged appropriately by standard investigation, detailed investigation must be conducted.

Table C9.3.1 Main check items in investigation

Stage of Deterioration	Initiation	Propagation	Acceleration	Deterioration
Change of appearance	O	O	O	O
Depth of carbonation	O	▲	▲	▲
Chloride ion concentration	▲*	▲*	▲*	▲*
Steel corrosion	▲	O	O	O
Concrete strength	▲*	▲*	▲	O
Load bearing capacity	▲*	▲*	▲	▲
Location of steel	O	▲	▲*	▲*
Environmental action	▲*	▲	▲	▲
Monitoring	▲*	▲*	▲*	▲*
Weathering and leakage	O	O	▲*	▲*

O : Items to be investigated on a priority basis

▲ : Items that should preferably be investigated

▲* : Items to be investigated on an as-needed basis

9.3.2.2 Investigation in initial assessment

(1) In initial assessment, appropriate check items for standard investigation shall be selected for newly constructed structures, existing structures, large-scale repairs and strengthened structures.

(2) If deterioration prediction, evaluation or judgment is difficult to make through a standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) Investigation in initial assessment is the first investigation conducted when the maintenance of a concrete structure is started. Investigation in initial assessment includes not only the first investigation of a newly constructed structure conducted before it goes into service but also the first investigation of an existing structure or a structure for which remedial measures have been taken in response to deterioration. Check items for the investigation may vary from structure to structure. Basic check items for standard investigations in initial assessment of a newly constructed structure are the document search on the design drawings and specifications and construction records and observation. It is good practice to check on such details as concrete cover, the state of steel and porosity through nondestructive testing on an as-needed basis. When investigating a structure for which remedial measures have been taken, it is also important to check for problems in repaired or reinforced parts of the structure. These should be included in check items of standard investigation. When an existing structure is investigated, check items are similar to those for a newly constructed structure if design drawings and specifications and construction records exist. If there is no such document or record, it is necessary to select check items of standard investigation with reference to Section **1.3.2.5** “Detailed investigation.” In cases where a prediction needs to be made with high accuracy about a structure to which maintenance category A (preventive maintenance) is applied, it is necessary to conduct investigations concerning the parameters used for the method described in Section **1.3.3** “Methods for predicting degradation of performance degradation of structures.”

Extremely important items in the investigation in initial assessment of a structure subject to carbonation are listed below.

(i) Concrete mix proportions, water-cement ratio (water-binder ratio) in particular

(ii) Type of cement, and existence, type and volume of additive

(iii) Concrete cover

(iv) Environmental condition

(v) Existence of initial defects

(vi) Condition of repaired or strengthened sections

Items (i) and (ii) are input values for equation (Eq. C9.3.2) and essential to the prediction of progress of carbonation. For newly constructed structures, data on these items can be obtained by searching construction records or other documents. For existing structures, however, acquiring data is frequently difficult because of unavailability of design and construction records. Then, estimation should be made based on the existing data on similar structures. Item (iii) is very important for estimating the time of start and rate of steel corrosion and sometimes may not be as specified in design. Verification is therefore necessary. In relation to item (iv), temperature, humidity, weathering and leakage should be identified. Carbonation generally progresses rapidly in wet sections. Steel may corrode and concrete composition may change in sections placed alternately under dry and wet conditions. It has also been reported that steel corrosion due to carbonation and resultant concrete peeling and spalling are greatly affected by weathering and leakage of water. Effects of water ascribable to poor bonding, waterproofing or starling have similar impact to that of weathering or leakage. Item (v) greatly affects the durability of structures regardless of carbonation. Detecting this item in the investigation in initial assessment is important. Investigating the deformation in repaired or strengthened sections and the condition of deformation (e.g. swelling or peeling of surface coating) (item (vi)) is also important.

(2) If evaluation and judgment cannot be made with high accuracy by standard investigation alone or if a highly deteriorated part of a structure is to be investigated, detailed investigation is necessary. Check items of detailed investigation are indicated in Section **1.3.2.5** “Detailed investigation.”

9.3.2.3 Investigation in routine assessment

(1) In routine assessment, standard investigation shall be conducted to detect not only the defect of concrete surface such as cracking in concrete, peeling and spalling of concrete covering, leaching of rebar rust, efflorescence and discoloring but also the leakage and the deterioration in appearance such as displacement and deformation.

(2) If deterioration prediction, evaluation or judgment is difficult through standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) The purpose of investigation in routine assessment is to detect deterioration at an early stage by checking on defect in the state of a structure over time. The determination of the time at which deterioration began in order to obtain information that is useful for predicting deterioration is another important purpose of the investigation. In the investigation focus should be placed on deterioration phenomena or their indicators such as cracking in concrete, peeling and spalling of concrete covering, leaching of rebar rust, efflorescence, discoloring, leakage, displacement and deformation. As for the structures to which maintenance category A (preventive maintenance) is applied, the evaluation of their performance and also the judgment whether remedial measures should be applied is generally difficult if they are in the initial stage, because investigation in routine assessment is conducted mainly by observation. Then, appropriate monitoring should also be employed and more items should be investigated as required. Specific monitoring methods include the measurement of corrosion of internal steel by an electrochemical method e.g. measuring half-cell potential and monitoring polarization resistance. Also effective is regularly measuring the depth of carbonation and steel corrosion in specimens made of the same concrete as the structure to be examined and exposed under the same condition. Exclusively inspecting the sections where deterioration was expected to progress as a result of initial assessment is also effective.

(2) If high-accuracy evaluation or judgment is difficult by conducting standard investigation alone or if severe deterioration has already occurred, detailed investigation is conducted. Check items of detailed investigation are described in detail in Section **1.3.2.5** “Detailed investigation.”

9.3.2.4 Investigation in regular assessment

(1) The purpose of investigation in regular assessment is to obtain information that is difficult to obtain in routine assessment. In regular assessment, standard investigation consisting of detailed observation of defects shall be conducted as in routine assessment.

(2) If deterioration prediction, evaluation or judgment is difficult through standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) Investigation in regular assessment is conducted for obtaining the information more detailed than that in routine assessment. Areas where signs of defects or deterioration have been detected in initial or routine assessment need to be examined intensively. The appearance of the structure should basically be examined as in routine assessment. Investigations of the depth of carbonation in concrete or steel corrosion may sometimes become necessary in addition to the examination of the appearance of the structure.

In the investigation in regular assessment, the depth of carbonation should be measured three to five times at equal intervals during the initiation stage. The volume of corroded steel is nearly in proportion to time. Steel corrosion should therefore be measured twice each in the progressing, acceleration and deterioration stages.

In the structures to which maintenance category A (preventive maintenance) is applied, the progress of carbonation is in proportion to the square root of time. Then, the depth of carbonation should be measured at the specified interval so that the increase in depth of carbonation between every measurement should be identical. The executing year of measurement can be given by multiplying the number of years in service from the initial measurement by X^2 ($X = 2, 3$ ...).

(2) If high-accuracy evaluation or judgment is difficult by conducting standard investigation alone or if severe deterioration has already occurred, detailed investigation is conducted. Check items of detailed investigation are described in detail in Section **1.3.2.5** "Detailed investigation."

9.3.2.5 Detailed Investigation

Detailed investigation shall be conducted to obtain detailed information on a structure subject to carbonation in cases where the deterioration of the structure is difficult to predict, evaluate or judge by standard investigation alone in initial, routine or regular assessment. Check items, methods and location of a detailed investigation shall be selected appropriately taking into consideration such factors as the purpose of investigation and the accuracy of obtained results.

[Commentary] When the determination of the present state of a structure and the deterioration prediction of the structure are difficult by standard investigation alone, detailed investigation is conducted in order to obtain the information necessary for those purposes. Examples of investigation items for structures subject to carbonation, and of data on the condition of the structure at the time of investigation and those in the future estimated from the investigation results are listed in Table C9.3.2. The evaluation items estimated from data in the table are evaluated after deterioration is predicted.

Major check items are outlined below. For other measurement items or testing methods than those described below, refer to **4.7** "Investigation."

(i) Depth of carbonation

The area of carbonation is defined as the uncolored portion of concrete when a solution of phenolphthalein (JIS K 8001) is applied to a fracture side of concrete. The depth from the concrete surface to the boundary between colored and uncolored portions is measured at several locations and the mean value is defined as the depth of carbonation. Measurement should be conducted immediately after core samples are collected. Concrete should be fractured in dry condition for investigation because using water for splitting concrete results in inaccurate measurement of the depth of carbonation. For the method of measuring the depth of carbonation, refer to JIS A 1152 "Methods for Measuring the Depth of Carbonation in Concrete."

The area of carbonation specified by the phenolphthalein test is not always identical to the area where calcium carbonate is generated due to carbonation. The testing method has, however, been generally adopted, and also the initiation of steel corrosion has been discussed in relation to the depth of carbonation. Note that employing measurement methods using samples of powder collected from drill holes has also been proposed recently.

Table C9.3.2 Examples of evaluation items in detailed investigation

Measurement item	Data obtained by investigation	Evaluation items predicable from obtained data
Temperature, humidity, carbon dioxide concentration, weathering and insulation	Temperature, humidity and water content	Rate of carbonation and rate of corrosion
Cracking (width, depth and density)	Grade of corrosion and aesthetic appearance	Grade of corrosion and aesthetic appearance
Concrete strength and modulus of elasticity	Concrete strength and stiffness	Depth of carbonation
Depth of carbonation	Rate of carbonation and initiation of corrosion	Water content
Water content	Water content	Rate of corrosion
Location and corrosion of steel (area and volume) and leaching of rust	Grade of corrosion, corrosion amount of steel and load bearing capacity	Rate of corrosion and load bearing capacity
Electrochemical indicators (e.g. half-cell potential, polarization resistance and electric resistivity)	Grade of corrosion and rate of corrosion	Grade of corrosion, rate of corrosion and load bearing capacity
Deflection and displacement	Stiffness and load bearing capacity	

Note: For the grade of corrosion, refer to Table C9.3.3.

(ii) Cracking

Cracking accelerates carbonation or steel corrosion by encouraging the transfer of substances. If the crack width is below an allowable value, there will be no problem. Excessive cracking, however, is likely to greatly accelerate deterioration and structural performance degradation. The reason for or degree of deterioration may be estimated at certain levels of cracking. In cases of cracking in concrete, therefore, data useful for determining the deterioration and predicting subsequent deterioration should be collected such as the location, spacing, pattern, width and depth of cracking.

(iii) Steel corrosion

Steel corrosion has a direct impact on the performance of the structure in numerous cases. In tests, therefore, the concrete cover should be chipped and whether corrosion has occurred or not should be determined and the location, area, weight and depth of pitting corrosion should be measured directly. Obtaining quantitative data on corrosion could enable the quantitative evaluation of the reduction of physical property values and degradation of structural performance. Detailed investigations are therefore necessary. To simplify the method of measurement, the state of steel corrosion may be graded for evaluation (Fig. C9.3.3).

Grades I through IV roughly correspond to grades I-1, I-2, II and III for structural appearance shown in Table C9.3.4. If no crack occurs due to corrosion and the location of corrosion is invisible from outside, decision should be made using a half-cell potential distribution map or by other means.

Table C9.3.3 Grades of corrosion and state of steel

Grade of corrosion	State of steel
I	Mill scale. Thin and compact rust layer all over the steel. No rust adhesion on concrete surface.
II	Swelling rust exists at some locations but is spotty in small areas.
III	No lack of section can be visually recognized. Swelling rust exists all around the reinforcement or throughout the length of reinforcement.
IV	Lack of section of reinforcement.

When monitoring steel corrosion by nondestructive testing, electrochemical indicators such as half-cell potential and polarization resistance should be measured. The values of these indicators are, however, affected by the state of concrete such as the water content and the degree of carbonation. Measurements should therefore be made in accordance with **4.7.3** “Investigation methods.” Electrochemical methods have been applied to steel corrosion due to carbonation in fewer cases than to chloride attack, and no evaluation standards have yet to be established. Then, care should be exercised.

(iv) Appearance of structures

In cases where performance of structure cannot be evaluated direct from the state of concrete and steel, the defect of appearance provides important data for performance evaluation. The grades of appearance of structures deteriorated due to carbonation are shown in Table C9.3.4. Grades II-1 and II-2 are differentiated by the quantity of corroded steel. Differentiation is, however, difficult at the present technological level for deterioration prediction. For differentiation, observation is therefore essential.

Table C9.3.4 Grades of structural appearance and stage of deterioration

Grade of structural appearance	State of deterioration
I-1 (initiation stage)	No defect found in appearance. Remaining carbonation is at or more than the limit for rust development.
I-2 (propagation stage)	No defect found in appearance. Remaining carbonation is below the limit for rust development. Corrosion starts.
II-1 (first half of acceleration stage)	Cracking occurs due to corrosion.
II-2 (second half of acceleration stage)	With the progress of cracking due to corrosion, peeling or spalling is found. No lack of section of steel.
III (deterioration stage)	Peeling and spalling are found with cracking due to corrosion. Lack of section of steel.

9.3.3 Methods for predicting performance degradation of structures

9.3.3.1 General

(1) In the maintenance of a structure subject to carbonation the performance of the structure shall be evaluated quantitatively at the time of investigation, and future degradation shall be predicted.

(2) In order to predict the performance degradation of a structure, deterioration due to carbonation shall be predicted quantitatively.

(3) If (2) is difficult, an alternative method is to predict performance degradation by estimating the length of the initiation, propagation, acceleration and deterioration stages, taking the progress of carbonation into consideration.

(4) Deterioration shall be predicted on the basis of investigation results.

[Commentary] (1) and (2) In the performance verification based maintenance system, changes (deterioration) in various performance attributes inherent in the structure should be predicted. To that end, the progress of material deterioration should be predicted quantitatively. The performance of the structure and the degree of deterioration of materials constituting the structure should be evaluated quantitatively at the time of investigation and the end of planned service period. Performance degradation of the structure or the degree of deterioration of materials constituting the structure at the time of investigation may be evaluated quantitatively by an appropriate method based on investigation results. The performance or the degree of deterioration at the end of the planned service period should be predicted quantitatively based on the previous periodic assessments. The prediction of deterioration progress is not always in agreement with actual progress of deterioration. The method of prediction should therefore be reviewed based on the results of investigations to be conducted later.

(3) When evaluating various performance attributes of a structure by combining the results of prediction of deterioration progress of concrete and steel, quantitative prediction is difficult at the present technological level. Then, the performance degradation of a structure due to carbonation is

examined during the initiation stage (in which the depth of carbonation reaches the limit for the occurrence of steel corrosion), propagation stage from the initiation of corrosion to cracking due to corrosion, acceleration stage (in which the rate of corrosion increases due to cracking), and deterioration stage (in which load bearing capacity decreases remarkably with the progress of steel corrosion). Each process of deterioration basically corresponds to the state (performance) of the structure, so deterioration may be predicted quantitatively by predicting the length of each stage.

The length of the initiation stage is calculated using the rate of carbonation. The length of the propagation stage is calculated using the rate of steel corrosion and the quantity of corroded steel at the time of cracking due to corrosion. The length of the acceleration stage is calculated using the rate of corrosion of steel subject to corrosion-induced cracking. The length of the deterioration stage is calculated using the rate of corrosion of steel subject to corrosion-induced cracking and the quantity of corroded steel at which load bearing capacity is reduced. The calculation methods are described in **1.3.3.2** "Prediction of carbonation" and **1.3.3.3** "Prediction of steel corrosion."

The “Design” volume of the standard specification stipulates that structures should be designed so that no steel may corrode, or so that deterioration may not reach the propagation stage by conducting performance check. The “Maintenance” volume of the standard specification discusses the propagation, acceleration and deterioration stages after the steel corrosion as well because it deals with the structures designed and constructed before the revision of specifications and because unexpected deterioration may progress even in the structures designed and constructed in accordance with the present specification.

(4) Investigation results are related to either the quality of concrete of the structure or the environment in which the structure is placed while in service. These parameters should be used as a basis for predicting deterioration. If no investigation result is available because the structure is now being planned or because the structure is already in existence, investigation results or deterioration conditions of similar structures under the similar environment may be consulted.

9.3.3.2 Prediction of carbonation

(1) The progress of carbonation shall be predicted properly considering the quality of concrete and the environment in which the structure is in service.

(2) The progress of carbonation may be predicted by one of the following methods.

(i) $\sqrt{t}$ **rule**

(ii) Use of accelerated test

(iii) Use of physico-chemical models

[Commentary] (1) Predicting the rate of progress of carbonation is important to accurate estimation of the length of the initiation stage. The rate of progress of carbonation is determined by the velocity of movement of carbon dioxide in concrete and the capacity of retaining pH of water in voids. The velocity of movement of carbon dioxide is affected by hardened cement and the quantity and structure of voids in aggregate. Thus, cement, admixtures, type of aggregate, water-cement ratio (water-binder ratio), and the degree of hydration of binder affect the rate of carbonation. Carbon dioxide moves at a much lower rate in the liquid phase than in the gaseous phase. In cases where voids are fully filled with water, therefore, the progress of carbonation can virtually be ignored. Under highly dry conditions, on the other hand, no carbonation occurs. Then, the rate of carbonation is affected by the water content of concrete, and temperature, humidity, frequency of precipitation, insulation and traffic volume (gas emissions) should be taken into consideration as environmental conditions. The capacity of retaining pH of water in voids of concrete is determined by the quantity of calcium hydroxide. Then, cement, type of admixture, water-cement ratio, cement content and the degree of hydration of binder affect the rate of carbonation. The effects should be evaluated properly for prediction.

(2) Three major methods for predicting the progress of carbonation are described below.

(i) $\sqrt{t}$ rule

Numerous works have confirmed that the depth of carbonation is in proportion to the square root of the period of carbonation.

$$y = b\sqrt{t} \qquad \text{(Eq. C9.3.1)}$$

where,

y: depth of carbonation (mm)

t: period of carbonation (years)

b: coefficient of the rate of carbonation (mm/$\sqrt{year}$)

In cases where the depth of carbonation has been measured, the coefficient of the rate of carbonation should be obtained based on the measurement for subsequent prediction. The coefficient of the rate of carbonation can be obtained principally using the data of one measurement. To enhance the reliability, however, the coefficient should be calculated by the least square method after conducting two or three measurements every few years. In cases where the depth of carbonation and the coefficient of rate of carbonation vary greatly according to the measurement location in a structure, the rate of carbonation may vary from region to region.

If no investigation result is available, the rate of carbonation should be predicted using a reliable equation for calculating the rate of carbonation properly considering the materials and mix proportions of concrete and the environmental conditions under which the structure is in service. As described in "Commentary (1)," the rate of carbonation is subject to various factors. Most equations for calculating the rate of carbonation use water-cement (water-binder) ratio and compressive strength as indicators of concrete quality. For predicting the rate of carbonation, using an equation for the same materials, mix proportions and environmental conditions as those for the structure under study is desirable. If no such equation is available, the following equation may be adopted.

$$y = (-3.57 + 9.0W/B)\sqrt{t} \qquad \text{(Eq. C9.3.2)}$$

where,

W/B: effective water-binder ratio

$= W/(Cp + kAd)$

W: unit-area mass of water

B: unit-area mass of effective binder

Cp: unit-area mass of Portland cement

Ad: unit-area mass of admixture

k: coefficient indicating the effect of admixture

For fly ash: $k = 0$

For ground blast furnace slag: $k = 0.7$

(ii) Use of accelerated test

Accelerated test is convenient for evaluating the relative rate of carbonation in a short period of time. Absolute evaluation is, however, difficult because the factor of acceleration (ratio of the rate of carbonation in accelerated testing to that under natural condition) depends on the materials, mix proportions, initial curing conditions before the initiation of acceleration and the dimensions of specimens. When estimating the rate of carbonation in accelerated test, therefore, not only the concrete in question but also concrete specimens with the same mix proportions as the concrete with a depth of carbonation found in natural weathering or in an actual structure should also be tested. It should be confirmed that the rate of carbonation in accelerated test does not exceed that of natural condition.

(iii) Calculation using physico-chemical models

Methods have recently been evaluated for modeling the movement and reaction of carbonation-related substances in concrete such as water, carbon dioxide and calcium hydroxide and predicting the progress of carbonation by numerical calculations. The methods are beneficial in accurately predicting the progress of carbonation and in increasing the efficiency of maintenance if the parameters required for calculation can be specified satisfactorily. Then, parameters should be specified carefully based on the results of various tests.

9.3.3.3 Prediction of steel corrosion

(1) The progress of steel corrosion due to carbonation shall be predicted properly considering the concrete quality and the environment in which the structure is in service.

(2) The initiation of steel corrosion should be determined based on the remaining concrete cover after carbonation

(3) The progress of steel corrosion before cracking occurs due to corrosion may be predicted by either of the following methods.

(i) Method based on the quantity of corroded steel obtained from the investigation

(ii) Method based on the rate of reaction of steel to corrosion

(4) Cracking due to corrosion may be predicted by either of the following methods.

(i) Predicting from the quantity of corroded steel

(ii) Predicting using a mechanical model

(5) The progress of steel corrosion after cracking due to corrosion should be predicted by properly evaluating the effects of cracking on the mobility of substances.

[Commentary] (1) Steel corrosion due to carbonation accelerates the performance degradation of the structure. Predicting steel corrosion is therefore important as well as predicting carbonation. Steel corrosion is affected by such factors as pH of water in voids in concrete at the location of steel, rate of oxygen supply and water content of concrete. The lower the pH is, the higher the rate of corrosion is. The rate of corrosion, however, remains constant in the range between pH 4 and 10 at atmospheric temperature. In the area where carbonation occurs, pH is said to be 8.2 to 10. When carbonation has progressed to some extent, the rate of corrosion may be at a constant level under the same conditions, which has been confirmed by previous experiments.

Since corrosion is attributed to oxygen, the rate of oxygen supply to the steel therefore naturally affects the rate of corrosion. The velocity of oxygen movement in concrete is affected by cement, admixtures, type of aggregate, water-cement (water-binder) ratio and degree of hydration of binder, and water content as for carbon dioxide. As the water content of concrete decreases, oxygen supply increases. In an excessively dry condition, because the progress of corrosion requires water, the rate of corrosion decreases. Then, predicting steel corrosion like the rate of carbonation requires proper evaluation of environmental conditions that affect the water content of concrete. In case of concurrent deterioration by steel corrosion and chloride attack, the rate of corrosion increases. Prediction therefore should be made carefully.

(2) Steel is corroded as pH drops around the steel. The rate of corrosion is not exactly zero even when pH is in the alkali area. Defining an indicator for determining the initiation of corrosion is therefore difficult. Numerous works and researches of structures have revealed that corrosion due to carbonation generally starts before carbonation reaches the steel. The initiation of corrosion is frequently identified using the thickness of remaining concrete cover, or the variance between the thickness of concrete covering and the depth of carbonation. The previous researches concluded that corrosion occurs as the thickness of remaining concrete cover falls below 10 mm. Actually, however, steel corrosion is affected not only by the thickness of remaining concrete cover but also by numerous other factors including the quality of concrete and environmental conditions. It cannot be therefore said that no steel corrodes under any condition as long as the thickness of remaining concrete cover exceeds 10 mm. There have been few cases of serious steel corrosion causing functional deterioration of a structure where the thickness of remaining concrete cover exceeded 10 mm. Then, carbonation can be assumed to start when the thickness of remaining concrete cover reaches 10 mm. In cases where concrete contains chloride ions, the chloride ions immobilized in the hydrate of cement are dissociated as carbonation progresses and are concentrated in the area free from carbonation. Then, corrosion starts earlier. The results of investigations of structures that contained chloride ions from sea sand and had progressed carbonation show that steel often corroded when the thickness of remaining concrete cover falls below approximately 15 mm. The value may vary according to the quantity of chloride ions or water content of concrete. The rate of steel corrosion in cases where chloride ions exist is higher than the rate of steel corrosion ascribable only to carbonation. The thickness of remaining concrete cover to determine the initiation of steel corrosion should therefore be specified properly by analyzing the results of investigations of the structure. The thickness of remaining concrete cover can be obtained using the predicted depth of carbonation shown in **1.3.3.2** "Prediction of carbonation."

In cases where cracking has occurred in concrete, the progress of carbonation should be predicted in cracked sections. If carbonation has occurred in the concrete at the interface with steel, corrosion occurs even if the crack width is small. The maximum depth of carbonation in the cracked area should be compared with the concrete cover.

When predicting the initiation of corrosion direct from pH of water in voids of concrete not using the thickness of remaining concrete cover, the ion composition of water in voids of concrete and the electrochemical mechanism of steel corrosion in concrete should be evaluated properly.

(3) Steel corrosion due to carbonation may sometimes progress relatively slowly. Few works are therefore available. Methods of predicting steel corrosion may not be highly reliable. More studies need to be done. The present prediction methods are outlined below.

(i) Method based on the volume of corroded steel obtained from investigation results

In cases where the change in volume of corroded steel has been measured in investigations, the progress of corrosion may be predicted through the regression analysis of the result. The results of past researches show that most of the curves representing the time-based change in volume of steel corroded by carbonation are nearly linear. The result has been verified by analyses using electrochemical models. In cases where the volume of corroded steel and the initiation of steel corrosion are known as a result of investigations, subsequent corrosion can be predicted relatively easily. Even where the initiation of corrosion is unknown, curves representing time-based change can be estimated if the results of measurement of the volume of corroded steel at two or more ages are available.

(ii) Method based on the velocity of reaction of steel to corrosion

In cases where no measurement of the volume of corroded steel are available, the progress of corrosion may be predicted by properly evaluating the rate of corrosion using an existing equation for calculating the rate of corrosion. As described in "Commentary (1)", the rate of steel corrosion is affected by the quantities of water and oxygen. Using electrochemical models considering the velocity of oxygen supply to concrete or the water content of concrete, and properly specifying parameters for models may increase the accuracy of estimation. It has been reported that the rate of steel corrosion under ordinary conditions (at a temperature of 20ºC and a relative humidity of 60 to 70%) is 2×10^{-3} mm/year, which can be referred when estimating the volume of corroded steel.

(4) Cracking of concrete due to steel corrosion increases the mobility of substances and accelerates the progress of corrosion, resulting in aesthetic problems. For predicting the crack appearance, determining the volume of steel corroded at the time of cracking is required. The following methods may be used to determine the volume of steel corroded at the time of cracking.

(i) Method based on the volume of corroded steel

Carbonation unlike chloride attack frequently causes general corrosion. The results of electrolytic corrosion testing can be used for reference because corrosion progresses uniformly around the rebar in the testing. As a result of electrolytic testing using deformed steel bars, it was found that cracking occurs due to corrosion where the volume of corroded steel is approximately 10 mg/cm^2 or greater. If the volume of steel corroded at the time of cracking due to corrosion is assumed to be 10 mg/cm^2, the timing of cracking due to corrosion can be estimated on the safe side.

(ii) Method using a mechanical model

It has been known that the volume of steel corroded at the time of cracking is affected by concrete cover, concrete strength and steel bar diameter. Various elastic and elasto-plastic analysis methods considering the effects have been proposed. These methods may be used by specifying model parameters properly.

(5) Researches are now being made on the methods for predicting steel corrosion after the crack appearance due to corrosion but none have yet been established. Among the parameters for various models of corrosion with no corrosion-induced cracking, it is better to replace the values related to the mobility of substances such as the velocities of movement of oxygen and water with those with cracking. The validity of methods should be verified by experiments.

9.3.3.4 Modification of prediction

If the state of deterioration determined in an investigation differs from a predicted state of deterioration, the cause of the difference shall be identified and the prediction shall be revised accordingly. If necessary, the maintenance planning shall be altered.

[Commentary] When the deterioration confirmed in investigations is different from the prediction, appropriate investigations should be conducted using the deterioration prediction methods shown in **9.3.3.2** "Prediction of carbonation" and **9.3.3.3** "Prediction of steel corrosion" and based on Table C9.3.2 to examine the cause for the difference, and the prediction should be modified. Then, the results of several investigations conducted until that are useful to the examination of causes and the modification of the prediction. Revising the subsequent maintenance plans including a review of investigation frequency based on the modified prediction is also important.

9.3.4 Evaluation and judgment

(1) The evaluation of performance and judgment as to whether remedial measures need to be taken based on the results of the investigation in initial, routine and regular assessment shall be made in accordance with Part 1 and Item (2) and subsequent items in this section.

(2) The performance of a structure subject to carbonation shall be evaluated by appropriately selecting performance attributes to be evaluated in view of the stage of deterioration of the structure.

(3) The evaluation of performance attributes at the time of investigation and at the end of the planned service period of the structure should be made by a quantitative method.

(4) If Item (3) is difficult to achieve, the evaluation of performance attributes at the time of investigation and at the end of the planned service period of the structure may be made by a semi-quantitative grading-based method.

(5) Judgment as to whether remedial measures need to be taken shall be made in view of the degree of performance degradation due to carbonation, the degree of importance of the structure, category of maintenance, and the remaining service life.

[Commentary] (1) The evaluation of performance and judgment of necessity for remedial measures in initial, routine and regular assessment for structures in which little progress of deterioration has been recognized are frequently more or less the same regardless of the deterioration mechanism. For details, refer to **Part 1**. The evaluation of performance and judgment of necessity for remedial measures for structures in which deterioration may have or has progressed vary according to the deterioration mechanism. When discussing the performance degradation due to carbonation, the descriptions in this chapter should be consulted.

(2) In structures subject to carbonation, the performance attribute to be affected by deterioration varies depending on whether deterioration is in the initiation, propagation, acceleration or deterioration stage. The performance attribute to be evaluated should be properly selected for each stage of deterioration. In the initiation stage, steel is likely to corrode with the progress of carbonation, and in the propagation stage, steel corrosion progresses due to the supply of oxygen

through the concrete cover. The steel protection, one of the durability parameters, should therefore be evaluated. In the acceleration stage, the volume of corroded steel remarkably increases due to the cracking caused by corrosion. Then, the steel protection performance, serviceability in such terms as the stiffness and ductility of members, hazards for third party such as peeling and spalling of concrete due to cracking, and aesthetic appearance should be evaluated. In the deterioration stage, corrosion progresses further. In addition to the performance attributes to be evaluated in the acceleration stage, safety performance including load bearing capacity should be evaluated.

In cases where the steel has corroded and has been subject to cyclic loading, the hazards for third party including the spalling of concrete may be an issue in early stages like the propagation stage.

(3) The performance of a structure at the time of investigation and at the end of the planned service period should be evaluated after quantitatively evaluating the deterioration of concrete and steel.

For evaluating the performance of a structure at the time of investigation, safety and serviceability are verified by obtaining the load bearing capacity and deformation by, for example, substituting the mechanical properties of materials obtained from investigation results into a structural calculation formula. Also conceivable is the verifying of the hazards for third party and aesthetic appearance and landscape based on the range and density of cracking or peeling and the degree of steel corrosion. Performance can be evaluated relatively explicitly at the time of investigation by such verifications in cases where deterioration is not serious. In cases where serious deterioration has occurred and the expansion of steel or the deterioration of bond with concrete is large, or in cases where concrete cover has been delaminated or spalled, appropriate methods reflecting these effects should be examined.

Performance at the end of the planned service period should be evaluated based on the results of performance evaluation at the time of investigation and the results of deterioration prediction. Evaluating performance with sufficient accuracy is difficult in numerous cases. As a supplementary measure, deterioration is generally predicted based on the rate of carbonation and the rate of steel corrosion using the methods shown in **1.3.3** "Methods for predicting performance degradation of structure." Then, the accuracy of the deterioration prediction method as well as the accuracy of the performance verification method is important. Prediction methods should therefore be selected carefully. Adequate safety should be guaranteed.

(4) In the performance verification type design system, structural performance should ideally be evaluated quantitatively. At present, however, there is no established method of quantitative estimation. As a practical method, the performance of a structure can be evaluated semi-quantitatively, with reference to Table C9.3.5, by performing appearance grading in accordance with Table C9.3.4.

The purpose of grading is to classify the present degree of deterioration of a structure semi-quantitatively instead of predicting and evaluating the degree of deterioration in future. It is also possible, however, to predict the performance of a structure at the end of the planned service period in accordance with Table C9.3.5 by estimating the stage of deterioration at the end of the planned service period on the basis of investigation results such as the rate of carbonation and steel corrosion. The method of estimating the degree of deterioration at a certain point of time in future by constructing a deterioration grade model based on a stochastic theory such as a Markov model has also been proposed.

If detailed maintenance records for a similar structure (type of structure, materials, construction, environment, state of use) are available and its progress of deterioration is also similar to that of the evaluated structure, then the evaluation results for the similar structure provide useful information.

(5) Because judgment is the act of deciding whether remedial measures need to be taken on the basis of structural performance evaluation results, there is no difference depending on deterioration factors. Therefore, refer to **Part 1**.

Table C9.3.5 Grades of appearance of structures and typical performance degradation

<table>
<tr><th>Grade of appearance of structure</th><th>Safety</th><th>Serviceability</th><th>Hazards for third party</th><th>Aesthetic appearance and landscape</th></tr>
<tr><td>I-1 (initiation stage)</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>I-2 (propagation stage)</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>II-1 (first half of acceleration stage)</td><td>-</td><td>-</td><td>-</td><td rowspan="3">Aesthetic deterioration
-Cracking
-Leaching of steel rust
-Exposure of steel</td></tr>
<tr><td>II-2 (second half of acceleration stage)</td><td>-</td><td rowspan="2">Deterioration of stiffness (increase of deformation and occurrence of vibration)
-Lack of section of steel
-Deterioration of bond between steel and concrete
-Reduction of concrete cross section due to swelling or peeling of concrete</td><td rowspan="2">Hazards for third party
-Peeling
-Spalling</td></tr>
<tr><td>III (deterioration stage)</td><td>Deterioration of load bearing capacity and ductility
-Lack of section of steel
-Reduction of concrete cross section due to swelling or peeling of concrete</td></tr>
</table>

9.4 Remedial Measures

9.4.1 Selection of remedial measures

(1) If it has been judged that remedial measures need to be taken in connection with performance degradation of a structure subject to carbonation, remedial measures by which the corrected structure meets the required performances shall be selected.

(2) If it is difficult to select remedial measures for a structure on the basis of performance verification, remedial measures may be selected from the measures corresponding to the grade of appearance.

[Commentary] (1) If it has been judged, as a result of evaluation, that remedial measures need to be taken, it is necessary to select one or more of the following measures: (i) intensified investigation, (ii) repair, (iii) strengthening, (iv) functional improvement, (v) restriction in service or (vi) dismantling/removal. Basically, decisions as to which measures to take should be made by the maintenance manager of the structure, but it is good practice to refer to **Part 1** for information on typical relationships between evaluation and judgment results and remedial measures.

(2) If it is difficult to select remedial measures for a structure through quantitative evaluation or judgment, remedial measures are selected from the measures corresponding to the deterioration grade of the structure. Remedial measures to be taken vary depending on the type of structure, the degree of importance of the structure, deterioration rate and the category of maintenance, but recommended standard measures are shown in Table C9.4.1.

Table C9.4.1 Grades of appearance of structure and remedial measures

Grade of appearance of structure	Intensified investigation	Repair	Strength -ening**	Functional improvement	Restriction in service	Dismantling /removal
I-1 (initiation stage)	**O****	**O****	**(X)**	**X**		
I-2 (propagation stage)	**O**	**O**	**X**	**X**		
II-1 (first half of acceleration stage)	**OO**	**OO**	**X**	**X**		
II-2 (second half of acceleration stage)	**OO**	**OO***	**X**	**X**	**O**	
III (deterioration						

stage)						

OO: Standard remedial measures **(OO*:** Including the restoration of mechanical performance), **O**: Remedial measures in some cases,

O*: Preventive measure

X: Remedial measure taken based on other criterion than the grade of appearance. Strengthening**: Enhancing the mechanical performance above the initiation level

9.4.2 Repair and strengthening

Methods and materials for the repair or strengthening of a structure shall be selected taking into consideration the performance degradation of the structure due to carbonation and life cycle cost, so that the required effect can be achieved.

[Commentary] In cases where repair or strengthening is carried out as a remedial measure, it is necessary to define the expected effect of repair or strengthening and the required performance (what level of performance to be maintained for how many years?). Ideally, it is desirable that remedial measures be taken after constructing a deterioration formula (for repair) or structural calculation formula (for strengthening) in view of such factors as the properties of the materials used and verifying the calculation results obtained from those formulas. In this case, it is also important to take life cycle cost into consideration according to the remaining planned service period.

When taking preventive measures for a structure to which maintenance category A (preventive maintenance) is applied, an appropriate method should be selected fully considering the effect that should be achieved by the method.

The methods of repair or strengthening for structures subject to performance degradation due to carbonation are listed in Table C9.4.2 by expected effect.

Table C9.4.2 Expected effects and methods of repair or strengthening

Expected effect	Examples of methods
Control the progress of carbonation	Surface treatment and grout injection into cracks
Reduce the depth of carbonation to none	Repair of cross section (corrosion protection and coating are included) and re-alkalization
Control the progress of steel corrosion	Surface treatment, (electrical protection), repair of cross section, re-alkalization, corrosion protection and water treatment
Restore or enhance load bearing capacity	(Adhesion of steel or fiber reinforced plastic plates), (use of external cable), (lining) and (increase of thickness)

( ): Method in the parenthesis is selected in cases with a high rate of steel corrosion or a high volume of corroded steel where the concentration of chloride ion is high.

Table C9.4. 3 Grades of structural appearance and methods of repair or strengthening

Grade of structural appearance	Standard methods
I-1 (initiation stage)	Surface treatment* and Re-alkalinization*
I-2 (propagation stage)	Surface treatment, (Patching) and Re-alkalization
II-1 (first half of acceleration stage)	Surface treatment, (Electrical protection), Re-alkalization and Patching
II-2 (second half of acceleration stage)	Patching
III (deterioration stage)	Patching, (Adhesion of steel or PRP), (External cable), (Jacketing) and (thickness increasing)

*: Preventive method

( ): Method in the parenthesis is selected in cases with a high rate of steel corrosion or a high volume of corroded steel where the concentration of chloride ion is high.

In weathering or leakage, water encourages steel corrosion due to carbonation. In order to control the progress of steel corrosion, therefore, water treatment measures such as dewatering, jointing and waterproofing should also be taken. When selecting the method, Table C9.4.2 and the present performance degradation of the structure should be considered. For the deterioration grade of appearance and remedial measures, refer to Table C9.4.3.

In the initiation stage, neither performance degradation nor deterioration has occurred in the structure. In this period, remedial measures are taken only for structures to which maintenance category A (preventive maintenance) is applied. Then, remedial measures are expected to control the progress of carbonation in concrete cover. Surface treatment should therefore be applied to prevent carbon dioxide from entering the concrete. Restoring pH in the concrete cover by implementing the re-alkalinization method is also effective.

In the propagation stage, steel has corroded but the volume of corrosion amount of steel is still low and little performance degradation has occurred. In this stage as in the initiation stage, surface treatment is generally selected. Patching or re-alkalinization may be considered.

In the first half of the acceleration stage, the deterioration of mechanical performance is not yet outstanding. Cracks have occurred in concrete cover due to steel corrosion. Applying re-alkalinization for restoring pH in the concrete cover or patching for removing the sections subject to carbonation should be considered. In order to prevent re-deterioration, surface treatment after the patching should also be considered.

In the second half of the acceleration stage, serviceability is reduced due to the deterioration of stiffness, and the concrete cover either is delaminated or spalls, resulting in serious hazards for third party. In this period, the concrete cover is removed and patching is applied to compensate for the deterioration of monolithic characteristics of members due to carbonation. Surface treatment after the patching, and the addition or replacement of reinforcing bars should also be considered.

In few cases, deterioration due to only carbonation has reached the deterioration stage. Concurrent deterioration due to carbonation and chloride attack sometimes reaches the deterioration stage and reduces load bearing capacity. Then, methods for restoring load bearing capacity such as the adhesion of steel or FRP, external cable, jacketing and thickness increasing should be applied in addition to the patching including the addition or replacement of reinforcing bars. These methods should be implemented after removing the concrete cover and patching, for preventing re-deterioration.

If the entry of carbon dioxide is blocked, which is a cause of carbonation, by surface coating or other means, no subsequent carbonation may be assumed. Many of the repair or strengthening methods applied have been developed only recently and few have been applied to actual structures. If such methods are adopted, the structure may be re-deteriorated and its performance may be degraded due to the factors not expected in the design phase. Measures should therefore be taken such as increasing the frequency of investigations after the repair or strengthening.

For details of the methods of repair and strengthening, refer to the "Guidelines of Strengthening Concrete Structures (draft)," "Guidelines for Repairing or Strengthening Concrete Structures Using Continuous Fiber Reinforced Membrane," "Guidelines for Design and Implementation of Electrochemical Protection (draft)," "Guidelines for Design and Implementation of Surface Protection (draft)," "Shotcreting Guidelines (draft) - Repair and Strengthening" and the "Reports of Concrete Structures Repair Method Committee I, II and III" and "Reports of Concrete Structures Restoration Committee" prepared by the Japan Concrete Institute. Applying the re-alkalinization or electrical protection method to a structure using reactive aggregate is likely to help deteriorate the structure due to alkali silica reaction. Then, the "Guidelines Concerning the Application of Electrochemical Protection Considering Alkali-silica Reaction" prepared by the Society of Materials Science, Japan should be consulted and the applicability of a repair method and the method of implementation should be determined carefully.

9.5 Recording

(1) Investigation, deterioration estimation, evaluation and judgment, and remedial measures shall be recorded in accordance with Part 1.

(2) Items relevant to carbonation shall be recorded.

[Commentary] As a general rule, the results of investigations, deterioration estimations, evaluations and remedial measures must be recorded in accordance with **Part 1**. Items relevant to carbonation require careful attention, particularly with respect to record keeping. Items to be recorded are indicated in Section **1.3.2** “Investigation in assessment" and the evaluation items indicated in Section **1.3.4** “Evaluation and judgment.”

CHAPTER 10 MAINTENANCE OF STRUCTURES SUBJECT TO CHLORIDE ATTACK

10.1 General

(1) This chapter provides standard methods for the maintenance planning, assessment, remedial measures and recording for structures that have been or are highly likely to be subject to performance degradation due to chloride attack. The items common to all the deterioration mechanisms are shown in Part 1.

(2) This chapter shall be applied to structures of the maintenance categories A (preventive maintenance) and B (corrective maintenance).

[Commentary] (1) Chloride attack that occurs in concrete structures means the progress of steel corrosion in concrete due to the existence of chloride ions in concrete, causing cracking or peeling in concrete due to the volume expansion of corrosion products or the lack of section of steel. Chloride attack also means the performance degradation of the structure caused by above phenomenons. Chloride ions not only accelerate steel corrosion but also change the composition of concrete. This chapter discusses the matters related to steel corrosion. Chloride ions are supplied either from external environments of the structure such as seawater and deicing agents or from the materials used for producing concrete. Any type of deterioration attributable to the steel corrosion accelerated by chloride ions is discussed in this chapter regardless of the source of supply of chloride ions.

Deterioration due to chloride attack and steel corrosion progresses during the initiation stage, propagation stage, acceleration stage and deterioration stage (Fig. C10.1.1 and Table C10.1.1). In each stage, deterioration has varying influences on the structure. The degree of performance degradation with the progress of deterioration also varies according to the performance attribute. The methods of assessment (investigation, deterioration prediction, evaluation or determination), remedial measures implementation and recording vary in respective deterioration stages. A standard maintenance procedure against chloride attack is shown in Fig. C10.1.2.

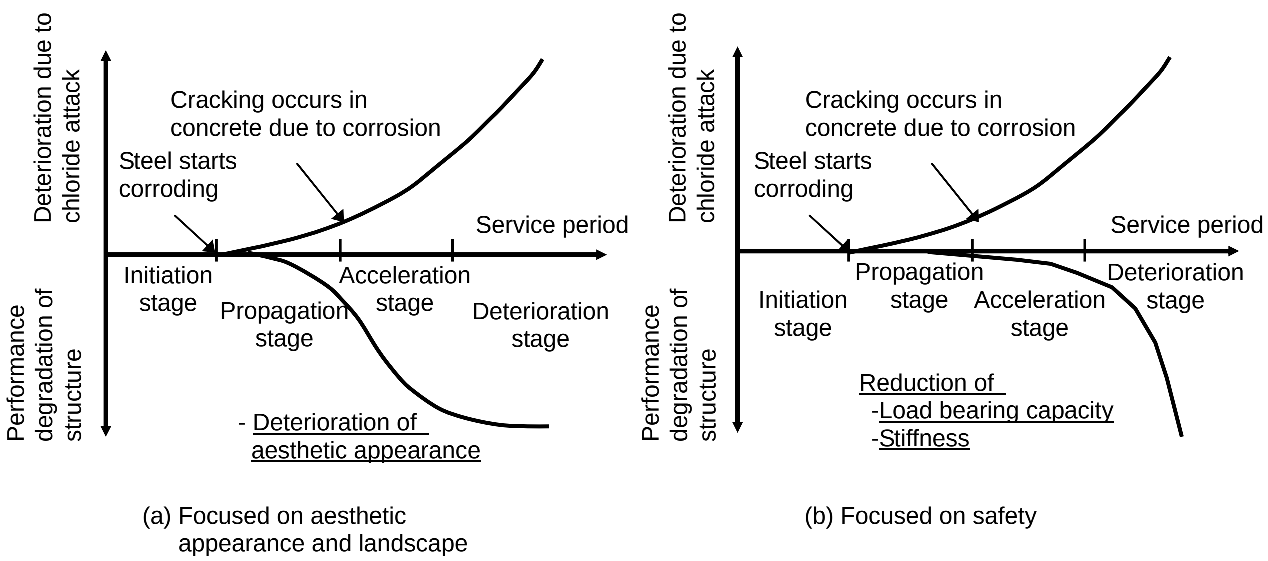


Fig. C10.1.1 Progress of deterioration progress due to chloride attack

Table C10.1.1 Definitions of deterioration stages

Stage of deterioration	Definition	Stage determined by
Initiation stage	Until the chloride ion concentration on the surface of steel reaches the marginal concentration for the occurrence of corrosion*	Diffusion of chloride ions Initially contained chloride ion concentration
Propagation stage	From the initiation of steel corrosion until cracking due to corrosion	Rate of steel corrosion
Acceleration stage	Stage in which steel corrodes at a high rate due to cracking due to corrosion	Rate of corrosion of steel with cracks
Deterioration stage	Stage in which load bearing capacity is reduced considerably due to the increase of corrosion amount	

*The standard value is 1.2 kg/m^3.

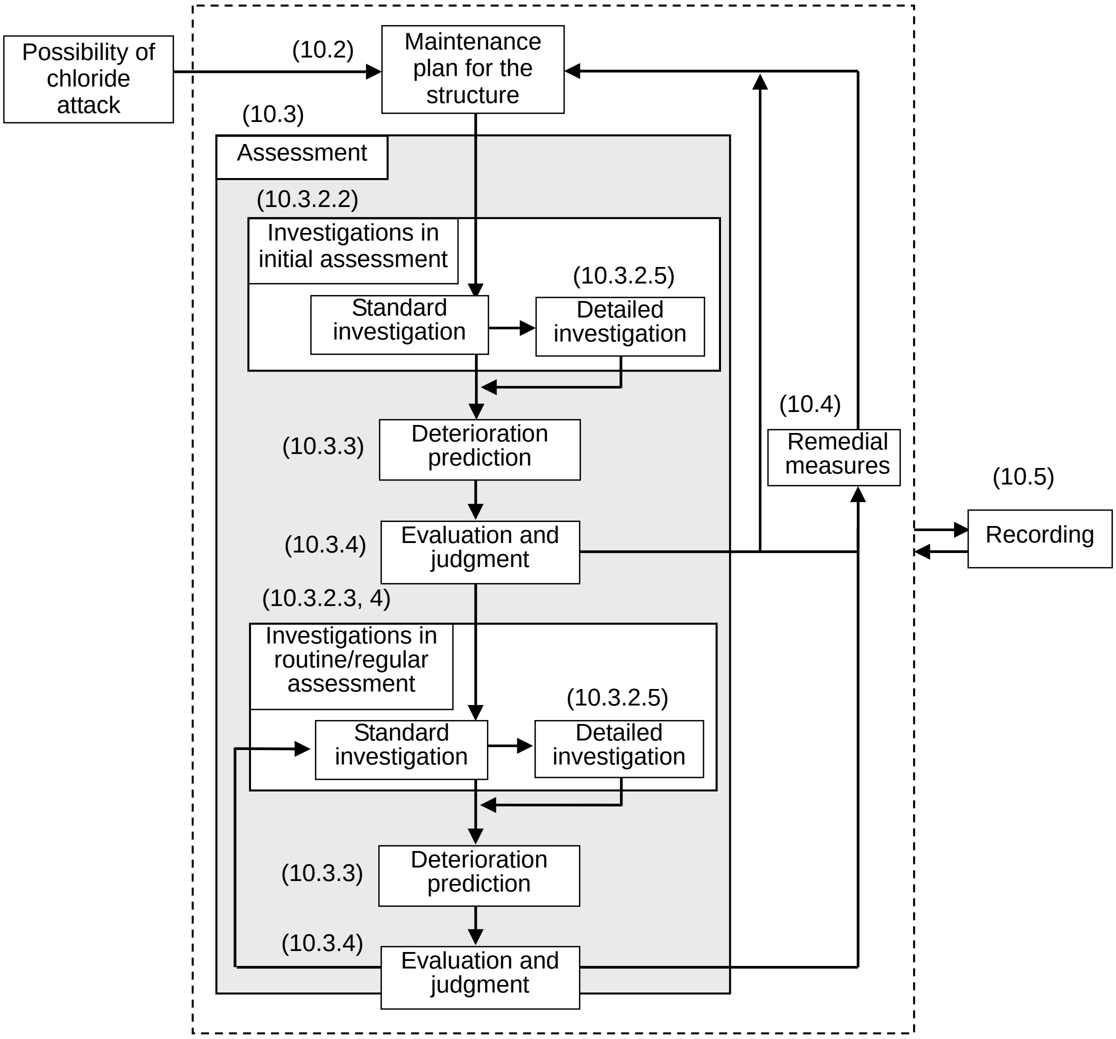


Fig. C10.1.2 Standard maintenance procedure against chloride attack

There have been cases where concurrent deterioration due to carbonation and chloride attack seriously damaged structures. This is because the movement and condensation of chloride ions in concrete with the progress of carbonation in concrete accelerates steel corrosion. In the phenomenon, deterioration due to chloride attack was accelerated by carbonation. The structures subjected to concurrent deterioration due to carbonation and chloride attack should be maintained in accordance with the descriptions in this chapter.

(2) Maintenance category B (corrective maintenance) has been designated for numerous existing structures. In the future, maintenance category A (preventive maintenance) is expected to be designated for more structures. In maintenance category A, remedial measures are taken early before performance degradation due to deterioration in view of the life-cycle cost. This chapter therefore mainly discusses structures for which maintenance category A or B has been designated. Structures for which maintenance category C (observational maintenance) has been designated should also be maintained by a basic method described in this chapter wherever possible.

For the matters that should be considered when specifying the maintenance category for structures that have been or are expected to be subjected to deterioration due to chloride attack, refer to **10.2.2** "Maintenance Categories." Special matters to be considered for respective maintenance categories are also described in the section.

10.2 Maintenance Planning

10.2.1 Basis of planning

In order to maintain a structure subject to chloride attack, the category of maintenance shall be selected, the service period planned, and a maintenance planning for activities including assessment, remedial measures and recording drawn up in advance in view of the service and environmental conditions such as the concrete drying conditions and water supplies.

[Commentary] When drawing up a maintenance planning, it is necessary to cover such details as check items and procedures for initial assessment and check items, procedures, timing and frequency for the investigations in routine and regular assessment, evaluation and judgment methods, actions to be taken in the event of deterioration, and recording methods, taking into consideration the type, degree of importance and planned service period of the structure, category of maintenance, and the quality of materials.

The type of structure, size and environmental conditions of concrete structures vary from structure to structure. A maintenance planning must be optimized for each structure. In a structure subjected to chloride attack in particular, chloride ions are supplied either from external environments of the structure such as seawater and deicing agents or from the materials used for producing concrete. The progress of deterioration of structures subjected to chloride attack varies greatly according to how chloride ions are supplied to concrete or how chloride ions exist in concrete. These points should be taken into consideration for preparing an appropriate maintenance plan.

It is usually difficult, at the stage of maintenance planning, to accurately predict the state of a structure during its service period. It is therefore good practice to draw up a maintenance planning with reference to the deterioration of a similar structure or a structure in a similar environment.

10.2.2 Determination of maintenance category

The category of maintenance of a structure subject to chloride attack shall be selected in view of the degree of importance of the structure, the type of structure, hazards for third party, the planned service period and the characteristics of deterioration due to chloride attack.

[Commentary] The determination of the category of maintenance is very important because maintenance planning varies widely depending on the category of maintenance. The progress of deterioration and performance degradation due to chloride attack is conceptually illustrated in Fig. C10.1.1.

Structures to which maintenance category A (preventive maintenance) is applied should be maintained so that they might be placed under the condition during the initiation stage with no steel corrosion, to prevent performance degradation. The state of the structure should therefore be identified as accurately as possible. Requirements include the following.

(i) Quantitative identification of supply of chloride ions to the surface of the structure

(ii) Quantitative identification and future prediction of chloride ion penetration into or accumulation in concrete

(iii) Verification and future prediction of steel corrosion in concrete

For structures with maintenance category A, remedial measures are taken before reinforcing bars corrode due to deterioration. Thus, large-scale repair or strengthening can be eliminated and the maintenance cost can be reduced accordingly in numerous cases.

Structures to which maintenance category B (corrective maintenance) is applied should be maintained so as to prevent the performance of the structure from failing to meet the requirements. Structures should be maintained to prevent deterioration from reaching the deterioration stage to ensure safety, the latter half of the acceleration stage to achieve serviceability or the former half of the acceleration stage to keep aesthetic appearance and landscape. Certain actions should be taken when any of the following types of deterioration has been detected.

(i) The corrosion of reinforcing bars in concrete

(ii) The leaching of corrosion rust on concrete surface

(iii) Cracking in the direction of axis of reinforcement on concrete surface

(iv) The spalling of concrete cover

For structures to which maintenance category B is applied, remedial measures should be taken in phase (i) or (ii) above because it is extremely difficult to stop the progress of corrosion of reinforcing bars in concrete once started. It should be noted that large-scale measures will be required if deterioration reaches phase (iii) or (iv).

One maintenance category is generally applied to one structure. In cases where the environmental conditions vary from region to region or from member to member, however, applying different maintenance categories to different regions or members may sometimes be effective. For example, in a bridge located along the seashore, maintenance category A (preventive maintenance) is applied to beams and category B (corrective maintenance) is applied to supplementary equipment including railings.

10.2.3 Preparation of maintenance manuals

A maintenance manual describing methods, procedures and frequency requirements should be prepared for each structure in accordance with the maintenance planning, taking the structure-specific conditions into consideration.

[Commentary] The service period of civil engineering structures is long, and maintenance of those structures is performed over a long period of time. It is recommended, therefore, that in order to inform investigators of maintenance concepts and policies, a maintenance manual be prepared so that detailed procedures and methods can be communicated accurately even to newly assigned responsible engineers.

Under certain circumstances such as in cases where the original maintenance planning is altered because the actual progress of deterioration turned out to differ from that assumed in the original maintenance planning, it is necessary to modify the maintenance manual and take appropriate maintenance measures accordingly.

When preparing maintenance manuals, "The Maintenance Manual for Structures Subjected to Chloride Attack Prepared in Accordance with the Standard Specifications for Design and Construction of Concrete Structures: Maintenance (draft) " may be consulted.

10.3 Assessment

10.3.1 General

In the assessment of a structure whose performance has declined or is highly likely to decline because of chloride attack, investigation, evaluation of the present state, prediction of deterioration and judgment of necessity for remedial measures shall be appropriately conducted in accordance with the maintenance planning.

[Commentary] In order to maintain concrete structures appropriately, this specification requires three types of assessment: initial assessment, periodic assessment and extraordinary assessment. Because the initial and periodic assessments are essential for the maintenance of structures, this chapter stipulates that those assessments must be conducted. Extraordinary assessments are regarded as assessments to be conducted on an as-needed basis and are therefore not dealt with in this chapter. By conducting periodic assessments during the maintenance period, defect in appearance of structures can be discovered before they occur or in early stages, and remedial measures including preventive measures and repairs can be taken systematically.

10.3.2 Investigation in assessment

10.3.2.1 General

Investigations in initial, routine and regular assessment of a structure subject to chloride attack shall be conducted appropriately according to the category of maintenance required for the structure. Prior to investigation, check items, methods, frequency and scope of standard investigation shall be determined appropriately. For each type of assessment, detailed investigation shall also be conducted on an as-needed basis.

[Commentary] It is important to select check items, methods, frequency and scope of investigation appropriately according to the purpose of investigation in accordance with the maintenance planning.

The major parameters that should be identified in investigations of structures subjected to chloride attack are the distribution of chloride ion concentrations and the corrosion of internal steel in concrete cover. In cases where deterioration has progressed considerably, investigations should be conducted to directly evaluate performance.

The items to be examined in investigations vary according to the degree of deterioration. In cases where it has been determined or assumed that the deterioration was in the initiation stage, investigations should be conducted mainly to identify the penetration of chloride ions. In cases where it has been determined or assumed that the deterioration was in or beyond the propagation stage, investigations should be conducted mainly to identify the progress of steel corrosion. Table C10.3.1 shows major items to be examined in respective stages of deterioration. Data on the items related to deterioration prediction such as the environmental action, chloride ion concentration, depth of carbonation, steel corrosion and location of steel should be collected in as early a stage as possible. Monitoring may be made for continuously identifying the penetration of chloride ions or whether steel corrodes or not in concrete for structures for which maintenance category A (protective maintenance) has been designated

Table C10.3.1 Main check items in investigation

Stage of deterioration	Initiation stage	Propagation stage	Acceleration stage	Deterioration stage
Defective appearance	O	O	O	O
Chloride ion concentration	O	O	O	▲
Carbonation depth	O	O	▲	▲*
Steel corrosion	▲	O	O	O
Concrete strength	▲*	▲*	▲	O
Load bearing capacity	▲*	▲*	▲	▲*
Rebar alignment	O	▲	▲*	▲*
Environmental action	O	▲	▲*	▲*
Monitoring	▲*	▲*	▲*	▲*

O: Items to be investigated on a priority basis
▲: Items that should preferably be investigated
▲*: Items to be investigated on an as-needed basis

The frequency and range of investigation should be determined considering the maintenance category, environmental conditions, structural format and the state of deterioration for the structure. Deterioration due to chloride attack is likely to occur on the beams on the side providing access to ships and on the side protected by revetment at piers; and bottom surface of the slab, beam ends, structurally cracking-prone sections and sections accepting wastewater from road surface on bridges in cases where bridges are subjected to the effect of deicing agents. These sections should be investigated.

Regardless of the category of maintenance, it is important to go through the design drawings and specifications, construction records, investigation results and the repair history prior to the investigation of a structure.

If the state of a structure cannot be judged appropriately by standard investigation, detailed investigation must be conducted.

10.3.2.2 Investigation in initial assessment

(1) In initial assessment, appropriate check items for standard investigation shall be selected for newly constructed structures, existing structures, large-scale repairs and strengthened structures.

(2) If deterioration prediction, evaluation or judgment is difficult to make through a standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) Investigation in initial assessment is the first investigation conducted when the maintenance of a concrete structure is started. Investigation in initial assessment includes not only the first investigation of a newly constructed structure conducted before it goes into service but also the first investigation of an existing structure or a structure for which remedial measures have been taken in response to deterioration. Check items for the investigation may vary from structure to structure. Basic check items for standard investigations in initial assessment of a newly constructed structure are the document search on the design drawings and specifications and construction records and observation. It is good practice to check on such details as concrete cover, the state of steel and porosity through nondestructive testing on an as-needed basis. When investigating a structure for which remedial measures have been taken, it is also important to check for problems in repaired or reinforced parts of the structure. These should be included in check items of standard investigation. When an existing structure is investigated, check items are similar to those for a newly constructed structure if design drawings and specifications and construction records exist. If there is no such document or record, it is necessary to select check items of standard investigation with reference to Section **10.3.2.5** "Detailed Investigation." In cases where a prediction needs to be made with high accuracy about a structure to which maintenance category A (preventive maintenance) is applied, it is necessary to conduct investigations concerning the parameters used for the method described in Section **10.3.3** "Method for Estimating Degradation of Performance of Structure."

Extremely important items in the investigation in initial assessment of a structure subject to chloride attack are listed below.

(i) Concrete mix proportions, water-cement ratio (water-binder ratio) in particular

(ii) Type of cement

(iii) Whether an additive is used or not, and type and volume of the additive

(iv) Initial chloride ion content

(v) Concrete cover

(vi) Environmental condition

(vii) Whether there are initial defects or not

(viii) Condition of repaired or strengthened sections

Items (i), (ii) and (iii) are input values for equations (Eq. C10.3.4) and (Eq. C10.3.5) and essential to the prediction of chloride ion diffusion. Item (iv) is important when obtaining the chloride ion concentration in concrete cover. Item (v) is a very important factor affecting the initiation and rate of steel corrosion and sometimes may not be as specified in design. Verification is therefore necessary. For item (vi), the volume of incoming chloride and cyclic wetting and drying conditions should be identified under the marine environment. In cases where deicing agents are sprayed, the frequency of application and the volume of agents should be identified. Item (vii) greatly affects the durability of structures not only in chloride attack but also in other phenomenon. Detecting defects in the initial investigation is important. Investigating the deformation in repaired or strengthened sections and the condition of deformation (e.g. swelling or peeling of surface coating) (item (viii)) is also important.

(2) If evaluation and judgment cannot be made with high accuracy by standard investigation alone or if a highly deteriorated part of a structure is to be investigated, detailed investigation is necessary. Check items of detailed investigation are indicated in Section **10.3.2.5** "Detailed Investigation."

10.3.2.3 Investigation in routine assessment

(1) In routine assessment, standard investigation shall be conducted to detect not only the defect of concrete surface such as cracking in concrete, peeling and spalling of concrete covering, leaching of rebar rust, efflorescence and discoloring but also the leakage and the deterioration in appearance such as displacement and deformation.

(2) If deterioration prediction, evaluation or judgment is difficult through standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) The purpose of investigation in routine assessment is to detect deterioration at an early stage by checking on defect in the state of a structure over time. The determination of the time at which deterioration began in order to obtain information that is useful for predicting deterioration is another important purpose of the investigation. In the investigation focus should be placed on deterioration phenomena or their indicators such as cracking in concrete, peeling and spalling of concrete covering, leaching of rebar rust, efflorescence, discoloring, leakage, displacement and deformation. As for the structures to which maintenance category A (preventive maintenance) is applied, the evaluation of their performance and also the judgment whether remedial measures should be applied is generally difficult if they are in the initial stage, because investigation in routine assessment is conducted mainly by observation. Then, appropriate monitoring should also be employed and more items should be investigated as required. Specific methods include the measurement of corrosion of internal steel by an electrochemical method e.g. measuring half-cell potential and monitoring polarization resistance, and the installation of sensors for estimating the penetration of chloride ions into concrete covering. Also effective is measuring the chloride ion concentration, apparent chloride ion diffusion coefficient or steel corrosion in specimens made of the same concrete as the structure to be examined and exposed under the same condition. Exclusively inspecting the sections where deterioration was expected to progress as a result of initial assessment is also effective.

(2) If high-accuracy evaluation or judgment is difficult by conducting standard investigation alone or if severe deterioration has already occurred, detailed investigation is conducted. Check items of detailed investigation are described in detail in Section **10.3.2.5** “Detailed Investigation.”

10.3.2.4 Investigation in regular assessment

(1) The purpose of investigation in regular assessment is to obtain information that is difficult to obtain in routine assessment. In regular assessment, standard investigation consisting of detailed observation of defects shall be conducted as in routine assessment.

(2) If deterioration prediction, evaluation or judgment is difficult through standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) Investigation in regular assessment is conducted for obtaining the information more detailed than that in routine assessment. Areas where signs of defects or deterioration have been detected in initial or routine assessment need to be examined intensively. The appearance of the structure should basically be examined as in routine assessment. Investigations of the distribution of chloride concentration in concrete or steel corrosion may sometimes become necessary in addition to the inspection of the appearance of the structure.

For predicting the initiation of corrosion accurately in periodic investigations, chloride ion concentration should be measured at least twice during the initiation stage. For predicting the rate of steel corrosion during the propagation or acceleration stage, the corrosion amount of steel should be measured at least twice in each stage because the increase of the corrosion amount of steel is nearly in proportion to the elapse of time.

For the structures for which maintenance category A (preventive maintenance) has been designated, the frequency of measurement should be increased during the expected initiation stage and propagation stage.

(2) If high-accuracy evaluation or judgment is difficult by conducting standard investigation alone or if severe deterioration has already occurred, detailed investigation is conducted. Check items of detailed investigation are described in detail in Section **10.3.2.5** “Detailed Investigation.”

10.3.2.5 Detailed investigation

Detailed investigation shall be conducted to obtain detailed information on a structure subject to chloride attack in cases where the deterioration of the structure is difficult to predict, evaluate or judge by standard investigation alone in initial, routine or regular assessment. Check items, methods and location of a detailed investigation shall be selected appropriately taking into consideration such factors as the purpose of investigation and the accuracy of obtained results.

[Commentary] When the determination of the present state of a structure and the deterioration prediction of the structure are difficult by standard investigation alone, detailed investigation is conducted in order to obtain the information necessary for those purposes. Examples of investigation items for structures subject to chloride attack, and of data on the condition of the structure at the time of investigation and those in the future estimated from the investigation results are listed in Table C10.3.2. The evaluation items estimated from data in the table are evaluated after deterioration is predicted.

Table C10.3.2 Examples of evaluation items in detailed investigation

Measurement item	Data obtained by investigation	Evaluation items predicable from obtained data
Temperature, humidity, weathering and insulation	Temperature, humidity and water content	Qualitative corrosion rate
Amount of air-born chloride	Amount of air-born chloride	Chloride ion concentration on concrete surface
Cracking (width, depth and density)	Grade of corrosion and aesthetic appearance	Grade of corrosion, aesthetic appearance
Concrete strength and modulus of elasticity	Concrete strength and stiffness	-
Carbonation depth	Carbonation depth and carbonation rate	Future depth of carbonation
Distribution of chloride ion concentrations	Apparent chloride ion diffusion coefficient, surface chloride ion concentration, initial chloride ion concentration and chloride ion concentration at the location of steel	Chloride ion concentration at the location of steel
Water content	Water content	Qualitative corrosion rate
Location and corrosion of steel (area and volume) and leaching of rust	Grade of corrosion, corrosion amount of steel and load bearing capacity	Corrosion rate, load bearing capacity
Electrochemical indicators (e.g. half-cell potential, polarization resistance and electric resistivity)	Whether corrosion occurred or not and rate of corrosion	Future grade of corrosion and corrosion rate
Deflection and displacement	Stiffness and load bearing capacity	-

Note: For the grade of corrosion, refer to Table C10.3.3.

Major investigation items are outlined below. For other investigation items, refer to **4.7** "Investigations in Assessment."

(i) Chloride ion concentration

For the methods of collecting concrete cores or concrete granulated by drilling for measuring the distribution on chloride ion concentrations in concrete, and for the methods for measuring the distributions of total chloride ion concentrations in concrete using the samples, refer to JSCE-G 573 "Measurement method for distribution of total chloride ion in concrete structure.”

(ii) Steel corrosion

Steel corrosion has a direct impact on the performance of the structure in numerous cases. In tests, therefore, the concrete cover should be chipped and whether corrosion has occurred or not should be determined and the location, area, weight and depth of pitting corrosion should be measured directly. Obtaining quantitative data on corrosion could enable the quantitative evaluation of the reduction of physical property values and degradation of structural performance. Detailed investigations are therefore necessary. To simplify the method of measurement, the state of steel corrosion may be graded for evaluation as shown in Table C10.3.3.

Table C10.3.3 Grades of corrosion and state of steel

Grade of corrosion	State of steel
I	Mill scale. Thin, compact rust layer all over the steel. No rust adhesion to concrete surface.
II	Swelling rust exists at some locations but is spotty in small areas.
III	No lack of section is visually recognized. Swelling rust, however, exists all around the reinforcement or throughout the length of reinforcement.
IV	Lack of section of reinforcement.

Grades I through IV roughly correspond to grades I-1, I-2, II and III for structural appearance shown in Table C10.3.4. If no crack occurs due to corrosion and the location of corrosion is invisible from outside, decision should be made using a half-cell potential distribution map or by other means.

When monitoring steel corrosion by nondestructive testing, electrochemical indicators such as half-cell potential and polarization resistance should be measured. The values of these indicators are, however, affected by the state of concrete such as the water content and the degree of penetration of chloride ions. Measurements should therefore be made in accordance with **4.7.3** “Inspection Methods.”

(iii) Appearance of Structures

In cases where performance of structure cannot be evaluated direct from the state of concrete and steel, the defect of appearance provides important data for performance evaluation. The grades of appearance of structures deteriorated due to chloride attack are shown in Table C10.3.4. Grades II-1 and II-2 are differentiated by the quantity of corroded steel. Differentiation is, however, difficult at the present technological level for deterioration prediction. For differentiation, observation is therefore essential.

Table C10.3.4 Grades of appearance of structure and state of deterioration

Grade of structural appearance	State of deterioration
I-1 (initiation stage)	No defect of appearance is found. The marginal chloride ion concentration for the occurrence of corrosion has not been exceeded.
I-2 (propagation stage)	No defect of appearance is found. The marginal chloride ion concentration for the occurrence of corrosion has been exceeded. Corrosion initiates.
II-1 (first half of acceleration stage)	Cracking occurs due to corrosion. Leaching of rust is observed.
II-2 (second half of acceleration stage)	Numerous cracks occur due to corrosion. Leaching of rust is observed. Partial peeling or spalling is found. The corrosion amount of steel increases.
III (deterioration stage)	Numerous cracks occur due to corrosion. Crack width is large. Leaching of rust is observed. Peeling and spalling are found. Great displacement and deflection are observed.

10.3.3 Methods for predicting performance degradation of structures

10.3.3.1 General

(1) In the maintenance of a structure subject to chloride attack, the performance of the structure shall be evaluated quantitatively at the time of investigation, and future degradation shall be predicted.

(2) In order to predict the performance degradation of a structure, deterioration due to chloride attack shall be predicted quantitatively.

(3) If (2) is difficult, an alternative method is to predict performance degradation by estimating the length of the initiation, propagation, acceleration and deterioration stages, taking the penetration of chloride ions into consideration.

(4) Deterioration shall be predicted on the basis of investigation results.

[Commentary] (1) and (2) In the performance verification based maintenance system, changes (deterioration) in various performance attributes inherent in the structure should be predicted. To that end, the progress of material deterioration should be predicted quantitatively. The performance of the structure and the degree of deterioration of materials constituting the structure should be evaluated quantitatively at the time of investigation and the end of planned service period. Performance degradation of the structure or the degree of deterioration of materials constituting the structure at the time of investigation may be evaluated quantitatively by an appropriate method based on investigation results. The performance or the degree of deterioration at the end of the planned service period should be predicted quantitatively based on the previous periodic assessments. The prediction of deterioration progress is not always in agreement with actual progress of deterioration. The method of prediction should therefore be reviewed based on the results of investigations to be conducted later.

(3) When evaluating various performance attributes of a structure by combining the results of prediction of deterioration progress of concrete and steel, quantitative prediction is difficult at the present technological level. Then, deterioration may be predicted quantitatively by predicting the lengths of initiation, propagation, acceleration and deterioration stages considering the penetration of chloride ions into concrete and the progress of steel corrosion. The respective stages of deterioration and the factors determining their lengths are shown in Table C10.1.1.

The length of the initiation stage is calculated using the chloride ion diffusion or initial chloride ion concentration. The length of the propagation stage is calculated using the rate of corrosion and the corrosion amount of steel at the time of cracking. The length of the acceleration stage is calculated using the rate of corrosion of steel subjected to cracking due to corrosion. The length of deteriorating stage is calculated using the rate of corrosion of steel subjected to cracking due to corrosion and the corrosion amount of steel when the load bearing capacity is reduced. The calculation methods are described in **10.3.3.2** "Prediction of Chloride Ion Diffusion" and **10.3.3.3** "Prediction of Progress of Steel Corrosion."

(4) Investigation results are related either to the quality of materials of the structure or to the environment in which the structure is placed while in service. These parameters should be used as a basis for predicting deterioration. If no data is available on the chloride ions in concrete for a newly constructed structure or no investigation results are available for an existing structure, investigation results or deterioration conditions for adjacent structures or for structures under the similar environment may be consulted.

10.3.3.2 Prediction of chloride ion diffusion

(1) Chloride ion diffusion shall be predicted properly considering the quality of concrete and the environment in which the structure is in service.

(2) Chloride ion diffusion may be predicted by one of the following methods.

(i) Obtaining an apparent chloride ion diffusion coefficient by applying a diffusion equation.

(ii) Obtaining the diffusion coefficient of the material by conducting accelerated test.

(iii) Making a numerical analysis considering the reaction of chloride ions or the movement of chloride ions at the boundary with the environment

(iv) Using investigation results

[Commentary] (1) Predicting chloride ion diffusion is important to accurate estimation of the length of the initiation stage. Chloride ions transfer in concrete using the concentration gradient in water existing in continuous fine pores as the driving force, or with the transfer of water. The transfer of chloride ions is greatly affected by the composition of concrete or the transfer of water under cyclic wetting and drying conditions. In cases where concrete has a high water-cement ratio or is cured poorly, concrete is no longer sufficiently tight and chloride ions may transfer easily. The transfer of chloride ions is also affected by the type of the cement or additive used. Under a severe condition with cyclic wetting and drying like in seawater splash zones, chloride ions penetrate into concrete substantially near the surface, greatly increasing the surface chloride ion concentration. In cases of concurrent deterioration attributable to carbonation and chloride attack, chloride ions are concentrated inside the carbonation front. Chloride ion diffusion should therefore be predicted by properly considering the method for specifying the parameters, the variations of quality of concrete cover and concrete and the effects of environmental conditions.

When predicting chloride ion diffusion, an appropriate safety factor should be specified considering the method for specifying parameters, variations of the quality in the structure to be studied and the effects of environmental conditions.

(2) Four major methods available for predicting chloride ion diffusion are described below.

(i) Obtaining an apparent diffusion coefficient by applying a diffusion equation

One method is to use a solution obtained by solving a diffusion equation known as Fick's second law of diffusion equation (Eq. C10.3.1) under an appropriate boundary condition while regarding the transfer of chloride ions in concrete as a simple diffusion process. Equation (Eq. C10.3.2) is a solution of equation (Eq. C10.3.1) obtained based on the assumption that the surface chloride ion concentration is constant. Equation (Eq. C10.3.2) has been generally used for analyzing the rate of penetration of chloride.

The chloride ion concentration in equation (Eq. C10.3.2) is not the liquid phase chloride ion concentration in concrete but the total chloride amount per unit volume of concrete. The mechanism of transfer of chloride in concrete in the form of chloride ion is not precisely represented. The chloride ion diffusion coefficient in equation (Eq. C10.3.2) is therefore referred to as an apparent diffusion coefficient.

$$\frac{\partial C}{\partial t} = Dc\left(\frac{\partial^2 C}{\partial x^2}\right) \qquad \text{(Eq. C10.3.1)}$$

where,

C: Chloride ion concentration in the liquid phase

D_c: Chloride ion diffusion coefficient

x: Depth from concrete surface

t: time.

$$C(x,t) = \gamma_{cl} \cdot Co\left(1 - erf\,\frac{x}{2\sqrt{D_{ap} \cdot t}}\right) \qquad \text{(Eq. C10.3.2)}$$

where,

$C(x, t)$: Chloride ion concentration (kg/m^3) at depth x (cm) and time t (years)

C_0: Chloride ion concentration at the surface (kg/m^3)

D_{ap}: Apparent chloride ion diffusion coefficient (cm^2/year)

erf: Error function

γ_{cl}: Safety factor for prediction precision

γ_{cl} is generally related to the precision of prediction, and should be specified considering the variations of the depth of concrete cover of the structure and of C_0 and D_{ap}, which are affected by environmental conditions. A value of 1.0 may generally be used.

Surface chloride ion concentration C_0 in equation (Eq. C10.3.2) is a boundary condition for solving equation (Eq. C10.3.1). Surface chloride ion concentration C_0 is determined by the external environment. Standard values are listed in Table C10.3.5. In addition to the values shown in the table, the amount of chloride ions mixed during the production of concrete should be considered in solving the equation.

The surface chloride ion concentration and apparent chloride ion diffusion coefficient should be obtained based on the investigation results by regression analysis of the distribution of chloride ion concentrations using equation (Eq. C10.3.2). In cases where initial chloride ions are involved, the value obtained by subtracting the initial chloride ion concentration from the measured chloride ion concentration should be used for regression analysis. The apparent chloride ion diffusion coefficient can be obtained from the distribution of chloride ion concentrations in the structure in accordance with JSCE-G 573 "Measurement method for distribution of total chloride ion in concrete structure.”

In cases where no investigation results are available or where neither the apparent chloride ion diffusion coefficient nor the surface chloride ion concentration can be obtained based on the investigation results, equations (Eq. C10.3.4) and (Eq. C10.3.5), and values in Table C10.3.5. may be used. In the structures on which deicing agents are sprayed, however, the surface chloride ion concentration should basically be obtained based on the investigation results. The concentration of chloride ions mixed into concrete from materials should be considered as *Ci* in equation (Eq. C10.3.3).

$$C(x,t) = \gamma_{cl} \cdot \left[C_0 \left(1 - erf \frac{x}{2\sqrt{D \cdot t}}\right) + C_i \right] \qquad \text{(Eq. C10.3.3)}$$

where,

C_i: Initially contained chloride ion concentration (kg/m^3)

γ_{cl}: Safety factor for prediction precision

<u>About apparent chloride ion diffusion coefficient</u>: When using ordinary Portland cement, equation (Eq. C10.3.4) may be used. When using Portland blast furnace slag cement, equation (Eq. C10.3.5) may be used.

$$\log_{10} D = -3.9(W/C)^2 + 7.2(W/C) - 2.5 \qquad \text{(Eq. C10.3.4)}$$

$$\log_{10} D = -3.0(W/C)^2 + 5.4(W/C) - 2.2 \qquad \text{(Eq. C10.3.5)}$$

where,

D: Apparent chloride ion diffusion coefficient (cm^2/year)

W/C: Water-cement ratio

<u>About surface chloride ion concentration C_0</u>: For the structures subjected to the effects of chloride ions in seawater, values in Table C10.3.5 may be used as surface chloride ion concentrations.

Table C10.3.5 Surface chloride ion concentration C_0 (kg/m3)

		Splash zone	Distance from seashore (km)				
			Near the shoreline	0.1	0.25	0.5	1.0
Areas with a high volume of air-born salt	Hokkaido, Tohoku, Hokuriku and Okinawa	13	9.0	4.5	3.0	2.0	1.5
Areas with a low volume of air-born salt	Kanto, Tokai, Kinki, Chugoku, Shikoku and Kyushu		4.5	2.5	2.0	1.5	1.0

C_0 may be obtained near the seashore based on the assumption that a height of 1 m corresponds to a distance of 25 m from the shoreline.

(ii) Obtaining the diffusion coefficient of the material by conducting accelerated testing

Methods of accelerated test concerning the penetration of chloride ions include increasing the chloride ion concentration in the environment, exposing concrete to alternate wetting and drying conditions and forcing chloride ions to transfer using the potential difference. Methods for calculating the apparent chloride ion diffusion coefficient using these methods have been standardized as the standards of the Japan Society of Civil Engineers (JSCE standards). When estimating the apparent chloride ion diffusion coefficient based on the results of accelerated test, testing both the concrete to be examined and the concrete specimen with the same mix proportions as the concrete for which the apparent chloride ion diffusion coefficient has been identified in natural exposure tests or in investigations for actual structures for comparison is useful when applying the results of accelerated testing to actual structures. The JSCE standards mentioned above are JSCE-G571 2007 "Test method for effective diffusion coefficient of chloride ion in concrete by migration" and JSCE-G572 2007 A "Test method for apparent diffusion coefficient of chloride ion in concrete by submergence in salt water." The diffusion coefficient obtained in accelerated testing may be used as the apparent diffusion coefficient in equation (Eq. C10.3.2) or (Eq. C10.3.3) when an appropriate safety factor is taken into consideration.

(iii) Making a numerical analysis considering the reaction of chloride ions or the transfer of chloride ions at the boundary with the environment

Researches have been conducted concerning the binding or adhesion of chloride ions to hydrate of cement, or the transfer of chloride ions with capillary water due to alternate wetting and drying. In the methods based on these mechanisms, no chloride ion concentration is calculated as an amount in unit volume of concrete but liquid phase chloride ion concentration is basically used.

(iv) Using investigation results

Simple method is to measure the chloride content using chipped concrete pieces during chipping tests to examine steel corrosion in an actual structure. When using such methods, accurately calculating the chloride diffusion coefficient is difficult but estimating the diffusion coefficient is possible based on some assumptions.

In cases where cracking has occurred in concrete due to corrosion, chloride ions penetrating the cracks have direct impact on reinforcing bars. Then, corrosion is highly likely to be accelerated. When calculating the chloride ion diffusion coefficient in the affected section, cracking should be taken into consideration. In concrete in which carbonation has progressed, the distribution of chloride ion concentrations varies. Chloride ion concentration decreases at concrete surface and increases inside the carbonation front. When calculating the apparent chloride ion diffusion coefficient, the effects of carbonation should be fully taken into consideration if the concrete is subjected to carbonation.

10.3.3.3 Prediction of steel corrosion

(1) The progress of steel corrosion due to chloride attack shall be predicted properly considering the concrete quality and the environment in which the structure is in service.

(2) The initiation of steel corrosion should be determined based on the chloride ion concentration in the concrete cover.

(3)The progress of steel corrosion before cracking occurs due to corrosion may be predicted by either of the following methods.

(i) Method based on the quantity of corroded steel obtained from the investigation

(ii) Method based on the rate of reaction of steel to corrosion

(4) Cracking due to corrosion may be predicted by either of the following methods.

(i) Predicting from the quantity of corroded steel

(ii) Predicting using a mechanical model

(5) The progress of steel corrosion after cracking due to corrosion should be predicted by properly evaluating the effects of cracking on the mobility of substances.

[Commentary] (1) Regarding the factors affecting the corrosion of steel reinforcement, chloride ion content, pH value in the pore solution at the position of reinforcement and amount of oxygen supply to steel surface and water content in concrete can be listed. However, the effects of these factors on the corrosion rate is not clarified quantitatively enough to achieve precise prediction

Corrosion reaction requires oxygen. The rate of oxygen supply to the steel therefore affects the rate of corrosion. The oxygen transfer rate in concrete is affected by the types of cement, admixture and aggregate, water-cement (water-binder) ratio, degree of hydration of binder and water content. As the water content of concrete decreases, oxygen supply increases. In an excessively dry condition, the rate of corrosion decreases because the corrosion reaction requires water. When predicting corrosion, therefore, environmental actions such as cyclic wetting and drying should be evaluated properly. No effects on environmental actions have, however, yet been quantitatively identified.

(2) The pore solution in concrete with a pH of 12 or higher is highly alkaline. Steel is in a passive state in a highly alkaline environment and is unlikely to corrode. The mechanism causing steel to turn passive is generally explained as the formation of a passive coating due to the chemical absorption of oxygen on the surface of steel and subsequent generation of a compact oxide layer. If chloride ions exist beyond the marginal chloride ion concentration for causing corrosion, the passive coating is destroyed and steel starts corroding.

If the marginal chloride ion concentration for causing corrosion can be obtained based on the investigation results for the structure, the value should in principle be used for predicting the initiation of steel corrosion. Otherwise, the marginal chloride ion concentration for causing corrosion may be set to be 1.2 kg/m^3 in accordance with "Standard Specification [Design]."

(3) Methods of predicting the progress of steel corrosion up to the crack appearance are described below.

(i) Method based on the corrosion amount of steel obtained from investigation results

In cases where the time-based change in corrosion amount of steel has been identified by investigations, the progress of corrosion should be predicted based on the result.

If the corrosion amount of steel and the initiation of steel corrosion are known as a result of investigations, for example, subsequent corrosion can be predicted by assuming a curve representing the time-based change in corrosion amount of steel. Even where the initiation of corrosion is unknown, curves representing time-based change can be estimated if the results of measurement of the corrosion amount of steel at two or more ages are available. Then, the progress of deterioration should be properly predicted considering that chloride attack causes severe partial corrosion of steel.

For chloride attack, the degree of deterioration can be evaluated in several grades of corrosion. If the relationship between the chloride ion concentration at the location of steel and the degree of steel corrosion is identified in advance, the grade of corrosion can be predicted by predicting chloride ion diffusion.

(ii) Method based on the reaction rate of steel to corrosion

A method for estimating the rate of reaction of steel to corrosion using amount of oxygen supply as well as chloride ion diffusion as parameters has been studied. The precision of prediction will increase if parameters in a model can be set properly based on the results of investigations.

(4) Cracking of concrete due to steel corrosion not only causes aesthetic deterioration but also lets more deterioration factors intrude into the structure and accelerates the progress of corrosion. If the progress of corrosion is predicted and the corrosion amount at the time of the crack appearance has been determined, the timing of crack appearance can be predicted. The following methods may be used for prediction.

(i) Method based on the volume of corroded steel

The timing of crack appearance is predicted by obtaining the corrosion amount of steel that triggers cracking by using test results on steel corrosion in concrete. One method for obtaining test results in a relatively short period of time is to accelerate steel corrosion by electrolytic corrosion test. Corrosion progresses homogeneously in steel in electrolytic corrosion testing unlike under the condition in chloride attack under which steel is subjected to serious partial corrosion. The mechanism is, however, the same that causes cracking in concrete due to corrosion with the expansion of corrosion products. The results of electrolytic corrosion test may be used for reference if investigations are conducted simultaneously.

(ii) Method using a mechanical model

The corrosion amount at the time of cracking is affected by concrete cover, concrete strength and steel bar diameter. Various elastic and elastoplastic analysis methods considering the effects have been proposed. These methods may be used by specifying model parameters properly.

(5) No methods have yet been established for predicting steel corrosion after the crack appearance due to corrosion. Of the parameters for various models of corrosion with no corrosion-induced cracking, replacing the values of parameters such as the apparent chloride ion diffusion coefficient, transfer rate of oxygen and water with the values of parameters for models subjected to cracking due to corrosion is realistic. The validity of methods should be verified by testing.

In the acceleration stage and deteriorating stage, load-bearing capacity should be evaluated by properly evaluating the reduction ratio of steel cross section, depth of pitting and bond strength.

10.3.3.4 Modification of prediction

If the state of deterioration determined in an investigation differs from a predicted state of deterioration, the cause of the difference shall be identified and the prediction shall be revised accordingly. If necessary, the maintenance planning shall be altered.

[Commentary] When the deterioration confirmed in investigations is different from the prediction, appropriate investigations should be conducted using the deterioration prediction methods shown in **10.3.3.2** “Prediction of Chloride Ion Diffusion” and **10.3.3.3** “Prediction of Progress of Steel Corrosion” and based on Table C10.3.2 in **10.3.2.5** “Detailed examinations” to examine the cause for the difference, and the prediction should be modified. Then, the results of several investigations conducted until that are useful to the examination of causes and the modification of the prediction. Revising the subsequent maintenance plans including a review of investigation frequency based on the modified prediction is also important.

10.3.4 Evaluation and judgment

(1) The evaluation of performance and judgment as to whether remedial measures need to be taken based on the results of the investigation in initial, routine and regular assessment shall be made in accordance with Part 1 and Item (2) and subsequent items in this section.

(2) The performance of a structure subject to chloride attack shall be evaluated by appropriately selecting performance attributes to be evaluated in view of the stage of deterioration of the structure.

(3) The evaluation of performance attributes at the time of investigation and at the end of the planned service period of the structure should be made by a quantitative method.

(4) If Item (3) is difficult to achieve, the evaluation of performance attributes at the time of investigation and at the end of the planned service period of the structure may be made

by a semi-quantitative grading-based method.

(5) Judgment as to whether remedial measures need to be taken shall be made in view of the degree of performance degradation due to chloride attack, the degree of importance of the structure, category of maintenance, and the remaining service life.

[Commentary] (1) The evaluation of performance and judgment of necessity for remedial measures in initial, routine and regular assessment for structures in which little progress of deterioration has been recognized are frequently more or less the same regardless of the deterioration mechanism. For details, refer to **Part 1**. The evaluation of performance and judgment of necessity for remedial measures for structures in which deterioration may have or has progressed vary according to the deterioration mechanism. When discussing the performance degradation due to chloride attack, the descriptions in this chapter should be consulted.

(2) In structures subjected to chloride attack, the performance attribute to be affected by deterioration varies depending on whether deterioration is in the initiation, propagation, acceleration or deterioration stage. The performance attribute to be evaluated should be properly selected for each stage of deterioration. In the initiation stage, steel is likely to corrode due to chloride ions, and in the propagation stage, steel corrosion progresses due to the supply of oxygen through the concrete cover. The steel protection performance, one of the durability parameters, should therefore be evaluated. In the acceleration stage, the corrosion amount of steel remarkably increases due to the cracking ascribable to corrosion. Then, the steel protection performance, serviceability in such terms as the stiffness and ductility of members, hazards for third party such as peeling and spalling of concrete due to cracking, and aesthetic appearance should be evaluated. In the deterioration stage, corrosion progresses further. In addition to the performance attributes to be evaluated in the acceleration stage, safety performance including load-bearing capacity should be evaluated.

In cases where the steel has corroded and has been subjected to cyclic loading, the hazards for third party including the spalling of concrete may be an issue in early stages like the propagation stage.

(3) The performance of a structure at the time of investigation and at the end of the planned service period should be evaluated after quantitatively evaluating the deterioration of concrete and steel.

For evaluating the performance of a structure at the time of investigation, safety and serviceability are verified by obtaining the load bearing capacity and deformation by, for example, substituting the mechanical properties of materials obtained from investigation results into a structural calculation formula. Also conceivable is the verifying of the hazards for third party and aesthetic appearance and landscape based on the range and density of cracking or peeling and the degree of steel corrosion. Performance can be evaluated relatively explicitly at the time of investigation by such verifications in cases where deterioration is not serious. In cases where serious deterioration has occurred and the expansion of steel or the deterioration of bond with concrete is large, or in cases where concrete cover has been delaminated or spalled, appropriate methods reflecting these effects should be examined.

Performance at the end of the planned service period should be evaluated based on the results of performance evaluation at the time of investigation and the results of deterioration prediction. Evaluating performance with sufficient accuracy is difficult in numerous cases. As a supplementary measure, deterioration is generally predicted based on the apparent diffusion coefficient of chloride and the rate of steel corrosion using the methods shown in **10.3.3** "Methods for Predicting Performance Degradation of Structure." Then, the accuracy of the deterioration prediction method as well as the accuracy of the performance verification method is important. Prediction methods should therefore be selected carefully. Adequate safety should be guaranteed.

(4) In the performance verification type design system, structural performance should ideally be

evaluated quantitatively. At present, however, there is no established method of quantitative estimation. As a practical method, the performance of a structure can be evaluated semi-quantitatively, with reference to Table C10.3.6, by performing appearance grading in accordance with Table C10.3.4.

The purpose of grading is to classify the present degree of deterioration of a structure semi-quantitatively instead of predicting and evaluating the degree of deterioration in future. It is also possible, however, to predict the performance of a structure at the end of the planned service period in accordance with Table C10.3.6 by estimating the stage of deterioration at the end of the planned service period on the basis of investigation results such as the apparent diffusion coefficient of chloride and steel corrosion. The method of estimating the degree of deterioration at a certain point of time in future by constructing a deterioration grade model based on a stochastic theory such as a Markov model has also been proposed.

If detailed maintenance records for a similar structure (type of structure, materials, construction, environment, state of use) are available and its progress of deterioration is also similar to that of the evaluated structure, then the evaluation results for the similar structure provide useful information.

Table C10.3.6 Grades of appearance of structures and typical performance degradation

<table>
<tr><th>Grade of appearance of structure</th><th>Safety</th><th>Serviceability</th><th>Hazards for third party</th><th>Aesthetic appearance and landscape</th></tr>
<tr><td>I-1 (initiation stage)</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>I-2 (propagation stage)</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>II-1 (first half of acceleration stage)</td><td>-</td><td>-</td><td>-</td><td rowspan="3">Aesthetic deterioration
-Cracking
-Leaching of steel rust
-Exposure of steel</td></tr>
<tr><td>II-2 (second half of acceleration stage)</td><td rowspan="2">Deterioration of load bearing capacity and ductility
-Lack of section of steel
-Reduction of concrete cross section due to swelling or peeling of concrete</td><td rowspan="2">Deterioration of stiffness (increase of deformation and occurrence of vibration)
-Lack of section of steel
-Deterioration of bond between steel and concrete
-Reduction of concrete cross section due to swelling or peeling of concrete</td><td rowspan="2">Hazards for third party
-Peeling
-Spalling</td></tr>
<tr><td>III (deterioration stage)</td></tr>
</table>

(5) Because judgment is the act of deciding whether remedial measures need to be taken on the basis of structural performance evaluation results, there is no difference depending on deterioration factors. Therefore, refer to **Part 1**.

10.4 Remedial Measures

10.4.1 Selection of remedial measures

(1) If it has been judged that remedial measures need to be taken in connection with performance degradation of a structure subject to chloride attack, remedial measures by which the corrected structure meets the required performances shall be selected.

(2) If it is difficult to select remedial measures for a structure on the basis of performance verification, remedial measures may be selected from the measures corresponding to the grade of appearance.

[Commentary] (1) If it has been judged, as a result of evaluation, that remedial measures need to be taken, it is necessary to select one or more of the following measures: (i) intensified investigation, (ii) repair, (iii) strengthening, (iv) functional improvement, (v) restriction in service or (vi) dismantling/removal. Basically, decisions as to which measures to take should be made by the maintenance manager of the structure, but it is good practice to refer to **Part 1** for information on typical relationships between evaluation and judgment results and remedial measures.

(2) If it is difficult to select remedial measures for a structure through quantitative evaluation or judgment, remedial measures are selected from the measures corresponding to the deterioration grade of the structure. Remedial measures to be taken vary depending on the type of structure, the degree of importance of the structure, deterioration rate and the category of maintenance, but recommended standard measures are shown in Table C10.4.1.

Table C10.4.1 Grades of appearance of structure and remedial measures

Grade of appearance of structure	Intensified investigation	Repair	Strengthening**	Functional improvement	Restriction in service	Dismantling /removal
Grade I-1 (initiation stage)	O	O**	X	X		
Grade I-2 (propagation stage)	O	O	X	X		
Grade II-1 (first half of acceleration stage)	OO	OO	X	X		
Grade II-2 (second half of acceleration stage)	OO	OO*	X	X	O	
Grades III (deteriorating stage)		O*	X	X	OO	OO

OO : Standard remedial measures (OO*:Including the restoration of mechanical performance)
O : Remedial measures in some cases
(O*: Including the restoration of mechanical performance)
O**: Preventive measure
X : Remedial measure taken based on other criterion than the grade of appearance
Strengthening**: Enhancing the mechanical performance above the initial level

10.4.2 Repair and strengthening

For repair or strengthening, methods and materials should be selected so as to achieve the designated required performances, considering the performance degradation due to chloride attack and the life-cycle cost.

[Commentary] In cases where repair or strengthening is carried out as a remedial measure, it is necessary to define the expected effect of repair or strengthening and the required performance (what level of performance to be maintained for how many years?). Ideally, it is desirable that remedial measures be taken after constructing a deterioration formula (for repair) or structural calculation formula (for strengthening) in view of such factors as the properties of the materials used and verifying the calculation results obtained from those formulas. In this case, it is also important to take life cycle cost into consideration according to the remaining planned service period.

When taking preventive measures for a structure to which maintenance category A (preventive maintenance) is applied, an appropriate method should be selected fully considering the effect that should be achieved by the method.

The methods of repair or strengthening for structures subject to performance degradation due to chloride attack are listed in Table C10.4.2 by expected effect. When selecting the method, Table C10.4.2 and the present performance degradation of the structure should be considered. For the grades of appearance deterioration of structure and remedial measures, refer to Table C10.4.3.

Table C10.4.2 Expected effects and methods of repair or strengthening

Expected effect	Examples of methods
Reduce the supply of corroding-factors	Surface treatment
Remove the corroding-factors	Patching and electrochemical desalination
Control the progress of steel corrosion	Surface treatment, Cathodic protection, Patching and Rust-preventing coating
Increase the load bearing capacity	FRP adhesion, patching, external cable, Jacketing and Thickness increasing

Table C10.4.3 Grades of structural appearance and standard methods of repair or strengthening

Grade of structural appearance	Standard method
I-1 (initiation stage)	Surface treatment*
I-2 (propagation stage)	Surface treatment, patching, Cathodic protection and electrochemical desalination
II-1 (first half of acceleration stage)	Surface treatment, patching, cathodic protection and electrochemical desalination
II-2 (second half of acceleration stage)	Patching
III (deteriorating stage)	FRP bonding, patching, external cable, Jacketing and Thickness increasing

*: Preventive method

In the initiation stage due to chloride attack, neither performance degradation nor deterioration has occurred in the structure. In the period, remedial measures are taken only for structures to which maintenance category A (preventive maintenance) is applied. Then, remedial measures are expected to prevent chloride ions from intruding into concrete and diffusing. Surface treatment should therefore be applied to prevent chloride ions from entering the concrete from the external environment.

In the propagation stage, steel has corroded but the corrosion amount of steel is still low and little performance degradation has occurred. In the stage as in the initiation stage, surface treatment is generally selected. Patching or electrochemical desalination may sometimes be applied to remove chloride ions that intruded into the concrete. A cathodic protection method may be applied to prevent steel corrosion from progressing.

In the first half of the deterioration acceleration stage, the deterioration of mechanical performance is not yet outstanding. Cracks occur in concrete cover due to steel corrosion. An electrochemical desalination method for removing the chloride ions from concrete or the patching for removing the concrete cover may be considered. As a part of the patching, surface treatment may also be applied after the repair. In order to prevent further progress of steel corrosion, applying cathodic protection should also be considered.

In the second half of the acceleration stage, serviceability is reduced due to the deterioration of stiffness, and the concrete cover either is delaminated or spalls, resulting in serious hazards for third party. In this stage, the concrete cover is removed and the patching is applied. As a part of the patching, simultaneously applying surface treatment should be considered, and the addition or replacement of reinforcing bars should also be considered.

In cases where the deterioration stage has been reached and the load bearing capacity has been reduced, methods for restoring the load bearing capacity by such means as the adhesion of steel or FRP plates/sheets, use of external cable, jacketing and the thickness increasing should be applied in addition to the patching through the addition or replacement of reinforcing bars. These methods should be implemented after removing the concrete cover and applying surface treatment, for preventing re-deterioration.

When selecting a method that has been applied in few cases, the frequency of post-repair or -strengthening investigations should be increased. Many of the repair or strengthening methods applied have been developed only recently and few have been applied to actual structures. If such methods are adopted, the structure may be re-deteriorated and its performance may be degraded due to the factors not expected in the design phase. Measures should therefore be taken such as increasing the frequency of investigations after the repair or strengthening.

For details of the methods of repair and strengthening, refer to the "Guidelines for Strengthening Concrete Structures (draft)," "Guidelines for Repairing or Strengthening Concrete Structures Using Continuous Fiber Reinforced Membrane," "Guidelines for Design and Implementation of Electrochemical Protection (draft)," "Guidelines for Design and Implementation of Surface Protection (draft)," "Shotcreting Guidelines (draft) - Repair and Strengthening," "Reports of Concrete Structures Repair Method Committee I, II and III" and "Reports of Concrete Structures Restoration Committee" prepared by the Japan Concrete Institute. Applying the re-alkalization or electrical protection method to a structure using reactive aggregate is likely to encourage the deterioration of the structure due to alkali silica reaction. Then, the "Guidelines Concerning the Application of Electrochemical Protection Considering Alkali-silica Reaction" prepared by the Society of Materials Science, Japan should be consulted and the applicability of the repair method and the method of implementation should be determined carefully.

10.5 Recording

(1) Investigation, deterioration estimation, evaluation and judgment, and remedial measures shall be recorded in accordance with Part 1.

(2) Items relevant to chloride attack shall be recorded.

[Commentary] As a general rule, the results of investigations, deterioration estimations, evaluations and remedial measures must be recorded in accordance with **Part 1**. Items relevant to chloride attack require careful attention, particularly with respect to record keeping. Items to be recorded are the investigation items indicated in Section **10.3.2** "Investigation in Assessment", and the evaluation items indicated in Section **10.3.4** "Evaluation and Judgment."

CHAPTER 11 MAINTENANCE OF STRUCTURES SUBJECT TO FROST ATTACK

11.1 General

(1) This chapter provides standard methods for the maintenance planning, assessment, remedial measures and recording for structures that have been or are highly likely to be subject to performance degradation due to frost attack. The items common to all deterioration mechanisms are shown in Part 1.

(2) This chapter shall be applied to structures of the maintenance categories A (preventive maintenance) and B (corrective maintenance).

[Commentary] (1) Frost attack damage, which is caused by the freezing expansion of water in concrete, is the deterioration of concrete resulting from the freezing and thawing cycles occurring over a long period of time. Typically, micro crack, scaling, pop-out, and the like occur at the concrete surfaces of structures subjected to frost attack. Micro cracks and scaling often occur in cases where the quality of concrete is low or air bubbles have not been entrained appropriately. Pop-outs are often seen in cases where the quality of aggregate is low. The degree of deterioration due to frost attack is determined by various factors, namely, factors related to materials such as the mix proportions (e.g., cement content, water/cementitious material ratio, air content) of concrete and the quality of aggregates, factors related to structures such as the shape of cross section and the amount of reinforcing steel, and factors related to the environmental conditions under which structures are used such as the degree of water supply, the influence of insulation, ambient temperature (especially the lowest temperature) and the number of freezing and thawing cycles.

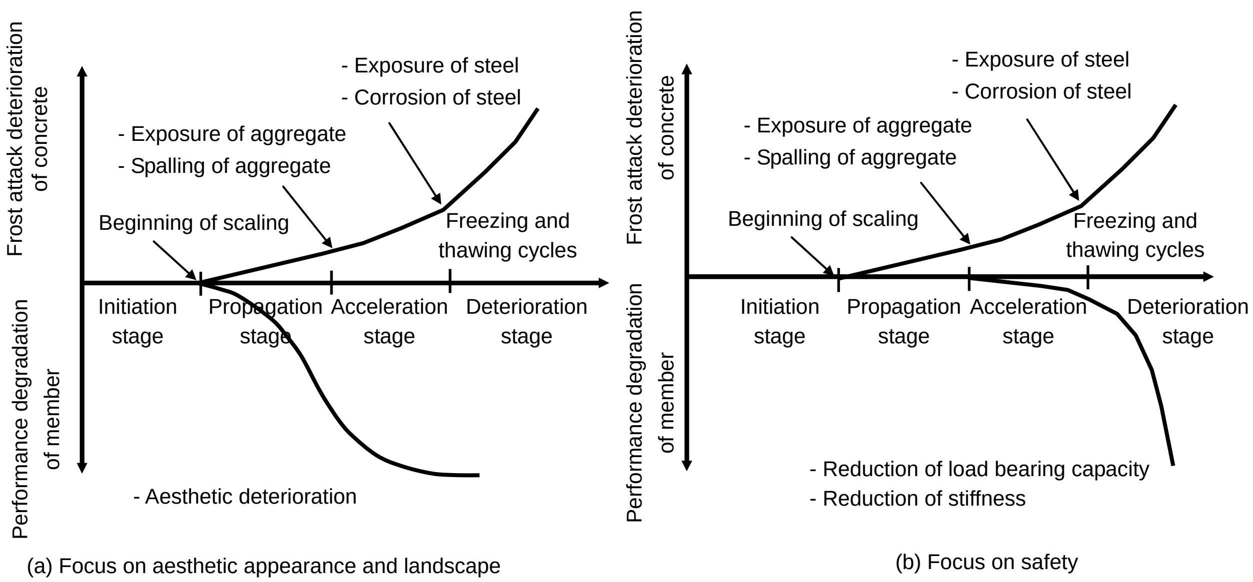


Fig. C11.1.1 Conceptual view of deterioration progress due to frost attack

Table C11.1.1 Definition of deterioration stages

Stage of Deterioration	Definition	Factor determining the stage
Initiation stage	Until concrete begins to scale under the influence of freezing and thawing cycles	Possibility of frost attack damage, lowest temperature, frozen water content, freezing and thawing cycles
Propagation stage	Until aggregate exposure or spalling occurs due to propagations of concrete surface deterioration	Lowest temperature, frozen water content, freezing and thawing cycles
Acceleration stage	Until steel exposure occurs or steel corrosion begins	Deterioration depth by frost attack, rate of steel corrosion
Deterioration stage	Stage in which load bearing capacity is reduced considerably due to increased steel corrosion	Deterioration depth by frost attack, rate of steel corrosion

Frost attack deterioration not only mars the appearance of structures but also reduces the mass transfer resistance of concrete. In areas where chloride attack as well as frost attack damage is problematic, steel corrosion could begin earlier under the influence of frost attack. A method for its prediction, however, is yet to be developed.

As shown in Fig. C11.1.1(a), degradation in appearance due to frost attack can be classified into four stages, namely, the initiation stage until the beginning of concrete surface scaling caused by freezing and thawing cycles, the propagation stage until the beginning of , the acceleration stage until steel exposure occurs due to lack of concrete cover, and the deterioration stage after occurrence of steel corrosion. From the viewpoint of the safety performance of structural members including resistance to steel corrosion, deterioration in terms of decreases in the strength and stiffness of structural members due to frost attack can also be classified, as shown in Fig. C11.1.1(b), into the initiation stage until the beginning of deterioration such as concrete surface scaling due to freezing and thawing cycles, the propagation stage until the occurrence of aggregate spalling, the acceleration stage until the occurrence of steel corrosion due to decreases in cover concrete, and the deterioration stage in which deteriorations such as decreases in load-carrying capacity result from steel corrosion.

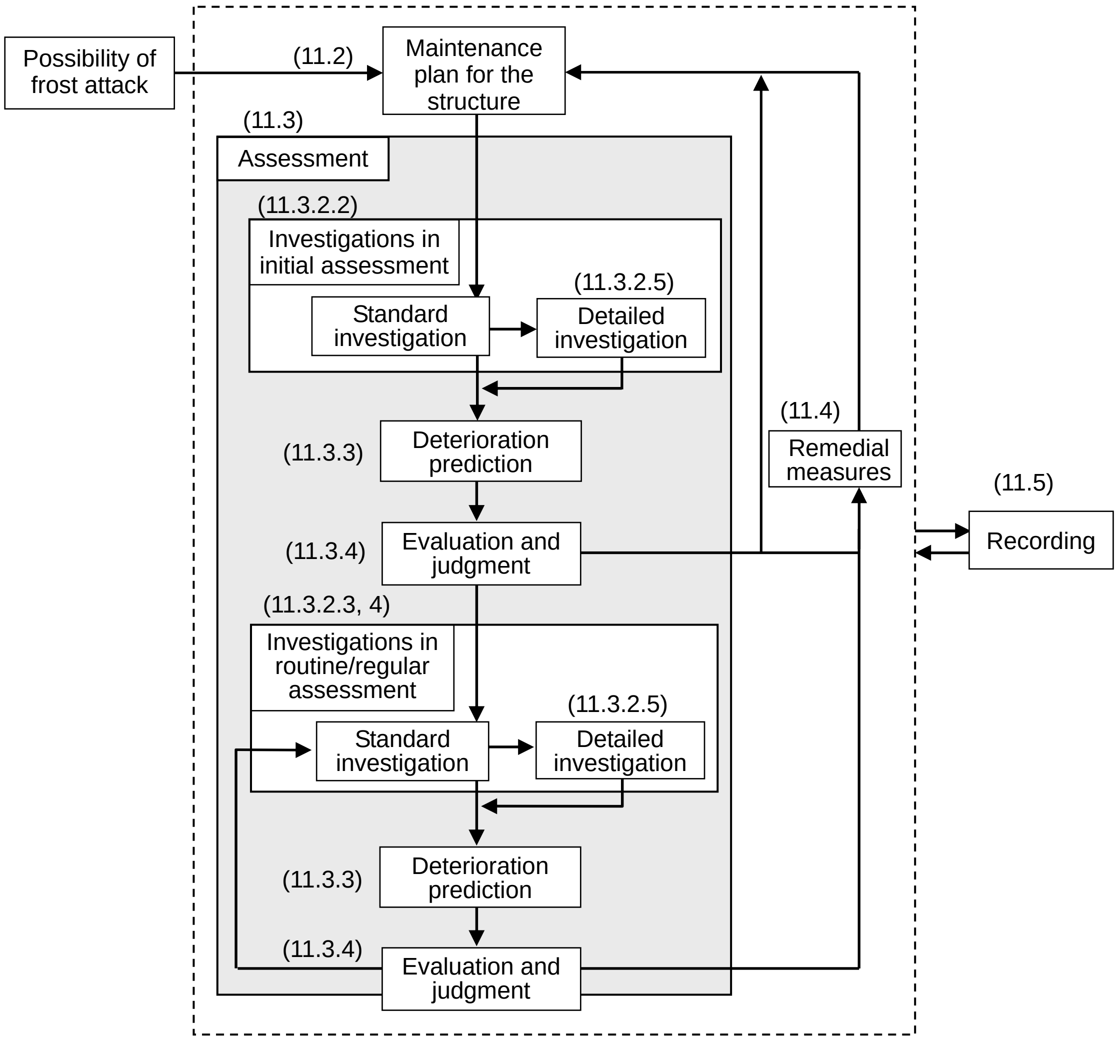
Table C11.1.1 shows the definitions of deterioration from the viewpoints of decreases in strength and stiffness of structural members and lists factors determining the stage of deterioration. In the management of structures in non-freezing environment, however, it is not advisable to leave a structure in the frost attack deterioration process unrepaired until the acceleration or deterioration stage defined in Table C11.1.1.

Fig. C11.1.2 shows standard procedures for the maintenance of structures in a frost attack environment.

(2) This maintenance standard is applicable to maintenance category A and B. Maintenance category B(corrective maintenance) is applied to many of existing ordinary structures. It is also likely, however, that if, for example, waterproofing measures such as surface treatment are taken for structures constructed in the coming years, structures requiring maintenance category A (preventive

maintenance) will increase. Even in the maintenance of structures to which maintenance category C (observational maintenance) is applied, it is necessary to carry out maintenance as described in this chapter.

For the matters that should be considered when determining the maintenance category for structures that have been or are expected to be subject to deterioration due to frost attack, refer to **11.2.2** "Maintenance Category." Special matters to be considered for respective maintenance categories are also described in this chapter.



Note: The numbers in parentheses indicate the relevant sections or subsections in this chapter.

Fig. C11.1.2 Standard maintenance procedure against frost attack

11.2 Maintenance Planning

11.2.1 Basis of planning

In order to maintain a structure subject to frost attack, the category of maintenance shall be selected, the service period planned, and a maintenance planning for activities including assessment, remedial measures and recording drawn up in advance in view of the service and environmental conditions such as the water supplies.

[Commentary] When drawing up a maintenance planning, it is necessary to cover such details as check items and procedures for initial assessment and check items, procedures, timing and frequency for the investigations in routine and regular assessment, evaluation and judgment methods, actions to be taken in the event of deterioration, and recording methods, taking into consideration the type, degree of importance and planned service period of the structure, category of maintenance, and the quality of materials.

The type of structure, size and environmental conditions of concrete structures vary from structure to structure. A maintenance planning must be optimized for each structure. The progress of deterioration due to frost attack varies considerably depending on the degree to which water is supplied, the influence of insulation, ambient temperature (especially the lowest temperature) and the number of freezing and thawing cycles. It is therefore necessary to draw up an appropriate maintenance plan, taking these factors into consideration. When measures such as surface protection are taken at the construction stage, it is also necessary to perform maintenance, taking into consideration the duration of the protection effect.

It is usually difficult, at the stage of maintenance planning, to accurately predict the state of a structure during its service period. It is therefore good practice to draw up a maintenance planning with reference to the deterioration of a similar structure or a structure in a similar environment.

11.2.2 Determination of maintenance category

The category of maintenance of a structure subject to frost attack shall be selected in view of the degree of importance of the structure, the type of structure, hazards for third party, the planned service period and the characteristics of deterioration due to frost attack.

[Commentary] The determination of the category of maintenance is very important because maintenance planning varies widely depending on the category of maintenance. The progress of deterioration and performance degradation due to frost attack is conceptually illustrated in Fig. C11.1.1.

Structures to which maintenance category A (preventive maintenance) is applied should be maintained so that they might be placed under the condition during the initiation stage with no scaling, to prevent performance degradation. The state of the structure should therefore be identified as accurately as possible. Requirements include the following.

(i) Evaluation of environmental conditions such as the supply of water and the lowest temperature

(ii) Quantitative evaluation and prediction of deterioration progress due to scaling of the surface layer of concrete

Structures to which maintenance category B (corrective maintenance) is applied should be maintained so as to prevent the performance of the structure from failing to meet the requirements. In the event of frost attack damage, the following stages of deterioration can be observed:

(i) Concrete surface deterioration is observed.

(ii) Exposed aggregates can be observed.

(iii) Aggregate spalling can be observed.

Once deterioration due to frost attack has started, it is extremely difficult to stop the progress of deterioration. It is desirable, therefore, that remedial measures be taken at Stage (i) or Stage (ii) mentioned above even in the case of a structure to which maintenance category B (corrective maintenance) is applied. It should also be kept in mind that large-scale remedial measures need to be taken if deterioration progresses to Stage (iii).

It is common practice to apply a single category of maintenance to a single structure. There are cases, however, where it is more reasonable to apply different types of maintenance to different parts or members of a structure. For example, it may be reasonable to apply maintenance category A (preventive maintenance) to the parts of a structure where appearance is important and maintenance category B (corrective maintenance) to the rest of the structure.

11.2.3 Preparation of maintenance manuals

A maintenance manual describing methods, procedures and frequency requirements should be prepared for each structure in accordance with the maintenance planning, taking the structure-specific conditions into consideration.

[Commentary] The service period of civil engineering structures is long, and maintenance of those structures is performed over a long period of time. It is recommended, therefore, that in order to inform investigators of maintenance concepts and policies, a maintenance manual be prepared so that detailed procedures and methods can be communicated accurately even to newly assigned responsible engineers.

Under certain circumstances such as in cases where the original maintenance planning is altered because the actual progress of deterioration turned out to differ from that assumed in the original maintenance planning, it is necessary to modify the maintenance manual and take appropriate maintenance measures accordingly.

11.3 Assessment

11.3.1 General

In the assessment of a structure whose performance has declined or is highly likely to decline because of frost attack, investigation, evaluation of the present state, prediction of deterioration and judgment of the necessity for remedial measures shall be appropriately conducted in accordance with the maintenance planning.

[Commentary] In order to maintain concrete structures appropriately, this specification requires three types of assessment: initial assessment, periodic assessment and extraordinary assessment. Because the initial and periodic assessments are essential for the maintenance of structures subject to frost attack, this chapter stipulates that those assessments must be conducted. Extraordinary assessments are regarded as assessments to be conducted on an as-needed basis and are therefore not dealt with in this chapter. By conducting periodic assessments during the maintenance period, defect in appearance of structures can be discovered before they occur or in early stages, and remedial measures including preventive measures and repairs can be taken systematically.

11.3.2 Investigation in assessment

11.3.2.1 General

Investigations in initial, routine and regular assessment of a structure subject to frost attack shall be conducted appropriately according to the category of maintenance required for the structure. Prior to investigation, check items, methods, frequency and scope of standard investigation shall be determined appropriately. For each type of assessment, detailed investigation shall also be conducted on an as-needed basis.

[Commentary] It is important to select check items, methods, frequency and scope of investigation appropriately according to the purpose of investigation in accordance with the maintenance planning.

The major parameters that should be identified in investigations of structures subject to frost attack are the state of water supply, the degree of saturation, anomalies in appearance, and depth of deterioration by frost attack. In cases where deterioration has progressed considerably, investigations should be conducted to directly evaluate performance.

The items to be examined in investigations vary according to the degree of deterioration. In cases where it has been determined or assumed that the deterioration was in the initiation stage, investigations should be conducted mainly to identify the progress of defects on concrete. In cases where it has been determined or assumed that the deterioration was in or beyond the propagation stage, investigations should be conducted mainly to identify the depth of deterioration by frost attack. Table C11.3.1 shows major items to be examined in the respective stages. Data on the items related to deterioration prediction such as the state of scaling and the environmental action should be collected in as early a stage as possible.

The frequency and range of investigation should be determined considering the maintenance category, environmental conditions, structural format and the state of deterioration for the structure. Frost attack damage tends to occur at places that are supplied with a large amount of moisture and are exposed to sunlight. It is desirable, therefore, that the entire structure is investigated and a plan be drawn up so that the parts of the structure where the conditions mentioned above should be met be investigated intensively.

Regardless of the category of maintenance, it is important to go through the design drawings and specifications, construction records, investigation results and the repair history prior to the investigation of a structure.

If the state of a structure cannot be judged appropriately by standard investigation, detailed investigation must be conducted.

Table C11.3.1 Main check items in investigation

Stage of Deterioration	Initiation Stage	Propagation Stage	Acceleration Stage	Deterioration Stage
Change of appearance	O	O	O	O
Depth of deterioration by frost attack*	▲	O	O	O
State of water supply and degree of saturation	O	O	O	O
Concrete strength	▲	▲	▲	▲*

O: Items to be investigated on a priority basis
▲: Item to be investigated on an as-needed basis
▲*: Items that should preferably be investigated
* See Section 11.3.3.3.

11.3.2.2 Investigation in initial assessment

(1) In initial assessment, appropriate check items for standard investigation shall be selected for newly constructed structures, existing structures, large-scale repairs and strengthened structures.

(2) If deterioration prediction, evaluation or judgment is difficult to make through a standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) Investigation in initial assessment is the first investigation conducted when the maintenance of a concrete structure is started. Investigation in initial assessment includes not only the first investigation of a newly constructed structure conducted before it goes into service but also the first investigation of an existing structure or a structure for which remedial measures have been taken in response to deterioration. Check items for the investigation may vary from structure to structure. Basic check items for standard investigations in initial assessment of a newly constructed structure are the document search on the design drawings and specifications and construction records and observation. It is good practice to check on such details as concrete cover, the state of steel and porosity through nondestructive testing on an as-needed basis. When investigating a structure for which remedial measures have been taken, it is also important to check for problems in repaired or reinforced parts of the structure. These should be included in check items of standard investigation. When an existing structure is investigated, check items are similar to those for a newly constructed structure if design drawings and specifications and construction records exist. If there is no such document or record, it is necessary to select check items of standard investigation with reference to Section **11.3.2.5** “Detailed Investigation.” In cases where a prediction needs to be made with high accuracy about a structure to which maintenance category A (preventive maintenance) is applied, it is necessary to conduct investigations concerning the parameters used for the method described in Section **11.3.3** “Methods for Predicting Degradation of Performance Degradation of Structures.”

Extremely important items in the investigation in initial assessment of a structure subject to frost attack are listed below.

I. Items related to the quality of concrete

(i) Quality of aggregate (absorption, loss of mass)

(ii) Mix proportion of concrete

(iii) Air content (air void spacing factor)

(iv) Degree of saturation of concrete (water content)

II. Items related to the quality of construction

(i) Cover concrete

(ii) Initial defects

III. Items related to environmental deterioration factors

(i) Lowest temperature

(ii) Number of freezing and thawing cycles

Among the items listed above, I–(i), (ii) and (iii) are essential for predicting the occurrence of frost attack damage, but these are used only in cases where mix proportion records are available. II–(i) needs to be checked because it affects the time of initiation and rate of steel corrosion, and its actual values tend to differ from design values. I–(iv) and III–(i) and III–(ii) are items necessary for estimating depth of deterioration by frost attack. Among these items, the lowest temperature and the number of freezing and thawing cycles are important for the prediction of the rate of deterioration. II–(ii) needs to be checked during the investigation in initial assessment because it greatly affects the durability—durability against not only frost attack but also other deterioration factors— of structures.

Basically, investigation is made through the examination of design and construction records and visual observation. It is good practice, however, to check surface temperature, the locations and state of steel, etc., through non-destructive testing on an as-needed basis.

In the investigation in initial assessment of a structure for which remedial measures have been taken, it is also important to check for defects (for example, peeling or detachment of concrete surface coating materials) in the repairing or strengthening areas.

(2) If evaluation and judgment cannot be made with high accuracy by standard investigation alone, detailed investigation is necessary. Check items of detailed investigation are indicated in Section **11.3.2.5** “Detailed Investigation.”

11.3.2.3 Investigation in routine assessment

(1) In routine assessment, standard investigation shall be conducted to detect the state of water supply (wettedness of concrete) and the defect of concrete surface such as micro cracking of concrete, scaling and pop-outs.

(2) If deterioration prediction, evaluation or judgment is difficult through standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) The purpose of investigation in routine assessment is to detect deterioration at an early stage by checking on defect in the state of a structure over time. The determination of the time at which deterioration began in order to obtain information that is useful for predicting deterioration is another important purpose of the investigation. A main check item is the observation of anomalies in the state of concrete surface due to phenomena peculiar to frost attack damage such as pop-outs, micro crack and scaling. Even if concrete deterioration is not detected, deterioration may occur at places where water is supplied to the concrete surface. It is therefore desirable that the state of water supply be checked during investigation. It is also good practice to intensively investigate the regions that were identified during the investigation in initial assessment as being prone to deterioration.

(2) If high-accuracy evaluation or judgment is difficult by conducting standard investigation alone or if severe deterioration has already occurred, detailed investigation is conducted. Check items of detailed investigation are described in detail in Section **9.3.2.5** “Detailed Investigation.”

11.3.2.4 Investigation in regular assessment

(1) The purpose of investigation in regular assessment is to obtain information that is difficult to obtain in routine assessment. In regular assessment, standard investigation consisting of detailed observation of visible properties, the state of water supply, etc., shall be conducted as in routine assessment.

(2) If deterioration prediction, evaluation or judgment is difficult through standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) Investigation in regular assessment is conducted for obtaining the information more detailed than that in routine assessment. Areas where signs of defects or deterioration have been detected in initial or routine assessment need to be examined intensively. The appearance of the structure should basically be examined as in routine assessment. It is also necessary to keep track of changes over time by measuring the depth of deterioration by frost attack in concrete, preparing a deterioration map or conducting ultrasonic wave propagation speed, surface strength or other tests using non-destructive testing equipment in addition to the examination of the appearance of the structure.

Frost attack damage occurs in winter, in which the water in concrete freezes. If the progress of deterioration is to be predicted with high accuracy in an investigation in regular assessment, therefore, it is desirable that investigations be conducted in summer, in which deterioration is not in progress. If depth of deterioration by frost attack is measured in an investigation in regular assessment, it is good practice to take measurements three to five times at equal intervals during the period in which deterioration is expected to occur. If maintenance category A (preventive maintenance) is applied, it is advisable to increase the frequency of measurement.

(2) If high-accuracy evaluation or judgment is difficult by conducting standard investigation alone or if severe deterioration has already occurred, detailed investigation is conducted. Check items of detailed investigation are described in detail in Section **11.3.2.5** “Detailed Investigation.”

11.3.2.5 Detailed investigation

Detailed investigation shall be conducted to obtain detailed information on a structure subject to frost attack in cases where the deterioration of the structure is difficult to predict, evaluate or judge by standard investigation alone in initial, routine or regular assessment. Check items, methods and location of a detailed investigation shall be selected appropriately taking into consideration such factors as the purpose of investigation and the accuracy of obtained results.

[Commentary] When the determination of the present state of a structure and the deterioration prediction of the structure are difficult by standard investigation alone, detailed investigation is conducted in order to obtain the information necessary for those purposes. Examples of investigation items for structures subject to frost attack, and of data on the condition of the structure at the time of investigation and those in the future predicted from the investigation results are listed in Table C11.3.2. The evaluation items estimated from data in the table are evaluated after deterioration is predicted.

Table C11.3.2 lists check items for evaluating anomalies in the state of concrete and steel. It is recommended that evaluators of anomalies in the state of concrete structures with surface protection refer to the investigation and evaluation items indicated in the Recommendation for Concrete Repair and Surface Protection of Concrete Structures.

Table C11.3.2 Examples of evaluation items in detailed investigation

Measurement item	Data obtained by investigation	Evaluation items predictable from obtained data
Depth of deterioration by frost attack	Depth of deterioration by frost attack, frost attack deterioration rate	Frost attack deterioration rate
Crack (width, depth, density)	Aesthetic appearance	Aesthetic appearance
Scaling	Aesthetic appearance	Aesthetic appearance
Pop-out	Aesthetic appearance, quality of aggregate	Aesthetic appearance
Concrete strength, elastic modulus	Concrete strength, stiffness	Concrete strength
Steel location (cover concrete) and state of corrosion	Corrosion grade, amount of steel corrosion, load bearing capacity	Corrosion rate, corrosion grade
Deflection, deformation	Stiffness, load bearing capacity	---
Pore structure (pore volume, pore size distribution)	Depth of deterioration by frost attack, concrete strength	Frost attack deterioration rate
Void structure (air content, air void spacing factor)	Depth of deterioration by frost attack	Frost attack deterioration rate
Water content rate (degree of saturation)	Water content rate	Frost attack deterioration rate
Temperature, insulation, water supply	Temperature, humidity, state of moisture	Frost attack deterioration rate

Note: For the grade of corrosion, refer to Table C9.3.3.

Major check items are outlined below. For other measurement items or testing methods than those described below, refer to **4.7** "Investigation."

(i) Environmental conditions: The degree and type of deterioration of a structure varies with the lowest temperature to which the structure is subjected, the number of freezing and thawing cycles and the degree of water supply. This means that frost attack damage to a structure does not occur even if the structure is under severe environmental conditions and water is supplied as long as the quality of concrete is sufficiently high. Even in cases where the quality of concrete is low, the degree of frost attack damage is low if environmental conditions are mild or there is no supply of water. In other words, severe frost attack damage to a structure occurs if the structure is in a harsh environment, water is supplied and the quality of concrete is low. It is desirable, therefore, that collected data on the environmental conditions be used for the prediction of deterioration progress by comparing the data with the performance degradation of the structure under consideration.

(ii) Depth of deterioration by frost attack: Depth of deterioration by frost attack should be evaluated comprehensively by measuring scaling depth and depth of deterioration due to micro crack. Scaling depth is measured at the surface of the structure, and the maximum and minimum values are determined. Depth of deterioration due to micro crack is determined by taking core samples from the place where frost attack damage was observed and evaluating, for example, measured ultrasonic wave propagation speeds at different depths.

(iii) Steel corrosion: Corrosion of reinforcing steel used in a structure tends to directly affect the performance of the structure. It is therefore important to chip off the cover concrete so that the reinforcing steel is exposed and measure the state, location, area and mass of corrosion, pitting corrosion depth, etc. By obtaining quantitative data on corrosion, the performance degradation of the structure can be evaluated quantitatively.

(iv) Appearance of structures: Anomalies in appearance of a structure deteriorated because of frost attack may provide information that is highly helpful in performance evaluation. It is therefore necessary to investigate the parts of the structure showing anomalies and the degree of change as quantitatively as possible. For reference purposes, Table C11.3.3 shows the relationship between the appearance grade of a structure and the state of deterioration involving steel corrosion.

Table C11.3.3 Relationship between appearance grade of a structure and the state of deterioration taking into account steel corrosion

Appearance grade of structure	State of deterioration
State I (initiation stage)	Stage at which the structure is subjected to freezing and thawing cycles, but there has been no performance degradation and the initial structural soundness is retained
State II (propagation stage)	Stage at which depth of deterioration by frost attack is so small as to have little impact on stiffness and steel corrosion has not occurred, but appearance is being affected
State III (acceleration stage)	Stage at which depth of deterioration by frost attack has become so large as to affect third parties through spalling, etc., and steel corrosion occurs
Stage IV (deterioration stage)	Stage at which depth of deterioration by frost attack is greater than cover concrete, and corrosion is so severe as to affect serviceability and safety performance

11.3.3 Methods of predicting performance degradation of structures

11.3.3.1 General

(1) In the maintenance of a structure subject to frost attack the performance of the structure shall be evaluated quantitatively at the time of investigation, and future degradation shall be predicted.

(2) In order to predict the performance degradation of a structure, deterioration due to frost attack shall be predicted quantitatively.

(3) If (2) is difficult, an alternative method is to predict performance degradation by estimating the length of the initiation, propagation, acceleration and deterioration stages, taking the progress of concrete deterioration by frost attack into consideration.

(4) Deterioration shall be predicted on the basis of investigation results. If investigation results are not available, the quality of the concrete protection layer and the quality of the concrete, and the environmental conditions under which the structure is used shall be evaluated appropriately, and a prediction shall be made by allowing for an appropriate margin of safety.

[Commentary] (1) and (2) In the performance verification based maintenance system, changes (deterioration) in various performance attributes inherent in the structure should be predicted. In order to predict the performance degradation of a structure in a frost attack environment, it is necessary to quantitatively predict the deterioration of the materials, namely, decreases in the cross sectional area of the concrete and the progress of corrosion of the steel in the concrete. The performance of the structure and the degree of deterioration of materials constituting the structure should be evaluated quantitatively at the time of investigation and the end of planned service period. Performance degradation of the structure or the degree of deterioration of materials constituting the structure at the time of investigation may be evaluated quantitatively by an appropriate method based on investigation results. The performance or the degree of deterioration at the end of the planned service period should be predicted quantitatively based on the previous periodic assessments. The prediction of deterioration progress is not always in agreement with actual progress of deterioration. The method of prediction should therefore be reviewed based on the results of investigations to be conducted later.

(3) When evaluating various performances attributes of a structure by combining the results of prediction of deterioration progress of concrete and steel, quantitative prediction is difficult at the present technological level. A practical method, therefore, is to predict the length of the initial, propagation, acceleration and deterioration stages by taking into consideration depth of deterioration by frost attack and the progress of steel corrosion. Table C11.1.1 shows examples of factors determining the length of stages of deterioration when the deterioration process is considered in terms of decreases in the load-carrying capacity and stiffness of structural members at each stage of deterioration. In this case, the length of the initiation stage can be roughly predicted from the period until the occurrence of frost attack damage, and the duration of the deterioration process from the propagation stage can be roughly predicted from depth of deterioration by frost attack. The prediction of the period until the occurrence of frost attack damage and depth of deterioration by frost attack is described in Section **11.3.3.2** "Prediction of Occurrence of Frost Attack," and Section **11.3.3.3** "Prediction of Depth of Deterioration by Frost Attack."

(4) Investigation results are related to either the quality of concrete of the structure or the environment in which the structure is placed while in service. These parameters should be used as a

basis for predicting deterioration. Many of the frost attack damage prediction methods currently in use, however, are based on the results of experiments conducted under controlled concrete quality and environmental conditions. In cases where the deterioration of a real structure is predicted, the accuracy of prediction may not be sufficiently high.

If no information is available on environmental conditions as in the case of a newly constructed structure or if investigation results are not available for an existing structure, investigation results for adjacent structures or structures in similar environments may be used for reference purposes.

11.3.3.2 Prediction of occurrence of frost attack

The occurrence of deterioration by frost attack shall be predicted according to the environmental conditions under which the structure and the investigation results concerning the quality of aggregate and the frost attack resistance of concrete.

[Commentary] The occurrence of frost attack damage to a structure must be predicted comprehensively in view of the used materials, the mix proportions and air content of the concrete, the environment of the structure and the degree of water supply. Since, however, it is difficult under present conditions to quantitatively evaluate the environment in which a structure is to be placed, common practice is to evaluate the possibility of occurrence of frost attack damage in view of a frost attack damage hazard map based on the weather conditions, such as the lowest temperature, to which the structure is to be subjected, of the properties of aggregate or of the results of freezing and thawing tests conducted under certain conditions. As a guide concerning the degree of vulnerability to frost attack damage, JASS 5 “Reinforced Concrete Work 2003” (Fig. 26.1, Frost attack Risk Distribution in Section 26) may be used.

From the viewpoint of materials, it is necessary to predict the occurrence of frost attack damage to both aggregate and concrete. Representative anomalies attributable to the quality of aggregate include pop-outs. Pop-outs occur when the surface mortar layer spalls because of expansion pressure generated by the freezing of water in the aggregates. The "Construction" volume of the Standard Specifications suggests an absorption of 3% or less and a loss of weight as determined by aggregate soundness testing of 12% or less as limit values of aggregate properties that meet the frost attack resistance requirements.

One way to evaluate the frost attack resistance of concrete is to conduct a freezing and thawing test on the concrete to be used or concrete designed to simulate it in accordance with JIS A 1148 “Method of test for resistance of concrete to freezing and thawing.” It is possible, to a certain extent, to evaluate the possibility of occurrence of frost attack damage from the test results thus obtained. Since, however, the environment of a real structure varies widely; it is difficult to predict the deterioration of a real structure quantitatively. For an existing structure, it is possible to conduct a freezing and thawing test using core specimens. For a similar reason, it is difficult to predict deterioration in a real-world environment. Regardless of the type of concrete specimens used (i.e., concrete to be used, concrete designed to simulate it, or core specimens), therefore, it is desirable that freezing and thawing test results be used for reference purposes only in evaluating the possibility of occurrence of frost attack damage.

11.3.3.3 Prediction of depth of deterioration by frost attack

The depth of deterioration by frost attack should be predicted on the basis of the depth and rate of deterioration by frost attack obtained from investigations.

[Commentary] Frost attack damage increases the porosity of concrete, causing adverse effects such as decreases in compressive strength and increases in the rate of chloride ion penetration and the rate of carbonation. It is therefore necessary to predict the depth and amount of textural alteration of concrete. A simulation model capable of predicting depth of deterioration by frost attack has not yet been developed. A practical approach, therefore, is to measure and analyze core specimens taken from a structure and use the obtained results for the prediction of the deterioration of the structure or the prediction of structures in adjacent areas.

Measurement and analysis methods currently under study include the method of determining depth of deterioration by frost attack from the distribution of ultrasonic wave propagation velocity at different depths from the concrete surface or the pore size distribution measured by mercury porosimetry. In the case of evaluation based on ultrasonic wave propagation velocity, evaluation by use of core specimens may be difficult because propagation velocity is greatly affected by aggregate. It is important to directly measure the structure on an as-needed basis. In the case of evaluation based on the pore size distribution, there are a number of areas in which further study is needed to achieve high-accuracy evaluation such as the variability of measurement results and the necessity of special measuring equipment, so much more data needs to be accumulated.

A method for estimating depth of deterioration by frost attack currently under development is the method of determining changes in the degree of deterioration such as the number of freezing and thawing cycles and the relative dynamic modulus of elasticity from the distribution of temperature and the degree of saturation in different parts of the concrete. At the present stage of development, freezing and thawing test results can be model, but further accumulation of data is needed in order to achieve agreement with real structures.

Studded tires were banned in March 1991, and the use of deicing agents has increased since then. Usually, the use of deicing agents increases scaling. When evaluating depth of deterioration by frost attack, therefore, it is necessary to take the use of deicing agents into consideration.

11.3.3.4 Modification of prediction

If the state of deterioration determined in an investigation differs from a predicted state of deterioration, the cause of the difference shall be identified and the prediction shall be revised accordingly. If necessary, the maintenance plan shall be altered.

[Commentary] When the deterioration confirmed in investigations is different from the prediction, appropriate investigations should be conducted using the deterioration prediction methods shown in **11.3.3.2** “Prediction of Occurrence of Frost Attack” and **11.3.3.3** “Prediction of Depth of Deterioration by Frost Attack” and based on Table C11.3.2 to examine the cause for the difference, and the prediction should be modified. Then, the results of several investigations conducted until that are useful to the examination of causes and the modification of the prediction. Revising the subsequent maintenance plans including a review of investigation frequency based on the modified prediction is also important.

11.3.4 Evaluation and judgment

(1) The evaluation of performance and judgment as to whether remedial measures need to be taken based on the results of the investigation in initial, routine and regular assessment shall be made in accordance with Part 1 and Item (2) and subsequent items in this section.

(2) The performance of a structure subject to frost attack shall be evaluated by appropriately selecting performance attributes to be evaluated in view of the stage of deterioration of the structure.

(3) The evaluation of performance attributes at the time of investigation and at the end of the planned service period of the structure should be made by a quantitative method.

(4) If Item (3) is difficult to achieve, the evaluation of performance attributes at the time of investigation and at the end of the planned service period of the structure may be made by a semi-quantitative grading-based method.

(5) Judgment as to whether remedial measures need to be taken shall be made in view of the degree of performance degradation due to frost attack, the degree of importance of the structure, category of maintenance, and the remaining service life.

[Commentary] (1) The evaluation of performance and judgment of necessity for remedial measures in initial, routine and regular assessment for structures in which little progress of deterioration has been recognized are frequently more or less the same regardless of the deterioration mechanism. For details, refer to **Part 1**. The evaluation of performance and judgment of necessity for remedial measures for structures in which deterioration may have or has progressed vary according to the deterioration mechanism. When discussing the performance degradation due to frost attack, the descriptions in this chapter should be consulted.

(2) As shown in Fig. C11.1.1, in structures subject to carbonation, the performance attribute to be affected by deterioration varies depending on whether deterioration is in the initiation, propagation, acceleration or deterioration stage. The performance attribute to be evaluated should be properly selected for each stage of deterioration. At the initiation stage, for example, basically deterioration has not become apparent, so degradation does not occur in any of the performance attributes. At the propagation stage, deterioration occurs at the concrete surface so that degradation occurs in appearance-related performance. At the acceleration stage, depth of deterioration by frost attack increases and degradation occurs in appearance, and degradation may occur in performance attributes related to third party impact due to spalling of concrete or other forms of degradation. Because the cross-sectional area of concrete begins to decrease considerably, decreases in load-carrying capacity or other performance attributes become a concern in the case of a structural member with a small cross-sectional area although such phenomena do not pose a serious problem in the case of a massive structure. At the deterioration stage, the deterioration of concrete due to frost attack becomes even more apparent, and steel corrosion begins. In the case of a structural member, therefore, degradation of serviceability due to deformation or degradation of safety performance due to a decrease in load-carrying capacity becomes a concern. If steel corrosion has occurred and the steel is under fatigue loading, it is necessary to consider third party impacts such as spalling of concrete in addition to safety and serviceability.

(3) and (4) In order to quantitatively evaluate the performance of a structure subjected to frost attack, taking into consideration the influence of steel corrosion, it is necessary to quantitatively evaluate the degradation of each performance attribute after quantifying the state of concrete

deterioration and steel corrosion due to frost attack. One way to do this is to substitute the property values for each material at the time of investigation and at the end of the planned service period in the structural calculation equations, verify safety and serviceability from the calculated values of such attributes as load-carrying capacity and deformation and check on third party impact and appearance by examining the ranges and degrees of cracking, scaling, pop-out, etc. If, however, structural calculation equations are applied, it must be confirmed in advance that the preconditions for the equations, such as bond properties and structural details, are satisfied. There are cases where evaluation at the time of investigation can be made with a certain level of accuracy, but it is not easy to predict property values at the end of the planned service period. A practical method, therefore, is to classify the states of deterioration into a number of grades as shown in Table C11.3.3 according to structural appearance investigation results and evaluate the degraded performance at the time of investigation semi quantitatively with reference to Table C11.3.4. The aim of deterioration grading is to evaluate the present degree of deterioration of a structure on a semi quantitative scale, instead of evaluating the future progress of deterioration. Performance evaluation, however, can be made if the state of deterioration at the end of the planned service period is predicted by, for example, estimating deterioration from the relationship between the service period and depth of deterioration by frost attack determined through a detailed investigation. In this case, however, it is important to allow for an appropriate factor of safety according to the accuracy of deterioration prediction.

If detailed maintenance records for a similar structure (type of structure, materials, construction, environment, state of use) are available and the progress of deterioration to date is similar to that of the similar structure, the evaluation results for that structure can be used as a guide.

(5) Because judgment is the act of deciding whether remedial measures need to be taken on the basis of structural performance evaluation results, there is no difference depending on deterioration factors. Therefore, refer to **Part 1**.

Table C11.3.4 Grades of appearance of structures and typical performance degradation

<table>
<tr><th>Grade of appearance of structure</th><th>Safety</th><th>Serviceability</th><th>Hazards for third party</th><th>Aesthetic appearance and landscape</th></tr>
<tr><td>State I
(initiation stage)</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>State II
(propagation stage)</td><td>-</td><td>-</td><td>-</td><td rowspan="3">Degradation of aesthetic appearance
-Scaling
-Pop-out
-Crack</td></tr>
<tr><td>State III
(acceleration stage)</td><td rowspan="2">Decrease in load bearing capacity
-Decrease in cross-sectional area of concrete
-Steel corrosion</td><td rowspan="2">Decrease in stiffness
-Decrease in cross-sectional area of concrete
-Deterioration of bond between steel and concrete
-Steel corrosion</td><td rowspan="2">Hazards for third party
-Peeling
-Spalling</td></tr>
<tr><td>State IV
(deterioration stage)</td></tr>
</table>

11.4 Remedial Measures

11.4.1 Selection of remedial measures

(1) If it has been judged that remedial measures need to be taken in connection with performance degradation of a structure subject to frost attack, remedial measures by which the corrected structure meets the required performances shall be selected.

(2) If it is difficult to select remedial measures for a structure on the basis of performance verification, remedial measures may be selected from the measures corresponding to the grade of appearance.

[Commentary] (1) If it has been judged, as a result of evaluation, that remedial measures need to be taken, it is necessary to select one or more of the following measures: (i) intensified investigation, (ii) repair, (iii) strengthening, (iv) functional improvement, (v) restriction in service or (vi) dismantling/removal. Basically, decisions as to which measures to take should be made by the maintenance manager of the structure, but it is good practice to refer to **Part 1** for information on typical relationships between evaluation and judgment results and remedial measures.

(2) If it is difficult to select remedial measures for a structure through quantitative evaluation or judgment, remedial measures are selected from the measures corresponding to the deterioration grade of the structure. Remedial measures to be taken vary depending on the type of structure, the degree of importance of the structure, deterioration rate and the category of maintenance, but recommended standard measures are shown in Table C11.4.1.

Table C11.4.1 Grades of appearance of structure and remedial measures

Grade of appearance of structure	Intensified investigation	Repair	Strengthening**	Restriction in service
I (initiation stage)	**(O)**	**(O)**	**(X)**	
II (propagation stage)	**OO**	**OO**	**X**	**O**
III (acceleration stage)	**O**	**OO** *	**X**	**OO**
IV (deterioration stage)		**O** *	**X**	**OO**

OO: Standard remedial measures **(OO*:** Including the restoration of mechanical performance), **O**: Remedial measures in some cases (**O***: including the restoration of mechanical performance), **X**: Remedial measure taken based on other criterion than the grade of appearance. Strengthening**: Enhancing the mechanical performance above the initiation level

11.4.2 Repair and strengthening

Methods and materials for the repair or strengthening of a structure shall be selected, taking into consideration the performance degradation of the structure due to frost attack and life cycle cost, so that the required effect can be achieved.

[Commentary] In cases where repair or strengthening is carried out as a remedial measure, it is necessary to define the expected effect of repair or strengthening and the required performance (what level of performance to be maintained for how many years?). Ideally, it is desirable that remedial measures be taken after constructing a deterioration formula (for repair) or structural calculation formula (for strengthening) in view of such factors as the properties of the materials used and verifying the calculation results obtained from those formulas. In this case, it is also important to take life cycle cost into consideration according to the remaining planned service period.

When taking preventive measures for a structure to which maintenance category A (preventive maintenance) is applied, an appropriate method should be selected fully considering the effect that should be achieved by the method.

The purposes of repair or reinforcement carried out in response to frost attack damage are to remove the deteriorated parts and restore the load-carrying capacity and stiffness of structural members. Table C11.4.2 shows examples of repair or reinforcement methods for achieving these purposes. Deterioration due to frost attack damage consists mainly of the deterioration of concrete. The properties of concrete damaged by frost attack, therefore, are in many cases altered considerably. Basically, therefore, an effective method is to replace the damaged part of concrete although the effectiveness of the method depends on the degree of deterioration. Wherever possible, remedial measures should be taken when the structure is dry. As shown in Table C11.4.3, repair or reinforcement methods to be used vary depending on the degree of deterioration. Usually, repair and reinforcement goals can be achieved with relatively simple remedial measures if taken at an early stage of deterioration. It is therefore necessary to decide on the timing for taking remedial measures appropriately according to the maintenance plan.

Table C11.4.2 Expected effects and methods of repair or strengthening (including preventive maintenance)

Expected effect	Examples of methods
Control of water supply	Surface treatment, grout injection into cracks, drainage
Removal of deteriorated part	Repair of cross section, grout injection into cracks
Increase in load bearing capacity	Increase of thickness, replacing, lining

Table C11.4.3 Grades of appearance of structure and examples of standard repair/strengthening methods

Grade of appearance of structure	Standard repair/strengthening method
I (initiation stage)	Surface treatment*
II (propagation stage)	Surface treatment
III (acceleration stage)	Surface treatment, grout injection into cracks, repair of cross section
IV (deterioration stage)	grout injection into cracks, increase of thickness, replacing, lining

*: preventive maintenance method

Deterioration due to frost attack damage does not occur if the supply of water is cut off. In the case of a structure with high frost attack damage risk, therefore, deterioration can be prevented by taking such measures as covering the concrete surface with a protective material when a new structure is constructed. In the case of a structure to which maintenance category A (preventive maintenance) is applied, if drying shrinkage or structural cracks are observed even when frost attack damage has not occurred, measures such as grout injection into cracks or taking water-related maintenance measures (e.g., drainage) help prevent frost attack damage.

In the case of frost attack damage, the post-repair/reinforcement frost attack deterioration rate varies depending on the quality of repair materials or reinforcement materials rather than the quality of existing concrete. This necessitates deterioration prediction in view of the frost attack resistance of repair materials or reinforcement materials. It is also necessary to pay attention to details and intervals of investigations in regular assessment after remedial measures are taken and to the selection of priority observation items.

For more details of repair and reinforcement methods, it is advisable to refer to the "Recommendations for Strengthening of Concrete Structures," "Recommendations for Concrete Repair and Surface Protection of Concrete Structures," Report of JCI Committee on "Rehabilitation of Concrete Structures (Japan Concrete Institute)," etc.

11.5 Recording

(1) Investigation, deterioration estimation, evaluation and judgment, and remedial measures shall be recorded in accordance with Part 1.

(2) Items relevant to frost attack shall be recorded.

[Commentary] As a general rule, the results of investigations, deterioration estimations, evaluations and remedial measures must be recorded in accordance with **Part 1**. Items relevant to carbonation require careful attention, particularly with respect to record keeping. Items to be recorded are indicated in Section **11.3.2** "Investigation in Assessment" and the evaluation items indicated in Section **11.3.4** "Evaluation and Judgment."

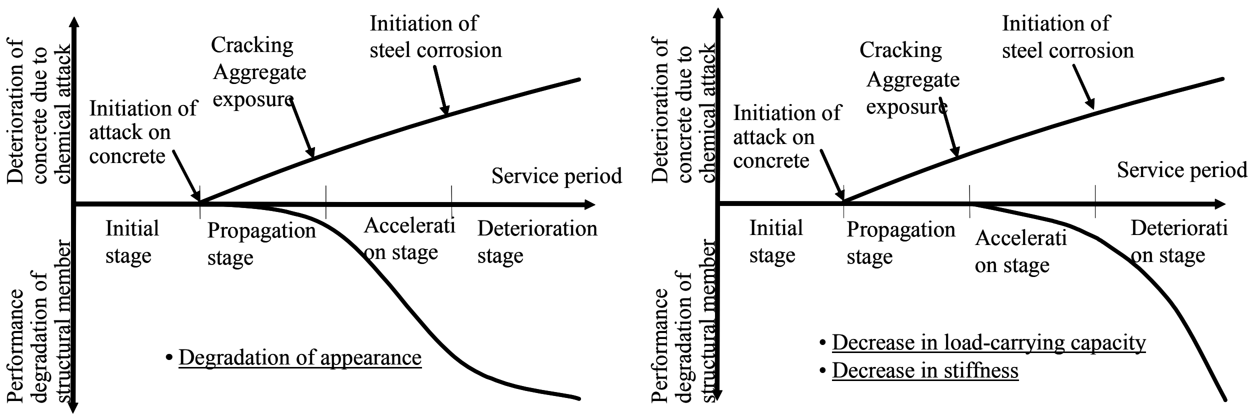
CHAPTER 12 MAINTENANCE OF STRUCTURES SUBJECT TO CHEMICAL ATTACK

12.1 General

(1) This chapter provides standard methods for the maintenance planning, assessment, remedial measures and recording for structures that have been or are highly likely to be subject to performance degradation due to chemical attack. The items common to all deterioration mechanisms are shown in Part 1.

(2) This chapter shall be applied to structures of the maintenance categories A (preventive maintenance) and B (corrective maintenance).

[Commentary] (1) Chemical attack can be classified, according to the mechanism of chemical attack, into major two types. One is the deterioration mechanism of concrete that occurs when cement hydrates and chemically aggressive substances react and turn hydrates into soluble substances. This type of chemical attack is caused by a majority of acids, inorganic salts, and corrosive gases such as hydrogen sulfide and sulfurous acid gas. The other is the deterioration mechanism of concrete caused by expansion pressure generated by expansive compounds produced when cement hydrates in the concrete react with substances that cause chemical attack. This type of chemical attack is caused by sulfate salts. Deterioration phenomena occur in sewer systems, chemical plants, other structures located in hot spring resorts, acidic rivers and acidic/sulfuric soil areas, water treatment facilities and water utilization facilities where leaching of alkalis from concrete is caused by contact with soft water, structures where de-icing salts are applied, and structures exposed to seawater. As chemically aggressive environments, this chapter deals mainly with sewer-related facilities, hot spring resorts, acidic rivers, etc., that are subject to acidic deterioration by sulfuric acid and soils subject to deterioration by sulfate salts. For information about structures subject to chloride attack caused by deicing agents, it is advisable to refer to **Chapter 10** "Maintenance of Structures Subject to Chloride Attack."



(a) Deterioration in terms of appearance (b) Deterioration in terms of safety

Fig. C12.1.1 Conceptual view of deterioration progress due to chemical attack

As shown in Fig. C12.1.1 and Table C12.1.1, the deterioration process of a structure due to chemical attack and resultant steel corrosion can be divided into the initiation, propagation, acceleration and deterioration stages. Because the influence of deterioration phenomena on structural performance varies according to the deterioration progress, methods for assessment (investigation, prediction of deterioration progress, evaluation and judgment), remedial measures and recording also vary from stage to stage. A structure in a chemically aggressive environment may have a protective layer over its concrete surface. The deterioration stages are defined differently, therefore, depending on the presence or nonpresence of protective layers.

Fig. C12.1.2 shows a standard procedure for maintenance in a chemically aggressive environment.

Table C12.1.1 Definition of deterioration stages

~~Deterioration stage~~Stage of deterioration	Definition in a structure without protect layer	Definition in a structure with protective layer over concrete	Factors determining the stage
Initial stage	Period until the alteration of concrete due to ingress of chemically aggressive substances into concrete	Period until the alteration of underlying concrete due to ingress of chemically aggressive substances through the protective layer	Rate of ingress of chemically aggressive substances into concrete or protective layer over concrete
Propagation stage	Period until the aggregates in the concrete are exposed and begin to peel off		Rate of concrete erosion
Acceleration stage	Period until initiation of steel corrosion due to the increase of deteriorated depth by chemical attack and reach of deterioration factors to steel reinforcement		Rate of concrete erosion
Deterioration stage	Stage in which load bearing capacity is reduced considerably due to loss of cross sectionof concrete or steel, etc.		Rate of concrete erosion Rate of corrosion of steel

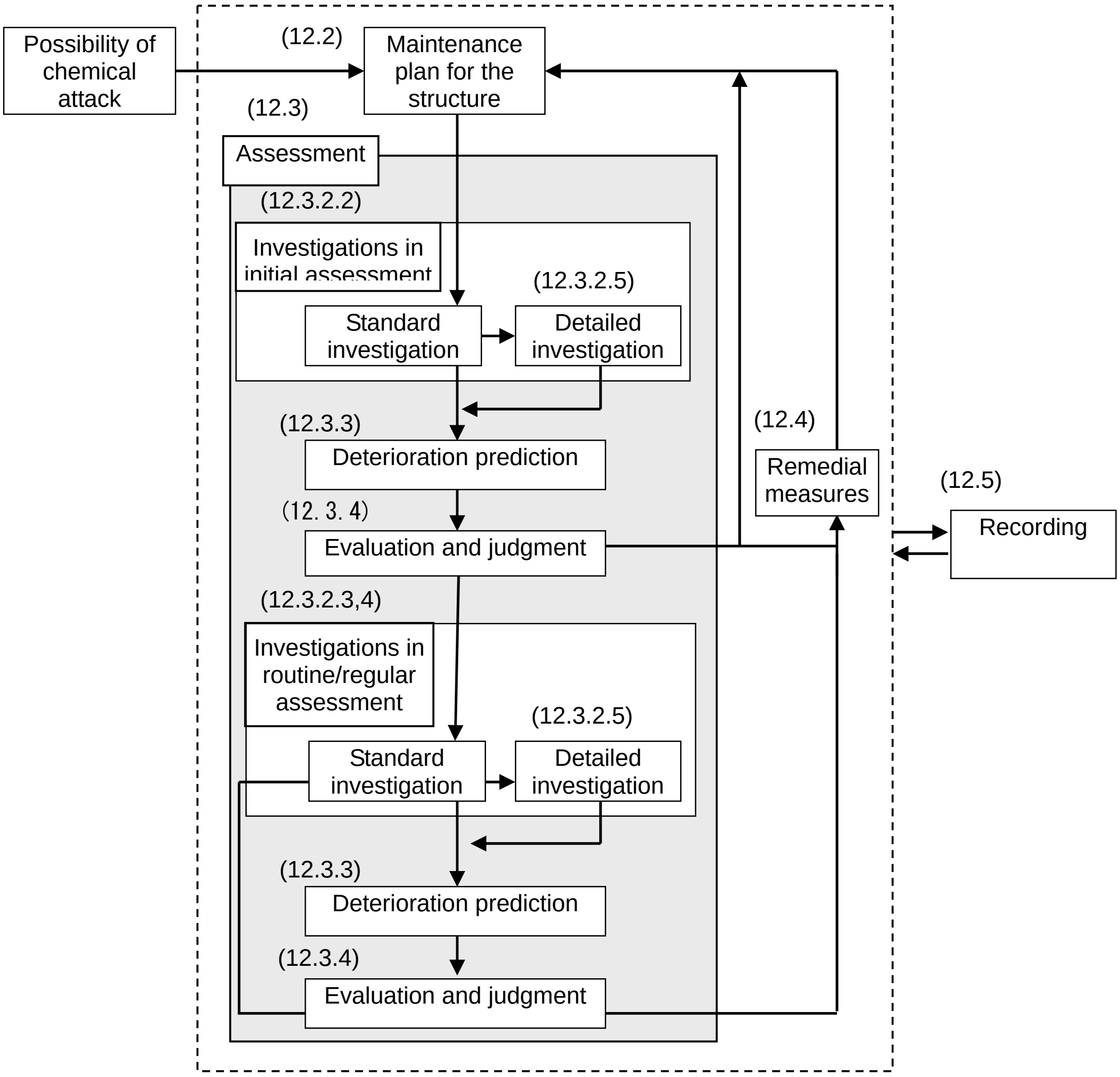


Fig. C12.1.2 Standard maintenance procedure against chemical attack

In the application of this chapter, it should be refered to Present State of and Upcoming Trends in Research on Reinforcing Steel Corrosion and Corrosion-proofing and Repairs I/II (Concrete Engineering Series 26), Present State of Research on Chemical Attack on Concrete and Leaching (Concrete Engineering Series 53), Report of the Committee on Material Design Support Systems (Japan Concrete Institute), Report of the Committee on Long-term Performance Verification Support Model for Concrete Structures (Japan Concrete Institute) and Guidelines for Corrosion Control Technology and Corrosion Prevention Technology for Concrete Structures of Sewerage Systems (Japan Sewage Works Agency).

(2) This maintenance standard is applicable to Type A maintenance (preventive maintenance) and Type B maintenance (corrective maintenance). At present, Type B maintenance is applied to many existing structures. In the coming years, however, structures in the Type A maintenance category (for example, sewerage facilities for which corrosion prevention measures such as surface protection are taken from the construction stage) are expected to increase. Structures in the Type C maintenance category (observational maintenance) should also be maintained with reference to this chapter.

12.2 Maintenance Planning

12.2.1 Basis of planning

In order to maintain a structure subject to chemical attack, the category of maintenance plan shall be selected, the service period planned, and a maintenance planning for activities including assessment, remedial measures and recording drawn up in advance in view of the service and environmental conditions such as the condition for supplying substances causing chemical attack.

[Commentary] When drawing up a maintenance plan, it is necessary to cover such details as check items and procedures for the initial assessment and check items, procedures, timing and frequency for routine and rugular assessments, methods for evaluation and judgment, action to be taken in the event of deterioration, and recording methods, taking into consideration the type, degree of importance and planned service period of the structure, category of maintenance, and the quality of materials.

The structure formalization, size and environmental conditions of concrete structures vary from structure to structure. A maintenance plan to be applied to a structure must be optimized for each structure. Drainage and exhaust equipment at chemical plants or sewer system often creates closed environments that could be filled with harmful gases or steam because vents and other ventilation devices could release obnoxious odors to cause complaints from neighbors. In those facilities, it is difficult to inspect frequently because ventilation or drainage of incoming water is necessary to carry out investigations, and sometimes considerable performance degradation has already been found when an investigation is conducted. Surface protection measures are often taken for a structure in a chemically aggressive environment, so the deterioration of protective materials should be considered in the maintenance.

It is usually difficult, at the stage of maintenance planning, to accurately predict the state of a structure during its service period. It is, therefore, good practice to draw up a maintenance planning with reference to the deterioration of a similar structure or a structure in a similar environment.

12.2.2 Determination of maintenance category

The category of maintenance of a structure subject to chemical attack shall be selected in view of importance of the structure, the type of structure, hazards for third party, the planned service period and the characteristics of deterioration due to chemical attack.

[Commentary] The determination of the category of maintenance is very important because maintenance plans vary widely depending on the category of maintenance. The progress of deterioration and the performance degradation due to chemical attack are conceptually illustrated in Fig. C12.1.1.

Structures to which maintenance category A (preventive maintenance) is applied should by maintained to prevent alteration of concrete, that is, at the initiation stage, regardless of the presence of a protective layer over the concrete. The state of the structure should therefore be identified as accurately as possible. To cope with deterioration due to chemical attack, requirements include the following:

(i) Quantitative evaluation of the supply of substances that cause chemical attack on the surface of the structure

(ii) Quantitative determination and prediction of the deterioration of the protective layer over the concrete

(iii) Quantitative determination and prediction of the intrusion and accumulation of substances that cause chemical attack in the concrete

(iv) Determination and prediction of the occurrence or nonoccurrence of corrosion of the steel in the concrete

Structures to which maintenance category B (corrective maintenance) is applied should be maintained so as to prevent tthe performance of the structure from failing to meet the requirements. For example, maintenance is performed so that deterioration can be prevented until the deterioration stage if attention is paid to safety and serviceability, until the acceleration stage if attention is paid to third party impact or until the propagation stage if attention is paid to appearance. Certain actions should be taken when any of the following types of deterioration has been detected:

(i) Deterioration of the protective layer over the concrete is observed.

(ii) Concrete surface deterioration is observed.

(iii) A loss in cross-sectional area or cracking is observed at the concrete surface.

(iv) Corrosion of steel in the concrete is observed.

Once concrete erosion is initiated, it is extremely difficult to stop the progress of deterioration. It is desirable, therefore, that repair is done at phase (i) or phase (ii) mentioned above even in the case of a structure to which maintenance category B (corrective maintenance) is applied. It should be noted that large-scale measures will be required if deterioration reaches phase (iii) or (iv).

It is common practice to apply a single category of maintenance to a single structure. There are cases, however, where it is more reasonable to apply different types of maintenance to different parts or members of a structure. For example, there may be a case where maintenance category A (preventive maintenance) is applied to the piers of a bridge located at a site where soil contains sulfate salts, and maintenance category B (corrective maintenance) is applied to the girders.

12.2.3 Preparation of maintenance manuals

A maintenance manual describing methods, procedures and frequency requirements should be prepared for each structure in accordance with the maintenance planning, taking the structure-specific conditions into consideration.

[Commentary] The service period of civil engineering structures is long, and maintenance of those structures is performed over a long period of time. It is recommended, therefore, that in order to inform investigation personnel of maintenance concepts and policies, a maintenance manual be prepared so that detailed procedures and methods can be communicated accurately even to newly assigned maintenance engineers.

Under certain circumstances such as in cases where the original maintenance plan is altered because the actual progress of deterioration turned out to differ from that assumed in the original maintenance plan, it may be necessary to modify the maintenance manual and take appropriate maintenance measures accordingly.

12.3 Assessment

12.3.1 General

In the assessment of a structure whose performance has been declined or is highly likely to decline because of chemical attack, investigation, evaluation of the present state, prediction of deterioration and judgment of the necessity for remedial measures shall be appropriately conducted in accordance with the maintenance planning.

[Commentary] In order to maintain concrete structures appropriately, this Specification requires three types of assessment: initial assessment, periodic assessment and extraordinary assessment. Because the initial and periodic assessments are essential for the maintenance of structures in a chemically aggressive environment, this chapter stipulates that those assessments must be conducted. Extraordinary assessments are regarded as assessments to be conducted on an as-needed basis and are therefore not dealt with in this chapter. By conducting periodic assessments during the maintenance period, anomalies in appearance of structures can be discovered before they occur or in early stages, and remedial measures including preventive measures and repairs can be taken systematically.

12.3.2 Investigation in assessment

12.3.2.1 General

Investigations in initial, routine and regular assessment of a structure subject to chemical attack shall be conducted appropriately according to the category of maintenance required for the structure. Prior to investigation, check items, methods, frequency and scope of standard investigations shall be determined appropriately. For each type of assessment, detailed investigations shall also be conducted on as-needed basis.

[Commentary] It is important to select check items, methods, frequency and scope of investigation appropriately according to the purpose of investigation in accordance with the maintenance planning.

Items that need to be ascertained through investigation in connection with a structure in a chemically aggressive environment are the type and concentration of chemically aggressive substances, the infiltration depth of chemically aggressive substances, the depth of concrete erosion, the depth of carbonation, and the corrosion of internal steel. In the event of severe deterioration, investigation for the purpose of directly evaluating structural performance needs to be conducted.

Check items in investigation varies with the degree of deterioration. If the deterioration of the structure is judged or inferred to be at the initiation stage, mainly investigations for determining the infiltration of chemically aggressive substances or the progress of chemical attack on the protective layer over the concrete need to be conducted. If the deterioration of the structure is judged or inferred to be at the propagation stage, mainly investigations for determining the progress of chemical attack on the concrete need to be conducted. If the deterioration of the structure is judged or inferred to be at the deterioration stage, mainly investigations for determining the progress of steel corrosion need to be conducted. Table C12.3.1 lists main check items at different stages of deterioration. It is desirable that data concerning check items related to deterioration prediction, such as the type, concentration and infiltration depth of chemically aggressive substances, anomalies in appearance, and reinforcing steel locations, among the check items necessary for deterioration prediction be collected at the earliest possible stage. Monitoring of a structure to which Type A maintenance (preventive maintenance) is applied may be conducted to continually check on the occurrence of hydrogen sulfide gas or the occurrence of rust on the steel in the concrete.

The frequency and scope of investigation must be determined in view of such factors as the category of maintenance required for the structure, environmental conditions, the type of structure and the state of deterioration. For example, places prone to the generation of hydrogen sulfide gas such as the gas-phase and mixed-phase zones and diameter-change sections of sewer conduits are prone to chemical attack.

Regardless of the category of maintenance, it is important to go through the design drawings and specifications, construction records, investigation results and the repair history prior to the investigation of a structure.

If the state of a structure cannot be judged appropriately, a detailed investigation must be conducted.

Table C12.3.1 Main check items in investigation

Stage of deterioration	Initiation	Propagation	Acceleration	Deterioration
Defective appearance	O	O	O	O
Type and concentration of chemically aggressive substance	O	O	O	▲
Depth of deterioration by chemical attack	O	O	O	▲
Carbonation depth	O	O	O	▲
Steel corrosion	▲□*□	▲□*□	▲	O
Concrete strength	▲□	▲	O	O
Load bearing capacity	□▲□*	▲□*	□	▲
Bar location	O	□	▲□*□	▲□*□
Monitoring	▲□*□	▲□*□	▲□*	▲□*□

O: Itemes to be investigated on a priority basis
▲:□ Items that should preferably be investigated
□□□▲□*□: Items to be investigated on an as-needed basis

12.3.2.2 Investigaion in iitial assessment

(1) In initial assessment, appropriate check items for standard investigation shall be selected for newly constructed structures, existing structures, large-scale repairs and

strengthned stuructures.

(2) If deterioration prediction, evaluation or judgment is difficult to make through a standard investigation alone, detailed investigations shall be conducted.

[Commentary] (1) Investigation in the initial assessment is the first investigation conducted when the maintenance of a concrete structure is started. Investigation in the initial assessment includes not only the first investigation of a newly constructed structure conducted before it goes into service but also the first investigation of an existing structure or a structure for which remedial measures have been taken in response to deterioration. Check items for the investigation may vary from structure to structure. Basic check items for standard investigations in the initial assessment of a newly constructed structure are the document serch on the design drawings, specifications and construction records, and visual ovservation. It is good practice to check on such details as concrete cover, the state of steel and porosity through nondestructive testing on an as-needed basis. When investigating a structure for which remedial measures have been taken, it is also important to check for problems in repaired or strengthened parts of the structure. These should be included in chck items of standard investigations. When an existing structure is inspected, check items are similar to those for a newly constructed structure if design and construction records exist. If there is no such record, it is necessary to select check items of standard investigation with reference to **12.3.2.5** “Detailed Investigation.” In cases where a prediction needs to be made with high accuracy about a structure to which Type maintenance category A (preventive maintenance) is applied, it is necessary to conduct investigations concerning the parameters used for the method described in **12.3.3** “Methods for Estimating Degradation of Performance of Structures.”

Extremely important items in the investigation in the initial assessment of a structure subject to chemical attack are listed below.

(i) Environmental conditions

(ii) Presence or nonpresence and type of protective layer over concrete

(iii) Type of cement

(iv) Mix proportions for concrete, particularly water/cementitious material ratio

(v) Use or nonuse, type and quantity of admixture

(vi) Concrete cover

(vii) Initial defects

(viii) The condition of repaired or reinforced parts

Among the items listed above, Item (i) is an item essential for the prediction of the progress of chemical attack, and it is necessary to check on the type and concentration of the chemically aggressive substance in addition to temperature and humidity. It is also important to identify the configuration of the structure and the environmental conditions. In the case of an unventilated sewer system, for example, the ceiling of the conduit becomes prone to condensation as humidity rises under the influence of sewage, and the deterioration of the ceiling zone is accelerated because the condensate contains sulfuric acid. In sewers, deterioration tends to become intense in the mixed-phase zone and in diameter-change sections. Item (ii) is important for predicting the progress of deterioration at the initiation stage. Items (iii), (iv) and (v) are important for evaluating predictions of the infiltration rate of a chemically aggressive substance and the rate of carbonation. Item (vi) is important as a factor affecting the initiation and rate of steel corrosion. Concrete cover needs to be checked because cover concrete may not have been placed as designed. Item (vii) greatly affects the durability of the structure with or without chemical attack, so it is important to discover initial defects during the investigation. For Item (viii), it is important to check whether there is any change in the state of a repaired or reinforced part and, if any, determine the state of that change (for example, peeling or detachment of surface protection materials).

(2) If evaluation and judgment cannot be made with high accuracy by standard investigations alone, detailed investigations are necessary. Check items of detailed investigations are indicated in **12.3.2.5** "Detailed Investigation."

12.3.2.3 Investigation in routine assessment

(1) In routine assessment, standard investigation shall be conducted to detect not only the defect of protect layer over concrete such as deterioration, cracking, scaling, spalling and the defect of concrete surface such as cracking, scaling, spalling, stain of rust, efflorescence, but also water leakage, deterioration in appearance such as displacement and deformation, and abnormal odors.

(2) If deterioration prediction, evaluation or judgment is difficult through standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) The purpose of investigation in routine assessment is to detect deterioration at an early stage by checking on anomalies in the state of a structure over time. The determination of the time at which deterioration began in order to obtain information that is useful for predicting deterioration is another important purpose of the investigation. In the investigation, focus should be placed on deterioration phenomena or signs of deterioration, such as anomalies of the surface of the protective layer over the concrete (e.g., alteration, cracking, scaling, spalling), concrete surface anomalies (e.g., alteration, cracking, scaling, spalling, rusty water, free lime), water leaks, displacement and deformation, and obnoxious odors.

In the case of chemical plant facilities and underground structures, deterioration may be triggered by synthesized organic acids or organic acids generated by the metabolism of microorganisms. The presence of organic acids can often be detected by odors. Since, however, organic acids, hydrogen sulfide and sulfuric acid could have adverse effects on human health, gas concentration must be measured prior to the investigation in a closed environment. Depending on circumstances, it may be necessary to install ventilation equipment or wear a gas mask and protective clothing.

Because a protective layer over concrete is by far more resistant to chemical attack than concrete, it is desirable that the occurrence of deterioration due to chemical attack be detected prior to the propagation stage. However, investigation in routine assessments usually depends mainly on visual observation, and it is difficult to make evaluation or judgment on the basis of investigation results. As for the structures to which maintenance category A (preventive maintenance) is applied, the evaluation of their performance should be conducted in conjunction with appropriate monitoring. It is important to determine whether chemically aggressive substances exist in advance by, for example, measuring changes in the type and concentration of the gases and liquids in contact with the structure with gas concentration meters or ion concentration meters. In the case of sewer-related facilities, the timing of monitoring needs to be determined appropriately because the type and concentration of the gases and liquids in the structure vary considerably depending on the rate of inflow and time. It is good practice to make a test specimen with a protective layer and concrete identical to those of a real structure, expose the specimen to the same environment as the environment of the real structure and measure the infiltration depth of chemically aggressive substances, chemical penetration depth, and the progress of steel corrosion. Intensive investigation in the sections where deterioration was expected to progress as a result of the initial assessment is also effective.

(2) If high-accuracy evaluation or judgment is difficult to make by results of standard investigations or if severe deterioration has already occurred, a detailed investigation is conducted. Check items of a detailed investigation are described in detail in Section **12.3.2.5** "Detailed Investigation."

12.3.2.4 Investigation in regular assessment

(1) The purpose of investigation in regular assessment is to obtain information that is difficult to obtain in routine assessment. In regular assessment, standard investigation consisting of detailed observation of defects shall be conducted as in routine assessment.

(2) If deterioration prediction, evaluation or judgment is difficult through standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) Investigations in regular assessment is conducted for obtaining information more detailed than the in routine assessment. Areas where signs of defects or deterioration have been detected in the initial or a routine assessment need to be examined intensively. The appearance of the structure should basically be examined as in routine assessment. Investigations of theinfiltration depth of chemically aggressive substances, the depth of carbonation and the state of steel corrosion may sometimes become necessary in addition to the examination of the appearance of the structure.

In order to predict the progress of deterioration due to chemical attack with high accuracy in rugular assessment, it is good practice to take measurements three to five times at equal intervals during the expected stages of initiation, propagation, acceleration and deterioration.

In the structures to which maintenance category A (preventive maintenance) is applied, it is good practice to increase measurement frequency during the expected stages of initiation and propagation.

(2) If high-accuracy evaluation or judgment is difficult by conducting standard investigation alone, detailed investigations are conducted. Check items of detailed investigations are described in detail in **12.3.2.5** "Detailed Investigation."

12.3.2.5 Detailed investigation

Detailed investigation shall be conducted to obtain detailed information on a structure subject to chemical attack in cases where the deterioration of the structure is difficult to predict, evaluate or judge by standard investigation alone in initial, routine or regular assessment. Check items, methods and location of detailed investigation shall be selected appropriately taking into consideration such factors as the purpose of investigation and the accuracy of obtained results.

[Commentary] A detailed investigation is conducted when the determination of the present state of a structure and the deterioration of the structure are difficult by results of standard investigations in order to obtain information necessary for those purposes. Examples of investigation items for structures subject to chemical attack, and of data on the condition of the structure at the time of investigation and those in the future estimated from the investigation results are listed in Table C12.3.2. The "evaluation item predictable from obtained data" in the table can be evaluated after deterioration is predicted.

Table C12.3.2 lists check items for evaluating anomalies in the state of concrete and steel. It is recommended that evaluators of anomalies in the state of concrete structures with surface protection refer to the investigation and evaluation items indicated in the Recommendations for Concrete Repair and Surface Protection of Concrete Structures.

Major check items are outlined below. For other measurement items and test methods than those described below, refer **4.7.3** “Methods for Investigation.”

(i) pH and concentration of a solution containing a chemically aggressive substance

In cases where liquid in contact with a structure is causing chemical attack, pH can be measured with a pH meter and the concentration of the chemically aggressive substance can be measured by high performance liquid chromatography or ion chromatography by taking liquid samples. In the case of liquid containing sulfuric acid ions, concentration measurement can be done with relative ease by the settling process using barium chloride.

Table C12.3.2 Examples of evaluation items in detailed investigation

Measurement item	Data obtainable by investigation	Evaluation items predicable from obtained data
Chemical substances pH, temperature and humidity in underground water, soil and air	Rate of ingress of chemically aggressive substances and deterioration by chemical attack	Rate of ingress of chemically aggressive substances, Deterioration depth by chemical attack, Corrosion rate
Depth of ingress of chemically aggressive substances	Rate of ingress of chemically aggressive substances (e.g., EPMA), grade in appearance	Rate of ingress of chemically aggressive substances, Deterioration depth by chemical attacak, Corrosion rate
Cracking (width, depth and density)	Rate of deterioration by chemical attack, grade in appearance, and aesthetic appearance	Rate of ingress of chemically aggressive substances, Carbonation rate, Corrosion rate and Aesthetic appearance
Lack of section of concrete	Rate of ingress of chemically aggressive substances and deterioration by chemical attack,and aesthetic appearance	Rate of ingress of chemically aggressive substances, Deterioration depth by chemical attack, Time of initiation of corrosion
hammer tapping test	Grade in appearance, defect	Concrete strength
Discoloration, efflorescence	Grade in appearance, aesthetic appearance	Aesthetic appearance
Carbonation depth	Carbonation rate, rate of ingress of chemically aggressive substances	Carbonation rate, Rate of ingress of chemically aggressive substances, Time of initiation of corrosion
Locations and state of steel (area, quantity)	Grade in appearance, amount of corrosion, load bearing capacity	Corrosion rate, Load bearing capacity
Electrochemical indicators (e.g., half-cell potential, polarization resistance, electric resistance)	Initiation of corrosion, corrosion rate	Future grade of corrosion, corrosion rate
Concrete strength and modulus of elasticity	Concrete strength and stiffness	Concrete strength, Load bearing capacity
Deflection and displacement	Stiffness and load bearing capacity	Stiffness, Load bearing capacity

(ii) Infiltration depth of chemically aggressive substance

It is desirable that the infiltration depth of chemically aggressive substances be determined qualitatively and quantitatively through chemical analysis or instrumental analysis. The reason is that performing an analysis by using an electron probe micro-analyzer (EPMA) is an effective method of investigating the type and distribution of chemically aggressive substances. For example, the distribution of ettringite can be evaluated through image processing from the distribution of calcium (Ca), aluminum (Al) and sulfur (S). Further information on EPMA analysis can be found in JSCE-G 574-2005, Method of Area Analysis of Regions in Concrete by the EPMA Method.

(iii) Appearance of structure

If the state of concrete and steel is not directly related to the performance of the structure, anomalies in appearance provide useful information for performance evaluation. It is necessary to investigate not only anomalies in the state of the protective layer over the concrete, cracks in the concrete, loss of concrete cross section, discoloration, efflorescence and the state of steel corrosion but also anomalies in the state of the environment such as land subsidence. When estimating the progress of deterioration, it is desirable that not only anomalies in appearance but also chemical penetration depth as indicated by cross-sectional loss, cracks, etc., be investigated. Appearance grades of a structure whose performance has deteriorated because of chemical attack are shown in Table C12.3.3.

Table C12.3.3 Grades of structural appearance and stagte of deterioration

Grade of appearance of structure	States of deterioration of a structure without protective layer	States of deterioration of a structure with protective layer
I (initiation stage)	Period until the deterioration of surface concrete begins; no defect of appearance is found.	While chemically aggressive substances have entered the protective layer, no defect of appeareance is found.
II (0ropagation stage)	Rough or cracked concrete surface is found.	Defects of the protective layer have been found and deterioration of underlying concrete has been initiated.
III (acceleration stage)	Cracking or lack of cross section of concrete is so severe as to cause the aggregate to be exposed or to be peeled off.	
IV (deterioration stage)	Cracking or lack of cross section of concrete has reached the reinforcing steel, and displacement and deflection of the structure is considerable due to decreases of cross-sectional area of steel, etc.	

(iv) Carbonation depth

In the case of chemical attack by acids, the carbonation depth of concrete can be used as an indicator of penetration depth. It should be kept in mind, however, that a chemical aggressive substance has already penetrated to a level deeper than the carbonation zone. The measuring method must be in accordance with **Chapter 9** "Maintenance of Structures Subject to Carbonation." The ph of a typical carbonation zone identified through measurement in a structure subject to carbonation ranges from about 8.2 to 10. In the case of carbonation due to chemical attack, pH levels of pore solutions of 7 and lower are measured.

(v) Steel corrosion

Corrosion of reinforcing steel used in a structure tends to affect the performance of the structure. It is therefore good practice to chip off the cover concrete so that the reinforcing steel is exposed and measure the state, location, area and mass of corrosion, pitting corrosion depth, etc. By obtaining quantitative data on corrosion, the performance degradation of the structure can be evaluated quantitatively.

In cases where steel corrosion is monitored, electrochemical indicators such as self-potential and polarization resistance are measured. These values, however, are affected by the state of concrete including the water content and the composition of pore solutions. Information helpful in determining the measuring method can be found in Section **4.7.3** “Methods for Investigation.” Care should be taken when applying an electrochemical method to steel corrosion due to chemical attack because application to chemical attack is less proven than application to chloride attack or carbonation and there are no established evaluation criteria.

12.3.3 Methods for predicting performance degradation of structures

12.3.3.1 General

(1) In the maintenance of a structure subject to chemical attack, the performance of the structure shall be evaluated quantitatively at the time of investigation, and future degradation shall be predicted.

(2) In order to predict the performance degradation of a structure, deterioration due to chemical attack shall be predicted quantitatively.

(3) If (2) is difficult, an alternative method is to predict performance degradation by estimating the length of initiation, propagation, acceleration and deterioration stages, taking the progress of erosion in the protective layer and concrete due to chemical attack and the steel corrosion into consideration.

(4) Deterioration shall be predicted on the basis of investigation results.

[Commentary] (1) and (2) In the performance-verification type maintenance method, anomalies (degradation) in various performance attributes of a structure are to be predicted. In order to do that, it is necessary to quantitatively predict the deterioration of the materials used in the structure subject to chemical attack, namely, chemical penetration into the concrete and the progress of corrosion of the steel in the concrete. It is also necessary to quantitatively evaluate the performance of the structure and the degree of deterioration of the materials used in the structure at the time of investigation and at the end of the planned service period on the basis of investigation results. The performance degradation of the structure or the degree of deterioration of the constituent materials at the time of investigation can be evaluated by using an appropriate method on the basis of the investigation results. Performance and the degree of deterioration at the end of the planned service period are estimated on the basis of the investigation results in periodic assessments. Because the deterioration estimation results do not necessarily agree with the actual progress of deterioration, it is important to review the estimation method on the basis of the results of multiple investigations conducted thereafter.

(3) In cases where the deterioration of the concrete and steel used in a structure are predicted, and various performance attributes of the structure are evaluated by combining the results thus obtained, it is not easy, at the present level of technology, to make quantitative predictions. A practical method, therefore, is to estimate the length of the initiation, propagation, acceleration and deterioration stages by taking into consideration the infiltration of chemically aggressive substances

into the concrete and the progress of concrete penetration and steel corrosion. The deterioration stages and factors determining their length are listed in Table C12.1.1.

The length of the initiation stage is calculated from the rate of penetration of the protective layer or the underlying concrete by the gas or liquid containing a chemically aggressive substance; the length of the propagation stage and the acceleration stage, from the rate of penetration of the concrete by a chemically aggressive substance; and the length of the deterioration stage, from the rate of steel corrosion and the amount of corrosion of the steel whose load-carrying capacity decreases. These calculations must be made in accordance with Section **12.3.3.2** "Prediction of Chemical Erosion", and Section **12.3.3.3** "Prediction of Steel Corrosion."

(4) Investigation results can be classified into two types: one type concerns the quality of the protective layer and the underlying concrete used in the inspected structure and the other concerns the environment in which the structure is used. As a general rule, deterioration must be estimated by analyzing these investigation results. If no information is available on environmental conditions as in the case of a newly constructed structure or if investigation results are not available for an existing structure, investigation results for adjacent structures or structures in similar environments may be used for reference purposes.

12.3.3.2 Prediction of chemical erosion

(1) The progress of chemical erosion shall be predicted considering the quality of protective layer and concrete and the environment in which the structure is in service.

(2) The progress of chemical erosion may be predicted by one of the following methods.

(i) Use of investigation results

(ii) Use of accelerated tests

(iii)Use of numerical analyses considering the reaction of chemically aggressive substances and their movement at the boundary with the environment

[Commentary] (1) The prediction of chemical erosion is important for accurate estimation of the initiation, propagation and acceleration stages. The rate of chemical erosion varies considerably depending on the type and concentration of the chemically aggressive substance concerned and the quality of concrete. Usually, the chemically aggressive substance has already reached a region deeper than the altered region and exists in high concentrations. When predicting the progress of chemical erosion, therefore, it is necessary to distinguish the penetration depth in the concrete from the infiltration depth of the chemically aggressive substance. Since, however, what can be observed visually or otherwise are anomalies in appearance of the concrete, it is desirable that the penetration depth in the concrete be estimated in order to predict the progress of chemical erosion. If a more detailed prediction is to be made, other indicators such as the infiltration depth of the chemically aggressive substance and the depth of carbonation should also be estimated. In the case of an underground structure, the environment of the structure needs to be appropriately taken into consideration because other chemically aggressive substances of different types and concentrations may infiltrate from the inner and outer parts of the structure.

In cases where a resin or other protective layer is provided over the concrete surface, not only the quality of concrete but also the quality of the protective layer material must be taken into consideration when estimating the progress of deterioration.

When making a prediction, it is necessary to use an appropriate factor of safety, taking into consideration the setting methods for the parameters used, the variability of the quality of the structure and the influence of the environmental conditions.

(2) Commonly used methods for predicting the progress of chemical erosion can be broadly classified into three types:

(i) Use of investigation results

Penetration depth of chemically aggressive substance in concrete may be proportional to the square root of time or to time, depending on the type and quantity of the chemically aggressive substance concerned.

Under conditions not conducive to separation or in the case of deterioration due to sulfate salts in a soil environment or in an environment without water flow, the penetration rate is in many cases proportional to the square root of time, as in the case of the infiltration rate of a chemically aggressive substance. Penetration depth in such cases can be expressed as

$$y = \gamma_c (a \cdot \sqrt{t} + b) \qquad \text{(Eq. C12.3.1)}$$

where

y: penetration depth in concrete (mm)

t: duration of exposure to chemically aggressive substance (year)

a: concrete penetration rate factor (mm/$\sqrt{year}$)

b: coefficient (deterioration from initial stage: b =0)

γ_c: factor of safety related to accuracy of prediction

In the equation shown above, γ_c, which is a factor of safety related to prediction accuracy, needs to be determined taking into account the variability of structures and the variability of the coefficient a, which is affected by environmental conditions. In general, 1.0 may be used.

Under conditions conducive to separation or in the case of deterioration due to acidic substances in an environment with water flow such as a water channel, the penetration rate is in many cases proportional to time. It is generally known that in the case of a sewer pipe, the concentration of hydrogen sulfide in the gas phase in the pipe is proportional to the penetration rate. The penetration depth in such cases can be expressed as

$$y = \gamma_c (c \cdot t + d) \qquad \text{(Eq. C12.3.2)}$$

where

y: penetration depth in concrete (mm)

t: duration of exposure to chemically aggressive substance (year)

c: concrete penetration rate factor (mm/year), $c = e\,[H_2S] + f$

$[H_2S]$: hydrogen sulfide concentration (ppm)

d, e, f: coefficients (deterioration from initial stage: $d = 0$)

γ_c: factor of safety related to accuracy of prediction

If investigation results include measured values of penetration depth, recommended practice is to determine the concrete penetration rate factor from the measurement results and make subsequent predictions accordingly. In theory, the concrete penetration rate factor can be calculated through one-time measurement. If a highly reliable value is to be obtained, however, it is desirable that the concrete penetration rate factor be calculated by the least squares method after conducting two or three measurements at intervals of several years. It should also be kept in mind that if concrete penetration depth and the penetration rate factor vary considerably with measurement locations in the structure, the penetration rate also varies among different parts of the structure.

If the pH of the solution is close to neutral even in the case of acid-induced deterioration, deterioration-related deposits may delay deterioration by clogging the pores. Chemical attack, therefore, does not necessarily occur as mentioned above. In chemical attack by sulfate salts, penetration depth is not necessarily proportional to the square root of time because the progress of deterioration may be greatly affected, for example, by cracks caused by the expansion of reaction products. If such deterioration is expected, it is necessary to conduct appropriate accelerated deterioration tests.

(ii) Use of accelerated test

In many cases, chemical erosion gradually occurs from the surface of the protective layer or the underlying concrete. Deterioration, therefore, can be easily detected visually. So far, however, no systematic method for predicting the progress of chemical erosion has been proposed. It is therefore desirable that accelerated deterioration tests be conducted under conditions that do not alter the deterioration mechanism of the chemically aggressive substance expected to come into contact with the structure, taking into consideration the environment of the structure, and concrete penetration depth, the infiltration depth of the chemically aggressive substance, etc., be estimated accordingly. This method enables highly reliable estimation but may require long time to obtain results. Method of Test for Chemical Resistance of Concrete in Aggressive Solution proposed by Japan Testing Center for Construction Materials is an informative reference on a test method of this kind.

If an accelerated deterioration test is conducted for a protective layer over concrete, it is desirable that the test be conducted on a protective layer integrated with the concrete. This is for the purpose of accurately evaluating the effect of the interface between the protective layer and the concrete.

(iii) Use numerical analyses considering the reaction of chemically aggressive substances and their movement at the boundary with the environment

A method for predicting the progress of chemical erosion by using a numerical analysis technique that enables quantitative evaluation of the chemical reaction between a chemically aggressive substance and cement hydrates and the resultant changes in properties has been proposed. At present, however, there are not many numerical analysis methods related to chemical erosion on concrete. In the case of sewer conduits, for example, the generation of hydrogen sulfide gas and the quantities of dissolved oxygen and sludge in sewage are among the factors governing the deterioration rate of concrete. In pipe sections with uneven bottoms or in areas where wastewater drops into a pit, a considerable amount of hydrogen sulfide gas is emitted so that the concrete penetration rate increases. It is desirable that an analysis technique capable of allowing for these conditions be used. When analyzing phenomena involving cracking caused by the expansion of reaction products as in deterioration caused by sulfate salts, it is desirable that an analysis capable of allowing for the effect of such phenomena be conducted.

12.3.3.3 Prediction of steel corrosion

(1) The progress of steel corrosion due to chemical attack shall be predicted properly considering the concrete quality and the environment in which the structure is in service.

(2) The initiation of steel corrosion should be determined based on the remaining uncarbonated depth.

(3) The progress of steel corrosion may be predicted by one of the following methods.

(i) Predicting from the investigation results

(ii) Predicting using accelerated tests

[Commentary] (1) In general, chemical attack occurs first at the surface of steel. In a state in which there is concern about steel corrosion, chemical attack has already occurred in the protective layer and the underlying concrete, so the protective layer and the underlying concrete cannot be expected to function as protective shields against steel corrosion. The prediction of steel corrosion due to chemical attack, therefore, is actually the prediction of steel corrosion due to a chemically aggressive substance. Factors affecting the rate of steel corrosion due to chemical attack include the concentration of the chemically aggressive substance at the steel location and the water content of concrete. It is not yet possible, however, to quantitatively evaluate the relationship between these factors and the corrosion rate.

(2) In the case of acid-induced deterioration, deterioration occurs as concrete is attacked by an acid and altered. In general, when concrete is attacked by an acid, the cross-sectional area of the attacked region decreases and carbonation occurs. In the case of deterioration caused by sulfuric acid, therefore, carbonation depth is often used as an easy-to-measure indicator of the infiltration depth of sulfuric acid ions. In the case of deterioration caused by sulfate salts, steel corrosion occurs as the concrete is porositized to cause early carbonation. In both cases, prediction should be based on the penetration depth of the chemically aggressive substance. Since, however, there seems to have been no steel corrosion research focusing on chemical attack and the infiltration depth of a chemically aggressive substance is difficult to measure by a simple method, this specification basically requires that the time of initiation of steel corrosion be judged in terms of the remaining

non-carbonated cover thickness.

There seems, however, to have been no research, either, on the relationship between the remaining non-carbonated cover thickness and the initiation of steel corrosion from the viewpoint of chemical attack. It is therefore necessary to identify the relationship between the remaining non-carbonated cover thickness and the time of initiation of steel corrosion through investigations or through accelerated deterioration tests that appropriately take into consideration the type of steel and the environmental conditions under which the structure of interest is to be used.

(3) Steel corrosion due to chemical attack tends to be by far faster than steel corrosion due to other deterioration mechanisms. The progress of steel corrosion due to chemical attack, therefore, must be estimated by one or more of the following methods:

(i) Method based on corrosion rates obtained as investigation results

If the rate of corrosion has been measured over time, the progress of corrosion can be predicted by regressing the measurement results. The shape of curves showing time-dependent changes in the rate of steel corrosion due to chemical attack varies depending on the type and concentration of the chemically aggressive substance concerned. It is desirable, therefore, that the corrosion rate be estimated from the corrosion rate–time curves by using corrosion rate measurements taken at three or more material ages.

(ii) Method using accelerated tests

If investigation results are not available, it is desirable that the corrosion rate be predicted through accelerated deterioration testing in due consideration of the type of steel and the environmental conditions under which the structure is placed.

At the deterioration stage, it is necessary to evaluate load-carrying capacity by appropriately evaluating the loss of the cross-sectional area of concrete, the steel corrosion rate, anchoring, etc.

12.3.3.4 Modification of prediction

If the state of deterioration determined in an investigation differs from a predicted state of deterioration, the cause of the difference shall be identified and the prediction shall be revised accordingly. If necessary, the maintenance planning shall be altered.

[Commentary]　If the state of deterioration determined in an investigation differs from a predicted state of deterioration, an appropriate investigation must be conducted with reference to the deterioration prediction methods described in Section **12.3.3.2** “Prediction of Chemical Erosion”, and Section **12.3.3.3** “Prediction of Steel Corrosion”, and Table C12.3.2 in Section **12.3.2.5** “Detailed Investigaiton”, to identify the cause of the difference from the prediction and revise the prediction accordingly. The results of a number of investigations conducted are useful for identifying the cause of the difference and revising the prediction. It is also important to reconsider such details as the frequency of investigation in view of the revised prediction and alter the maintenance plan if necessary.

12.3.4 Evaluation and judgment

(1) The performance of a structure shall be evaluated and the necessity for remedial measures shall be judged based on the results of the investigation in initial, routine and regular assessments in accordance with Part 1 and Item (2) and subsequent Items in this section.

(2) The performance of a structure subject to chemical attack shall be evaluated by appropriately selecting performance attributes to be evaluated in view of the ~~deterioration stage~~stage of deterioration of the structure.

(3) The evaluation of performance attributes at the time of investigation and at the end of the planned service period of the structure should be made by a quantitative method.

(4) If Item (3) is difficult to achieve, the evaluation of performance attributes at the time of investigation and at the end of the planned service period of the structure may be made by a semi quantitative grading-based method.

(5) The necessity for remedial measures shall be judged in view of the degress of performance degradation due to chemical attack, the degree of importance of the structure, category of maintenance, and the remaining planned service life.

[Commentary] (1) The evaluation of the performance and judgment of necessity for remedial measures in initial, routine and regular assessment for stuructures in which littlie progress of deterioration has been recognized are frequently more ore less the same, regardless of deterioration mechanisms. For details, refer to **Part 1**. The evaluation and judgment for a structure that may be deteriorated to some extent vary with deterioration mechanisms. Evaluation and judgment, therefore, concerning performance degradation due to chemical attack need to be made in accordance with the provisions of this chapter.

(2) In the case of a structure in a chemically aggressive environment, performance attributes affected by deterioration vary depending on the stage of deterioration (initiation stage, propagation stage, acceleration stage or deterioration stage). Performance attributes to be evaluated, therefore, need to be selected appropriately for each stage of deterioration. At the initiation stage, for example, either chemical attack is not visible or the chemically affected zone is within the protective layer over the concrete. The performance attribute to be evaluated, therefore, is the capability of the protective layer, etc., in preventing chemical attack on the concrete. At the propagation stage, appearance and third party impact due to the spalling of the concrete surface or other forms of deterioration need to be evaluated. At the acceleration stage, chemical attack on concrete occurs, so performance attributes such as the stiffness and ductility of structural members under the influence of decreases in cross-sectional area, the serviceability of water channels such as discharge capacity, and the capability of the cover concrete to protect the reinforcing steel are evaluated. In addition, it is also necessary to evaluate third party impact and appearance because deterioration becomes severe. At the deterioration stage, the cross-sectional area of the concrete decreases considerably, and steel corrosion occurs. It is therefore necessary to pay attention to decreases in stiffness and ductility of structural members and safety performance items such as load-carrying capacity. third party impact and appearance degradation due to a partial loss of the cross section of concrete and steel corrosion also need to be evaluated.

(3) The performance of a structure at the time of investigation and at the end of the planned service period needs to be evaluated after the state of deterioration of the constituent materials of

the structure, namely, the concrete protection materials, concrete and steel, is evaluated quantitatively. For example, in the performance evaluation at the time of investigation, safety and serviceability are checked by determining load-carrying capacity, the amount of deflection and the amount of deformation by substituting the dynamic properties obtained from investigation results in the structural calculation equations. It is also possible to verify third party impact and appearance by, for example, evaluating cracks, the extent and density of scaling and spalling and the degree of steel corrosion. By these verification methods, it may be possible to evaluate performance in a relatively straightforward manner at the time of investigation. It is usually difficult, however, to evaluate performance at the end of the planned service period with sufficient accuracy. A reasonable method, therefore, is to supplement such evaluation by verifying durability through deterioration prediction based on the chemical attack rate coefficient and the steel corrosion rate with reference, for example, to the method described in Section **12.3.3** "Methods for Predicting Performance Degradation of Structures." In this case, not only the accuracy of the performance verification method used at the time of investigation but also the accuracy of the deterioration prediction method are important considerations. Prediction methods, therefore, need to be carefully selected, and it is important to allow for a reasonable factor of safety.

(4) In the performance verification type design system, structural performance should ideally be evaluated quantitatively. At present, however, there is no established method for doing it. As a practical method, the performance of a structure at the time of investigation can be evaluated semiquantitatively, with reference to Table C12.3.4, by performing grading in accordance with Table C12.3.3.

The purpose of grading is to classify the present degree of deterioration of a structure semiquantitatively instead of predicting and evaluating the degree of deterioration in future. It is also possible, however, to predict the performance of a structure at the end of the planned service period in accordance with Table C12.3.4 by estimating the stage of deterioration at the end of the planned service period on the basis of investigation results such as the chemical attack rate, the infiltration rate of the chemically aggressive substance, the carbonation rate and the steel corrosion rate.

If detailed maintenance records for a similar structure (type of structure, materials, construction, environment, state of use) are available and the progress of deterioration thus far of the structure of interest is similar to that of the similar structure, then the evaluation results for that structure provide useful information.

(5) Because judgment is the act of deciding whether remedial measures need to be taken on the basis of structural performance evaluation results, there is no difference depending on deterioration factors. Therefore, refer to **Part 1**.

Table C12.3.4 Grades of appearance of structures and typical performance degradation

Grade of appearance of structure	Safety	Serviceability	Hazards for third party	Aesthetic appearance and landscape
I (initiation stage)	—	—	—	—
II (propaga tion stage)	—	—	Hazards for third party • Peeling and spalling of concrete	Degradation of aesthetic appearance • Peeling of protective layer over concrete • Deterionration and cracking of concrete
III (acceleration stage)	Decrease in load bearing capacity • Decrease of cross section of concrete	Decrease in stiffness (increase in deformation, occurrence of vibration) • Decrease in cross section of concrete • Decrease in flow rate, etc.		Degradation of aesthetic appearance • Deterioration and cracking of concrete
IV (deterioration stage)	Decrease in load bearing capacity and ductility • Decrease in cross section of concrete • Decrease in cross section of steel	Decrease in stiffness (increase in deformation, occurrence of vibration) • Deterioration of bond between steel and concrete • Decrease in cross section of concrete • Decrease in cross section of steel		Degradation of aesthetic appearance • Deterioaration and cracking of concrete • Stain of rust • Exposure of steel

12.4 Remedial Measures

12.4.1 Selection of remedial measures

(1) If it has been judged that remedial measures need to be taken in consideration with performance degradation of a structure subject to chemical attack, remedial measures by which the the corrected structure meets the required performances shall be selected.

(2) If it is difficult to select remedial measures for a structure on the basis of performance verification, remedial measures may be selected from the measures corresponding to the grade of appearance.

[Commentary] (1) If it has been judged, as a result of evaluation, that remedial measures need to be taken, it is necessary to select one or more of the following measures: (i) intensified investigation, (ii) repair, (iii) strengthening, (iv) functional improvement, (v) restriction in service or (vi) dismantling/removal. Basically, decisions as to which measures to take should be made by the maintenance manager of the structure, but it is good practice to refer to **Part 1** for information on typical relationships between evaluation and judgment results and remedial measures.

(2) If it is difficult to select remedial measures for a structure through quantitative evaluation or judgment, remedial measures are selected from the measures corresponding to the deterioration grade of the structure. Remedial measures to be taken vary depending on the type of structure, the degree of importance of the structure, deterioration rate and the category of maintenance, but recommended standard measures are shown in Table C12.4.1.

Table C12.4.1 Grades of appearance of structures and remedial measures

Grade of appearance of structure	Intensified invsetigati on	Repair	Strength ening**	Functional improvement	Restriction in service	Dismantli ng/remova l
I (initiation stage)	**O**	**O****	**X**	**X**		
II (propagation stage)	**OO**	**OO**	**X**	**X**		
III (acceleration stage)	**OO**	**OO***	**X**	**X**	**O**	
IV (deterioration stage)		**O***	**X**	**X**	**OO**	**OO**

OO: standard remedial measures [**OO***: including the restoration of mechanical performance]
O: remedial measures in some cases
[**O***: including restoration of mechanical performance, **O****: preventive measures]
X: remedial measures taken based of other criteria other than the grade of appearance
Strengthening**: Enhancing the mechanical performance above the initial level

12.4.2 Repair and strengthening

Methods and materials for the repair or strengthening of a structure shall be selected taking into consideration the performance degradation of the structure due to chemical

attack and life cycle cost, so that the required effect can be achieved.

[Commentary] In cases where repair or strengthening is carried out as a remedial measure, it is necessary to define the expected effect of repair or strengthening and the required performance (what level of performance to be maintained for how many years?). Ideally, it is desirable that remedial measures be taken after constructing a deterioration formula (for repair) or structural calculation formula (for strengthening) in view of such factors as the properties of the materials used and verifying the calculation results obtained from those formulas. In this case, it is also important to take life cycle cost into consideration according to the remaining service life. In cases where preventive maintenance measures are taken for a structure to which Type A maintenance (preventive maintenance) is applied, it is necessary to select an appropriate method in due consideration of the effect expected of the method.

Repair and strengthening methods for structures deteriorated by chemical attack can be classified, according to expected effects, as shown in Table C12.4.2. When deciding on which method to use, it is necessary to take into consideration the present state of performance degradation of the structure concerned besides Table C12.4.2. For the correspondence between appearance deterioration grades and remedial methods, refer to Table C12.4.3.

Table C12.4.2 Expected effects and methods of repair or strengthening

Expected effect	Examle of methods
Control the progress of chemical erosion	Surface treatment (resin lining, sheet lining), FRP adhesion, Embedded form, Ventilation, Washing
Control the progress of steel corrosion	Surface treatment, Patching, Rust-preventing coating
Restore or enhance load-bearing capacity	FRP adhesion, Thickness increasing, Jacketing

Table C12.4.3 Grades of structural appearance and methods of repair or strenghening

Grade of appearance of structure	Standard methods
I (initiation stage)	Surface treatment, Ventilation, Washing
II (propagation stage)	Surface treatment, Patching, Embedded form, Ventilation, Washing
III (acceleration stage)	Patching, Surface treatment, Thickness increasing, Embedded form, ventilation & washing
IV (deterioration stage)	FRP sheet bonding, Patching, Surface treatment, Thickness increasing, Jacketing, Embedded form, Ventilation, Washing

If a structure is at the initiation stage of deterioration due to chemical attack, performance degradation or deterioration has not yet occurred. Structures for which remedial measures are taken at this stage, therefore, are only those to which Type A maintenance (preventive maintenance) is applied. The expected effect in this case is to prevent the infiltration and diffusion of chemically aggressive substances into the concrete. This means that it is necessary to devise surface treatment methods for preventing the penetration of chemically aggressive substances and ventilation and washing methods for preventing the occurrence or attachment of chemically aggressive substances.

If a structure is at the propagation stage, penetration into the concrete has already begun. The degree of penetration, however, is still low, and little degradation of performance has occurred. Remedial measures taken at this stage, therefore, consist mainly of surface treatment as in the case of a structure at the initiation stage.

If a structure is at the acceleration stage, the degradation of mechanical performance is not yet substantial, but the exposure of aggregates near the concrete surface and cracking of concrete have already occurred. It is therefore necessary to consider the use of such measures as cross-sectional restoration and left-in-place form installation.

If a structure is at the deterioration stage and the load-carrying capacity has already decreased, it is necessary to use repair methods for restoring cross sections and load-carrying capacity by, for example, increasing or replacing reinforcing bars, such as FRP sheet bonding, jacketing, overlay or left-in-place formwork methods. In order to prevent the recurrence of deterioration, it is also necessary to apply such methods after removing the deteriorated portions and restoring cross sections.

Many of the repair and strengthening methods in use today were developed in recent years, and some of them have not been field-tested extensively. Those methods might fail to prevent the recurrence of deterioration or achieve the required performance because of factors that could not be expected at the design stage. It is desirable, therefore, that precautionary measures such as increasing investigation frequency be taken after repair or strengthening work is done.

For details of various repair and strengthening methods, refer to, for example, Recommendations for Strengthening of Concrete Structures, Recommendations for Concrete Repair and Surface Protection of Concrete Structures, Report of the Committee on Repair Methods for Concrete Structures (I, II and III) (Japan Concrete Institute), Report of JCI Committee on Rehabilitation of Concrete Structures (Japan Concrete Institute) and Guidelines for Corrosion Control Technology and Corrosion Prevention Technology for Concrete Structures of Sewerage Systems (Japan Sewage Works Agency).

12.5 Recording

(1) Investigation, deterioration estimation, evaluation and judgment, and remedial measures shall be recorded in accordance with Part 1.

(2) Items relevant to chemical attack shall be recorded.

[Commentary] As a general rule, the results of investigations, deterioration estimations, evaluations and remedial measures must be recorded in accordance with **Part 1**. Items relecant to chemical attack require careful attention, particularly with respect to record keeping. Items to be recorded are the investigation items indicated in Section **12.3.2** “Investigation in Assessment”, and the evaluation items indicated in Section **12.3.4** “Evaluation and Judgment.”

CHAPTER 13 MAINTENANCE OF STRUCTURES SUBJECT TO ALKALI–SILICA REACTION

13.1 General

(1) This chapter provides standard methods for the maintenance planning, assessment, remedial measures and recording for structures that have been or are highly likely to be subject to performance degradation due to ASR. The items common to all deterioration mechanisms are shown in Part 1.

(2) This chapter shall be applied to structures of the maintenance categories A (preventive maintenance) and B (corrective maintenance).

[Commentary] (1) Alkali–aggregate reaction and ASR: The alkalis (Na^2SO^4 and K^2SO^4) contained in cement are dissolved in the pore water solution in the concrete during the hydration of cement to become a strong alkali (pH = 13 to 13.5) water solution composed mainly of alkali hydroxides (NaOH and KOH). Aggregates containing certain types of silica minerals may react with the strong alkali water solution in the concrete to cause abnormal expansion and resultant cracking of concrete. Reaction of this kind is referred to collectively as alkali–aggregate reaction. In Japan, in the second half of the 1970s, deterioration due to alkali–aggregate reaction due to alkali–aggregate reaction was found in structures built mainly by using crushed andesite aggregate in the Kansai, Chugoku and Hokuriku regions. It is generally said that such alkali–aggregate reaction can be classified into two types, namely, alkali–silica reaction (ASR) and alkali–carbonate reaction, and alkali–aggregate reaction problems reported in Japan concern mainly ASR. This chapter, therefore, deals the maintenance of structures subject to ASR.

A hypothesis that has come to be widely accepted as a result of recent research is that what used to be termed "alkali–carbonate reaction" is actually ASR involving microcrystalline silica contained in limestone.

Defect caused by ASR and contributing factors: This chapter is applicable to structures consisting of reinforced concrete, prestressed concrete or steel–concrete composite structures subject to ASR, but it is intended mainly for application to reinforced concrete structures.

In structures subject to ASR, defect becomes visible in the form of concrete cracks several years after construction. Defect of structures caused by ASR usually occurs over a long period of time in the presence of moisture and alkalis. It is generally known that the degree of change caused by ASR varies considerably depending on (1) factors related to concrete such as the type and content of reactive aggregate, the type and alkali content of cement and concrete mix proportions (cement content, water/cementitious material ratio, air content, and the type and content of admixtures), (2) factors related to concrete structures such as the cross-sectional shapes of structural members, the amount of reinforcing steel and constraint conditions and (3) factors related to the service environmental conditions under which the structure is placed such as the supply of moisture and alkalis, insulation, and exposure to rain.

It is also generally known that in cold regions in Japan, ASR is accelerated by salts (e.g., NaCl) widely used as deicing agents.

ASR-induced deterioration: As shown in Fig. C13.1.1 and Table C13.1.1, the deterioration process of a structure due to ASR can be divided into the initiation, propagation, acceleration and deterioration stages. The influence of deterioration phenomena on the performance of structures varies among these deterioration stages, and the degree of performance degradation due to the progress of deterioration at each stage also varies depending on the performance attribute concerned.

The reason why two types of deterioration process are shown in Fig. C13.1.1 is that the progress of deterioration due to ASR is affected by various factors as mentioned above, and that cannot be expressed with a single illustration. Fig. C13.1.1(a) shows a case in which the expansibility of concrete is high and the concrete is cracked so severely that the integrity of the structural members is lost or expansion continues until the reinforcing steel is damaged (yielding, cracking or fracture). Fig. C13.1.1(b) shows a case in which cracking occurs because of ASR, but ASR-induced expansion converges at a certain point in time for some reason (e.g., the reactive material on the aggregate surface has been used up) and, consequently, the transition from the propagation stage of deterioration to the acceleration stage does not occur. Although not shown here, there may be a case in which ASR-induced deterioration stops at the acceleration stage. Thus, one characteristic of ASR is that a single deterioration process cannot be identified, and identification of deterioration stages and deterioration prediction are difficult to make.

(2) Currently known characteristics of a structure that has deteriorated or is likely to deteriorate because of ASR and remedial measures taken for the structure are as follows:

(i) It is difficult to detect deterioration, even by monitoring, before expansion cracks occur. Even if reactive aggregate is used or there is a large amount of alkalis, whether expansion actually occurs is unpredictable.

(ii) Even if deterioration as mentioned in (i) is detected, there is no established method for preventing further progress of deterioration from the initiation stage.

(iii) For the reasons mentioned in (i) and (ii), there are too many uncertain factors to take remedial measures for structures at the initiation stage of ASR-induced deterioration (i.e., all structures that have not shown any sign of ASR-induced deterioration) merely because ASR-induced deterioration could occur in future.

Because of these characteristics, in the case of an ordinary structure, it is common practice to perform maintenance while checking on defect in the state of the structure. This chapter, therefore, focuses mainly on structures in the maintenance category B.

In the case of a structure that is highly likely, judging from the results of a fact-finding investigation of a nearby structure or a structure built with similar materials, to be affected by ASR, if requirements related to hazards for third party or appearance are demanding or if remedial measures are difficult to take, it is desirable that a maintenance plan based mainly on concepts and methods in the maintenance category A be drawn up on an as-needed basis. It should also be kept in mind that structures in the maintenance category C (observational maintenance) are not maintenance-free. Instead, it is necessary to take maintenance measures consistent with the basic concepts and methods described in this chapter as much as possible.

For considerations in deciding on the category of maintenance for a structure that has deteriorated or is likely to deteriorate because of ASR, refer to Section 13.2.2, “Determination of Category of Maintenance.” Fig. C13.1.2 illustrates a standard procedure for maintenance in connection with ASR.

In connection with the application of this chapter, it is advisable to refer to Report of the Subcommittee on Alkali–Aggregate Reaction Control Measures (Japan Society of Civil Engineers), Ministry of Construction Comprehensive Technology Development Project: Development of

Concrete Durability Improvement Technology (Public Works Research Center), Report of the Committee on Alkali–Aggregate Reaction (Japan Concrete Institute) or Report of the Subcommittee on Deterioration of Concrete Structures Due to Deicing Agents (Japan Concrete Institute).

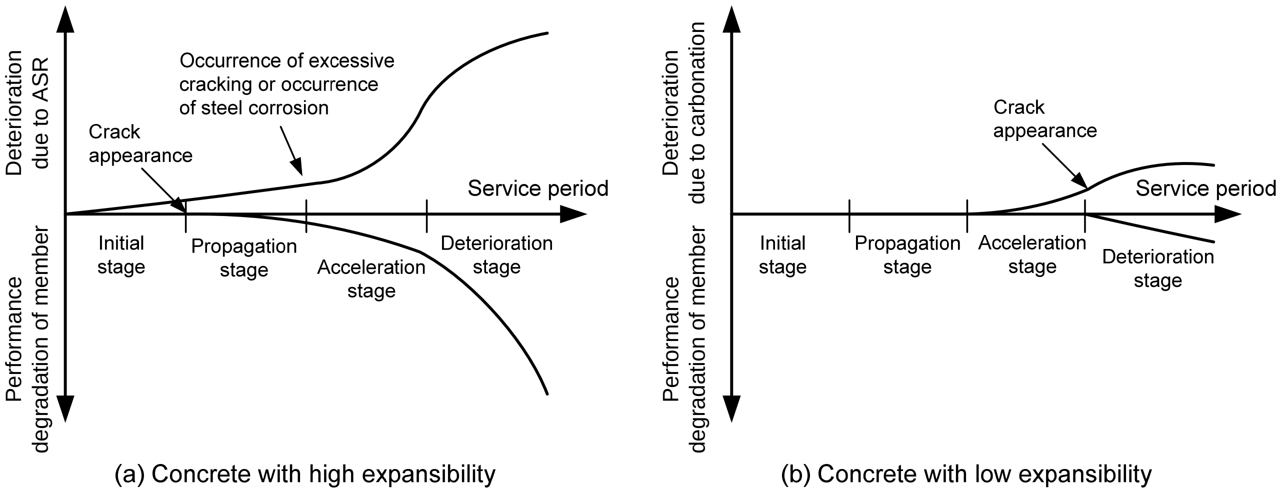


Fig. C13.1.1 Conceptual view of deterioration progress due to ASR

Table C13.1.1 Definition of deterioration stages

Stage of deterioration	Definition	Factor determining the stage
Initiation stage	Period in which ASR occurs but neither expansion nor resultant cracking has not yet occurred	Rate of alkali–silica gel formation (type and quantity of reactive minerals, quantity of alkalis)
Propagation stage	Period in which expansion occurs continuously and cracking occurs in the presence of water and alkalis, but steel corrosion does not occur	Water-induced expansion rate of alkali–silica gel (supply of water and alkalis)
Acceleration stage	Period in which water-induced expansion is maximized, crack propagate and steel corrosion may or may not occur	Water-induced expansion rate of alkali–silica gel (supply of water and alkalis)
Deterioration stage	Period in which the width and density of cracks increase and the integrity of structural members is lost, the cross-section area decreases because of steel corrosion or the load-carrying capacity decreases considerably because of steel damage, etc.	Water-induced expansion rate of alkali–silica gel (supply of water and alkalis) Steel corrosion rate Rate of increase in tensile stress in steel

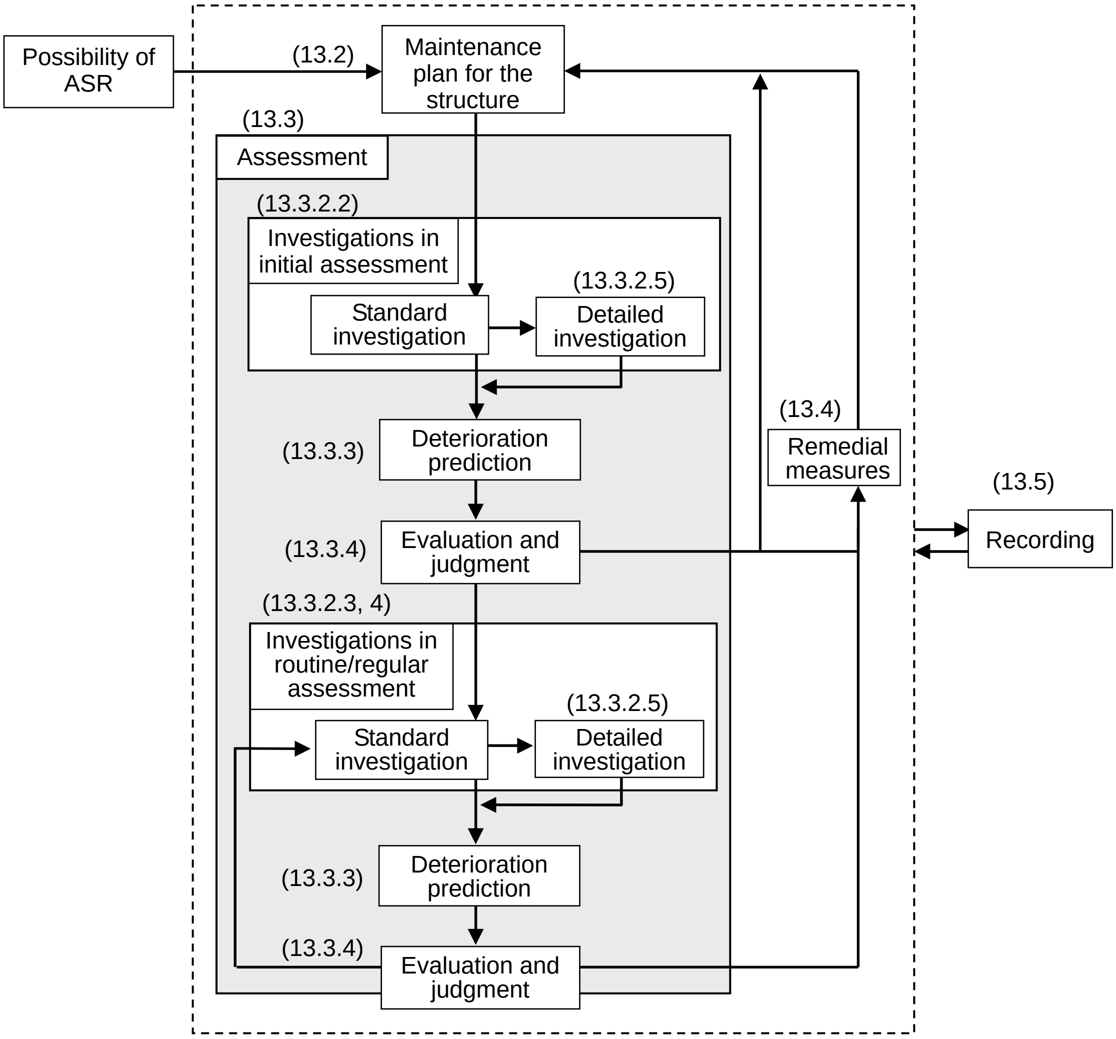


Fig. C13.1.2 Standard maintenance procedure against ASR

13.2 Maintenance Planning

13.2.1 Basis of planning

In order to maintain a structure subject to ASR, the category of maintenance shall be selected, the service period planned, and a maintenance planning for activities including assessment, remedial measures and recording drawn up in advance in view of the service and environmental conditions

[Commentary] When drawing up a maintenance planning, it is necessary to cover such details as check items and procedures for initial assessment and check items, procedures, timing and frequency for the investigations in routine and regular assessment, evaluation and judgment methods, actions to be taken in the event of deterioration, and recording methods, taking into consideration the type, degree of importance and planned service period of the structure, category of maintenance, and the quality of materials.

The type of structure, size and environmental conditions of concrete structures vary from structure to structure. A maintenance planning to be applied to a structure must be optimized for each structure. Deterioration of a structure due to ASR varies considerably depending on the service and environmental conditions for the structure such as the supply of water and alkalis, insulation, and exposure to rain. An appropriate maintenance planning needs to be drawn up, therefore, in view of these factors.

It is usually difficult, at the stage of maintenance planning, to accurately predict the state of a structure during its service period. It is therefore good practice to draw up a maintenance planning with reference to the deterioration of a similar structure or a structure in a similar environment.

13.2.2 Determination of maintenance category

The category of maintenance of a structure subject to ASR shall be selected in view of the degree of importance of the structure, the type of structure, hazards for third party, the planned service period and the characteristics of deterioration due to ASR.

[Commentary] The determination of the category of maintenance is very important because maintenance planning varies widely depending on the category of maintenance. The progress of deterioration and performance degradation due to ASR is conceptually illustrated in Fig. C13.1.1.

Structures to which maintenance category B (corrective maintenance) is applied should be maintained so that performance of structure does not fail to meet the required performances. For example, maintenance needs to be performed in view of performance degradation at and after the acceleration stage if attention is paid to safety and at and after the propagation stage if attention is paid to serviceability, hazards for third party and appearance. Indicators of deterioration due to ASR include the following:

(i) Cracking, discoloration and bleeding of alkali–silica gel have occurred.

(ii) The width and density of cracks have increased, and there is rusty water due to steel corrosion.

(iii) The width and density of cracks have further increased, and surface unevenness, displacement and local scaling and spalling occur.

(iv) There is rusty water indicating further corrosion of steel.

(v) There are cracks and steel damage due to environmental deterioration factors.

(vi) Displacement and deformation have increased.

Because it is extremely difficult to stop the progress of deterioration after the reinforcing steel in the concrete begins to be corroded, it is desirable that even in cases where maintenance category B (corrective maintenance) is applied, repair should be carried out at the stage of (i) or (ii) mentioned above. It should be kept in mind that if stage (iii), (iv) or (v) is reached, very large-scale measures such as cross-sectional restoration need to be taken. Thus, it is necessary to fully understand the target level of maintenance, the characteristics of ASR-induced deterioration and the characteristics of maintenance methods required for different categories of maintenance, and to determine the category of maintenance, taking life cycle cost into consideration.

13.2.3 Preparation of maintenance manuals

A maintenance manual describing methods, procedures and frequency requirements should be prepared for each structure in accordance with the maintenance planning, taking the structure-specific conditions into consideration.

[Commentary] The service period of civil engineering structures is long, and maintenance of those structures is performed over a long period of time. It is recommended, therefore, that in order to inform investigators of maintenance concepts and policies, a maintenance manual be prepared so that detailed procedures and methods can be communicated accurately even to newly assigned responsible engineers.

Under certain circumstances such as in cases where the original maintenance planning is altered because the actual progress of deterioration turned out to differ from that assumed in the original maintenance planning, it is necessary to modify the maintenance manual and take appropriate maintenance measures accordingly.

13.3 Assessment

13.3.1 General

In the assessment of a structure whose performance has declined or is highly likely to decline because of ASR, investigation, evaluation of the present state, prediction of deterioration and judgment of the necessity for remedial measures shall be appropriately conducted in accordance with the maintenance planning.

[Commentary] In order to maintain concrete structures appropriately, this specification requires three types of assessment: initial assessment, periodic assessment and extraordinary assessment. Because the initial and periodic assessments are essential for the maintenance of structures subject to ASR, this chapter stipulates that those assessments must be conducted. Extraordinary assessments are regarded as assessments to be conducted on an as-needed basis and are therefore not dealt with in this chapter. By conducting periodic assessments during the maintenance period, defect in appearance of structures can be discovered before they occur or in early stages, and remedial measures including preventive measures and repairs can be taken systematically.

13.3.2 Investigation in assessment

13.3.2.1 General

Investigations in initial, routine and regular assessment of a structure subject to ASR shall be conducted appropriately according to the category of maintenance required for the structure. Prior to investigation, check items, methods, frequency and scope of standard investigation shall be determined appropriately. For each type of assessment, detailed investigation shall also be conducted on an as-needed basis.

[Commentary] It is important to select check items, methods, frequency and scope of investigation appropriately according to the purpose of investigation in accordance with the maintenance planning.

Defect due to ASR include cracking, discoloration, bleeding of alkali–silica gel, pop-out, displacement, deformation and localized surface unevenness. Different investigations focusing on these items are conducted to determine whether defect occurring in a structure have been caused by ASR. In practice, the standard procedure is as follows: on-site visual observation, core sampling, indoor investigations, the evaluation of investigation results, and the prediction of the possibility of expansion. Items to be checked in an investigation of a structure affected by ASR are the amount of expansion of concrete and the resultant cracking and steel corrosion and damage (yielding, cracking, fracture). In the event of severe deterioration, it may be necessary to consider conducting an investigation in which the performance of the structure such as load-carrying capacity can be evaluated directly.

Check items in investigation varies with the degree of deterioration, but defects in appearance including cracking due to the expansion of concrete are necessary check items, regardless of the degree of deterioration. If deterioration is judged or estimated to be at or after the acceleration stage, an investigation in which steel corrosion and damage can be checked also needs to be conducted. Table C13.3.1 lists main check items at different stages of deterioration.

Table C13.3.1 Main check items in investigation

Stage of Deterioration	Initiation	Propagation	Acceleration	Deterioration
Change of appearance	O	O	O	O
Reactivity of aggregate	▲	▲	▲	▲
Residual expansion	▲*	▲	O	O
Steel corrosion/damage	▲*	▲*	▲	O
Concrete strength	▲*	▲	O	O
Load bearing capacity	▲*	▲*	▲	O
Environmental action	O	O	O	O

O: Items to be investigated on a priority basis

▲: Items that should preferably be investigated

▲*: Items to be investigated as required

The frequency and scope of investigation must be determined in view of such factors as the category of maintenance required for the structure, environmental conditions, the type of structure and the state of deterioration. ASR becomes faster at places subject to the influence of insulation, exposure to rain, deicing agents, etc., and steel corrosion occurs in a humid condition. Although a sufficient amount of data on steel damage are not available, steel damage tends to occur in cases where the amount of expansion is large. Consequently, the rate of deterioration may vary among different parts of the structure. By identifying such deterioration-prone portions at an early stage, maintenance at subsequent stages can be performed efficiently.

Regardless of the category of maintenance, it is important to go through the design drawings and specifications, construction records, investigation results and the repair history prior to the investigation of a structure.

If the state of a structure cannot be judged appropriately by standard investigation, detailed investigation must be conducted.

13.3.2.2 Investigation in initial assessment

(1) In initial assessment, appropriate check items for standard investigation shall be selected for newly constructed structures, existing structures, large-scale repairs and strengthened structures.

(2) If deterioration prediction, evaluation or judgment is difficult to make through a standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) Investigation in initial assessment is the first investigation conducted when the maintenance of a concrete structure is started. Investigation in initial assessment includes not only the first investigation of a newly constructed structure conducted before it goes into service but also the first investigation of an existing structure or a structure for which remedial measures have been taken in response to deterioration. Check items for the investigation may vary from structure to structure. Basic check items for standard investigations in initial assessment of a newly constructed structure are the document search on the design drawings and specifications and construction records and observation. It is good practice to check on such details as concrete cover, the state of steel and porosity through nondestructive testing on an as-needed basis. When investigating a structure for which remedial measures have been taken, it is also important to check for problems in repaired or reinforced parts of the structure. These should be included in check items of standard investigation. When an existing structure is investigated, check items are similar to those for a newly constructed structure if design drawings and specifications and construction records exist. If there is no such document or record, it is necessary to select check items of standard investigation with reference to Section **13.3.2.5** "Detailed Investigation." In cases where a prediction needs to be made with high accuracy about a structure to which maintenance category A (preventive maintenance) is applied, it is necessary to conduct investigations concerning the parameters used for the method described in Section **13.3.3** "Methods for Predicting Degradation of Performance Degradation of Structures."

Check items that are very important in the initial investigation of a structure subject to ASR are listed below.

(i) Source area of aggregate used

(ii) Total alkali content of concrete

(iii) State of cracking, discoloration, bleeding of alkali–silica gel, etc.

(iv) Repair or reinforcement status

Among the items listed above, information on Item (i) can be found on the geological maps of Japan showing the distribution of reactive stone because the distribution of ASR-causing stone is dependent on geological conditions. It is difficult, however, to judge whether rocks in a particular area are reactive from the rock type and geologic age information shown on the geological maps alone. Surveys on the distribution of reactive aggregates in Japan have been conducted by a number of institutions. If alkali‐ silica reactivity is suspected, therefore, it is advisable to refer to the results of these surveys. Concerning Item (ii), it is good practice to check, from the alkali content of the concrete used and the cement content of the concrete, whether the total alkali content exceeds the limit value (3 kg/m^3) of total alkali content. Item (iii) is necessary for the investigation of an existing structure in initial assessment. In cases where an investigation of a structure for which remedial measures have been taken is conducted in initial assessment, Item (iv) should be added to the check items of normal examinations because it is important to check on defect (e.g., peeling or detachment of covering materials) of repaired or reinforced parts.

Signs of ASR cannot be detected at the time of final investigation because at least several years will pass before ASR-induced cracks become visible. If reactive aggregate is used in concrete, expansion might occur after many years of use even if no sign of deterioration such as cracks is detected in the initial assessment. Because it is extremely difficult to estimate the amount of expansion of concrete used in a real structure, (1) reactivity of aggregate, (2) possibility of expansion and (3) the actual amount of expansion as a quantitative indicator need to be checked in that order in subsequent investigations. Although it is not possible at present to predict the progress of deterioration quantitatively even by using the investigation results in initial assessment, it is possible to evaluate deterioration potential qualitatively.

(2) If evaluation and judgment cannot be made with high accuracy by standard investigation alone or if a highly deteriorated part of a structure is to be investigated, detailed investigation is necessary. Check items of detailed investigation are indicated in Section **13.3.2.5** “Detailed Investigation.”

13.3.2.3 Investigation in routine assessment

(1) In routine assessment, standard investigation shall be conducted to detect not only the defect of concrete surface such as cracking, discoloration, bleeding of alkali–silica gel, rusty water, scaling and spalling, but also appearance deterioration such as displacement, deformation, localized surface unevenness and joint filler defect, water supply conditions, etc.

(2) If deterioration prediction, evaluation or judgment is difficult through standard investigation alone, detailed investigation shall be conducted.

[Commentary]　(1) The purpose of investigation in routine assessment is to detect deterioration at an early stage by checking on defect in the state of a structure over time. The determination of the time at which deterioration began in order to obtain information that is useful for predicting deterioration is another important purpose of the investigation in routine assessment. In a routine assessment, therefore, attention should be paid to deterioration phenomena and signs of deterioration, namely, concrete surface defect such as cracking, discoloration, bleeding of alkali–silica gel, rusty water, scaling and spalling, and other defect such as displacement, deformation, localized surface unevenness and joint filler defect. In areas where water is supplied such as wet concrete surfaces, deterioration, whether caused by ASR or otherwise, is expected in the near future. It is desirable, therefore, that water supply conditions be investigated.

ASR-induced cracks are not uniform. Instead, cracks occurring in a structure vary considerably depending on the environmental conditions (temperature, humidity, insulation and exposure to rain) and the constraint conditions (the amount and arrangement of steel, presence of external constraints). In the case of a plain concrete structure or a structure with a small amount of reinforcing steel, mesh cracks or map cracks occur over the entire structure. If ASR-induced expansion is constrained by longitudinal reinforcing steel or prestressing tendons, cracks perpendicular to the constraint are effectively prevented, so directional cracks along the longitudinal steel reinforcement or prestressing tendons often result along with map cracks.

Normal examinations depend mainly on visual investigation. If, therefore, deterioration is detected, ASR is already at a highly advanced stage, and it is difficult to evaluate or judge a structure at the initiation stage on the basis of investigation results in routine assessment. In the case of a structure to which maintenance category A is applied, therefore, it is necessary to add check items as appropriate by, for example, using an appropriate monitoring method.

It is also important to conduct intensive investigations of deterioration-prone areas identified in the initial assessment.

(2) If high-accuracy evaluation or judgment is difficult by conducting standard investigation alone or if severe deterioration has already occurred, detailed investigation is conducted. Check items of detailed investigation are described in detail in Section **13.3.2.5** “Detailed Investigation.”

13.3.2.4 Investigation in regular assessment

(1) The purpose of investigation in regular assessment is to obtain information that is difficult to obtain in routine assessment. In regular assessment, standard investigation consisting of detailed observation of defects shall be conducted as in routine assessment.

(2) If deterioration prediction, evaluation or judgment is difficult through standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) Investigation in regular assessment is conducted for obtaining the information more detailed than that in routine assessment. Areas where signs of defects or deterioration have been detected in the initial assessment or the routine assessment need to be inspected intensively. Check items consist mainly of observatory items as in the routine assessment, but check items that make it possible to determine changes over time in the width, number and density of cracks by paying attention to the location and direction of ASR-induced cracks should be added. In the case of a structure to which maintenance category A is applied, it is necessary to increase check items as appropriate, such as using an appropriate monitoring method.

Measuring crack propagation and expansion behavior of a structure by installing chips for contact gauges by which to measure the propagation of cracks in the concrete and displacement meters by which to measure the deformation of structural members is helpful in maintaining a structure and deciding on repair and reinforcement measures. In the case of an ASR-affected structure, stepped patterns of expansion, in which expansion increases in spring to summer and remains unchanged in autumn to winter, tend to occur because of the temperature dependence of ASR. The amount of expansion in future, therefore, can be estimated by measuring the expansion behavior of a real structure over a period of one year.

(2) If high-accuracy evaluation or judgment is difficult by conducting standard investigation alone or if severe deterioration has already occurred, detailed investigation is conducted. Check items of detailed investigation are described in detail in Section **13.3.2.5** “Detailed Investigation.”

13.3.2.5 Detailed investigation

Detailed investigation shall be conducted to obtain detailed information on a structure subject to ASR in cases where the deterioration of the structure is difficult to predict, evaluate or judge by standard investigation alone in initial, routine or regular assessment. Check items, methods and location of a detailed investigation shall be selected appropriately taking into consideration such factors as the purpose of investigation and the accuracy of obtained results.

[Commentary] A detailed investigation is conducted when the determination of the present state of a structure and the deterioration of the structure are difficult by normal examination results alone in order to obtain information necessary for those purposes.

A detailed investigation of an ASR-affected structure should cover check items that make it possible to evaluate the degree of influence of cracking on the steel corrosion, load-carrying capacity, stiffness, etc., of the structure and the residual expansion concerned with future performance degradation. A detailed investigation of a structure is conducted to evaluate the degree of performance degradation due to ASR, make judgments as the necessity of repair or reinforcement and the scope of repair or reinforcement, and obtain information necessary for selecting repair or reinforcement methods and materials. On-site tests conducted for a structure include the measurement of crack width and amount of expansion of a real structure and investigations using core samples. Because the performance degradation of a concrete structure due to ASR is greatly affected by the environmental conditions, it is necessary not only to investigate the environmental conditions under the influence of insulation and exposure to rain in detail but also to investigate the influence of seawater, deicing agents and deterioration due to the combined effect of freeze–thaw cycles and chemical attack. Core samples taken from a structure are used, for example, for the prediction of residual expansion, compressive strength testing, alkali–silica gel detection by scanning electron microscope, chemical analysis, concrete texture observation by use of thin specimens, the evaluation of alkali–silica reactivity of aggregate used, and petrological testing. In general, ASR-affected concrete is characterized by a considerable decrease in the modulus of elasticity, compared with compressive strength, indicating that the modulus of elasticity is more sensitive than compressive strength to changes in the dynamic properties of concrete. A method for estimating the degree of ASR-induced deterioration from this relationship has been proposed. When a detailed investigation is conducted, the investigation results should be used to re-evaluate deterioration prediction and the investigation results in regular assessment. If the results differ from the initial predictions, it is necessary to reconsider the service and environmental conditions for the structure that contribute to deterioration, such as the supply of moisture and alkalis, insulation and exposure to rain.

Depending on the circumstances, a structure that has undergone excessive ASR-induced expansion may have not only defect of the concrete surface such as cracking and alkali–silica gel bleeding, but also a decrease in the load-carrying capacity due to a decreased in concrete strength or steel corrosion or damage (yielding, cracking, fracture). It is therefore necessary to investigate the deformation properties of the structure or its members or steel strains through loading tests or by other means. In areas with localized surface unevennesses or displacements, the state of steel corrosion and steel damage need to be investigated by appropriate nondestructive testing or by chipping away the cover concrete.

Table C13.3.2 shows investigation check items for a structure subject to ASR and examples of information obtainable from investigation results concerning the estimated state of the structure at the time of investigation and in future. The "evaluation item predictable from obtained information" in the table can be evaluated after deterioration prediction is made. The measuring methods for main investigation items are briefly described below. For other details, refer to Section 4.7.3, "Investigation Methods".

Table C13.3.2 Examples of evaluation items in detailed investigation

Measurement item	Data obtained by examinations	Evaluation items predicable from obtained data
Alkali–silica reactivity of aggregate	Deterioration rate of ASR	Deterioration rate of ASR
Residual expansion	Deterioration rate of ASR	Deterioration rate of ASR
Crack (width, depth, density)	Deterioration rate of ASR, appearance	Deterioration rate of ASR, appearance
Location and state of corrosion of steel (area, amount)	Corrosion grade, load-carrying capacity	Corrosion rate, load-carrying capacity
Steel damage	Load-carrying capacity	Load-carrying capacity
Discoloration, alkali–silica gel bleeding	Appearance	Concrete strength, modulus of elasticity
Concrete strength, modulus of elasticity	Concrete strength, stiffness, alkali–silica reaction rate	Concrete strength
Displacement, deformation	Stiffness	Load-carrying capacity
Rock type of aggregate (type and content of reactive minerals)	Alkali–silica reactivity of deterioration rate of ASR	Deterioration rate of ASR
Alkali content of concrete	Deterioration rate of ASR	Deterioration rate of ASR
Temperature, humidity, insulation, exposure to rain	Deterioration rate of ASR	Deterioration rate of ASR
Influence of seawater and deicing agents	Deterioration rate of ASR	Deterioration rate of ASR
Density indicators (e.g., ultrasonic wave propagation velocity)	Cracking, strength, stiffness	

Note: For the grade of corrosion, refer to Table C10.3.3.

(i) Appearance of structure

If the state of the concrete or steel used in a structure is not directly related to the performance of the structure, defect in appearance may provide useful information necessary for performance evaluation. The appearance grades of structures whose performance has deteriorated because of ASR are tabulated in Table C13.3.3.

Table C13.3.3 Grades of structural appearance and stage of deterioration

Grade of structural appearance	State of deterioration
I (initiation stage)	ASR-induced expansion and resultant cracking have not yet occurred, and there is no anomaly in appearance.
II (propagation stage)	Expansion occurs continuously in the presence of moisture and alkalis, cracking occurs, and discoloration and alkali–silica gel bleeding can be seen. There is no rusty water due to steel corrosion.
III (acceleration stage)	This is the stage at which the rate of expansion due to ASR is maximized. Cracking occurs and crack with and density increase. Rusty water due to steel corrosion may be seen.
IV (deterioration stage)	Crack width and density increase further, and localized surface unevenness, displacement and localized scaling and spalling occur. Steel corrosion continues and rusty water can be seen. Cracks or steel damage due to environmental deterioration factors may be seen. Displacement and deformation increase.

(ii) Alkali–silica reactivity of aggregate

The alkali–silica reactivity of aggregate is tested by the chemical method specified in JIS A 1145 and the mortar-bar method specified in JIS A 1146. These test methods, however, are not suitable for the evaluation of the alkali–silica reactivity of all types of aggregate, and there are certain types of aggregate that cannot be evaluated by those methods. Another problem is that evaluation by the mortar-bar method takes as long as three to six months. Because of these circumstances, test methods for obtaining results quickly are used in other countries.

(iii) ASR resistance of concrete

The most reliable method for checking the ASR resistance of concrete is to expose concrete specimens prepared by using the same mix proportions and other conditions as will be used for a real structure under the same environmental conditions as those under which a real structure will be placed and check whether cracking occurs. This approach, however, is not realistic. A commonly used method is to evaluate the ASR resistance of concrete specimens through accelerated curing tests. An example is a method conforming to JCI AAR-3, Test for Alkali–Silica Reactivity of Concrete. It has been confirmed experimentally and empirically that a six-month expansion of 0.1% determined by this method can be used as a threshold for the occurrence of ASR-induced damage. In cases where alkalis are supplied from an external source, the method of curing concrete specimens by reproducing the conditions under which alkalis are expected to be supplied to a real structure and checking the six-month expansion similarly may be used.

(iv) Residual expansion of concrete

A commonly used method of residual expansion measurement by use of core samples is the method of using a humid air chamber kept at a temperature of 40°C and a relative humidity of 100% (JCI-DD2). Other methods include a method using a 1M NaOH solution at 80°C (Canadian method, ASTM C 1260-94) and a method using a saturated NaCl solution at 50°C (Danish method).

Threshold values used for accelerated expansion testing are often determined in accordance with the criteria for the test of the alkali–silica reactivity of aggregate. The threshold values used to judge residual expansion in accelerated expansion tests on core samples, however, are not based on accumulated research findings. It should be kept in mind, therefore, that at least at present, the relationship of those threshold values with the future expansion behavior of real structures is not necessarily clear.

13.3.3 Methods for predicting performance degradation of structures

13.3.3.1 General

(1) In the maintenance of a structure subject to ASR the performance of the structure shall be evaluated quantitatively at the time of investigation, and future degradation shall be predicted.

(2) In order to predict the performance degradation of a structure, deterioration due to ASR shall be predicted quantitatively.

(3) If (2) is difficult, an alternative method is to predict performance degradation by estimating the length of the initiation, propagation, acceleration and deterioration stages, taking the progress of ASR into consideration.

(4) Deterioration shall be predicted on the basis of investigation results.

[Commentary] (1) and (2) In the performance verification based maintenance system, changes (degradation) in various performance attributes of a structure are to be predicted. In order to estimate the performance of a structure subject to ASR, it is necessary to quantitatively predict the deterioration of the materials used in the structure. It is also necessary to quantitatively evaluate the performance of the structure and the degree of deterioration of the materials used in the structure at the time of investigation and at the end of the planned service period on the basis of investigation results. The performance of the structure or the degree of deterioration of the constituent materials at the time of investigation can be evaluated by using an appropriate method on the basis of the investigation results. Performance and deterioration at the end of the planned service period are predicted on the basis of the investigation results in regular assessment by estimating the subsequent progress of deterioration over time.

Anomalous expansion of concrete due to ASR results from the water-induced expansion of the alkali–silica gel formed by the chemical reaction of the reactive silica minerals contained in the aggregate with a water solution composed mainly of alkali hydroxides in the concrete. Alkali–silica gel formed in reactive aggregate absorbs water, and the aggregate expands. The expansion of the reactive aggregate generates internal stress not only to cause in aggregate particles but also to destroy the cement paste around the aggregate particles. With further progress of ASR, microscopic cracks grow to cause macroscopic cracks to appear at the surface of the structure. ASR-affected concrete, therefore, has not only relatively large cracks but also many microscopic cracks in and around the aggregate particles.

The temperature and humidity of the surface layer of an ASR-affected concrete member differ from those of the inner concrete. Consequently, a difference in the amount of expansion occurs between the surface layer and the inner concrete. The stress caused by such differences in the amount of expansion among different parts of the concrete and the restraining effect of reinforcing steel and the stress caused by differential deformation of different members also cause cracking.

ASR-induced cracking could cause steel corrosion in the presence of water and oxygen supplied through cracks. It has also been found that in the event of extreme expansion of concrete due to ASR, part of the reinforcing steel in the concrete may be damaged (yielding, cracking, fracture).

This chapter assumes, therefore, that items to be predicted are the expansion of concrete (and resultant crack propagation), the progress of steel corrosion, and the occurrence of steel damage.

(3) In cases where the deterioration of the concrete and steel used in a structure are predicted, and various performance attributes of the structure are evaluated by combining the results thus obtained, it is not easy, at the present level of technology, to make quantitative predictions. A practical method, therefore, is to estimate the length of the initiation, propagation, acceleration and deterioration stages by taking the progress of the ASR of concrete into consideration. The deterioration stages and factors determining their length are listed in Table C13.1.1. As shown in Fig. C13.1.1 with two types of illustrations, the ASR-induced deterioration process can be modeled differently depending on the expansibility of concrete. If the quantity of reactive minerals contained in the aggregate is large and the expansibility of the formed alkali–silica gel is high, the ASR-induced expansion of concrete may occur over a long period of time so that severe deterioration results because the large amount of expansion is large. If the quantity of reactive minerals contained in the aggregate is relatively small, the ASR-induced expansion of concrete may converge at a certain stage, and further change may not occur even after a sufficiently long period of time. This means that as far as ASR-induced deterioration is concerned, not all structures reach the deterioration stage. It is not easy, however, to derive performance degradation curves from such information as the investigation results for the structure. Predicted values of residual expansion due to ASR will contain large errors. Even if the structure to be maintained is considered to be relatively free from expansion, therefore, it is necessary to maintain the structure appropriately by, for example, carefully checking for ASR-induced defect.

(4) The results of investigation of a structure be classified into two types: one concerns the quality of concrete used in the structure and the other concerns the environment in which the structure is used. As a general rule, deterioration prediction must be based on these investigation results. For example, in the case of a structure in which the number, length, width, etc., of ASR-induced cracks have changed very little for a long period of time, ASR-induced expansion may have largely converged. In that case, the state of deterioration can be expected to remain unchanged for a while as shown in Fig. C13.1.1(b). At the present level of technology, however, it is difficult to accurately predict changes in various performance attributes of a structure even if information is available about ASR-induced cracking, etc., through investigation. It is advisable, therefore, even in cases where deterioration prediction is made on the basis of investigation results, to evaluate the performance attributes of a structure by appropriately evaluating investigation results about the reactivity of aggregate, concrete mix proportions and the environmental conditions under which the structure is used and allowing for an appropriate factor of safety in making predictions.

If no information is available on the ASR of concrete as in the case of a newly constructed structure or if investigation results for an existing structure are not available, investigation results for an adjacent structure or a structure in a similar environment can be used as a guide. It is good practice to refer to investigation results for an adjacent structure on an as-needed basis because there may be similarities to the concrete (especially aggregate) used for an adjacent structure or the environment in which the structure is used. For example, if it is known that severe ASR-induced deterioration has occurred at a structure built with the same type of concrete, care must be taken because ASR-induced deterioration may occur when certain environmental conditions (e.g., supply of water) are met even if little or no sign of ASR-induced deterioration has been observed thus far.

13.3.3.2 Prediction of ASR-induced expansion of concrete

(1) The progress of ASR-induced expansion of concrete used in a structure shall be predicted in due consideration of the influence of the environmental conditions under which the structure is used.

(2) The amount of ASR-induced expansion of concrete may be predicted by one or more of the following methods.

(i) Use of investigation results

(ii)Use of accelerated curing test on core samples

[Commentary] (1) If the aggregate used is reactive, expansion may occur after a long period of use even if no sign of ASR is found at the time of investigation. It is generally known that the process of ASR-induced expansion consists of a chemical reaction process in which alkali–silica gel is formed by chemical reaction and a physical process in which alkali–silica gel absorbs water and expands. These processes do not occur simultaneously. Instead, the expansion process begins after chemical reaction progresses sufficiently. It is thought that the rate of progress of the chemical reaction process is determined mainly by the type and content of reactive minerals, the type and alkali content of cement, and concrete mix proportions. The rate of progress of the physical process is affected by the environmental conditions (e.g., supply of water, temperature) under which the structure is used. The rate of progress of ASR-induced expansion of concrete needs to be estimated by taking these factors into consideration.

(2) Experiment results have shown that the rate of formation of alkali–silica gel in the chemical reaction process and the amount of expansion of concrete are not necessarily related proportionally. Thus, it is difficult to predict with high accuracy the progress of ASR-induced expansion of concrete because there are still many unknowns about the rate of progress of the two processes mentioned above. In maintaining a structure that has deteriorated because of ASR, however, it is necessary to conduct a study on the possibility of concrete expansion by some kind of method in advance. Current practice is to use one or more of the methods described below in order to predict the progress of ASR-induced expansion of concrete.

(i) Method based on investigation results

The progress of deformation and cracking of structural members is measured, for example by the contact gauge method, in advance, and the progress of future cracking of the members is estimated from the measured changes over time. It is therefore necessary to obtain investigation data required for estimation. The occurrence of ASR-induced expansion and resultant cracking is greatly affected by the environmental conditions of the structure. Measuring both heavily crack parts and relatively intact parts of the structure in an investigation is helpful in estimating the expansion behavior of the entire structure. The use of data on the expansion of the real structure makes it possible to estimate the rate of expansion so as to provide information useful for repair and reinforcement.

It is desirable that investigation results used here be ones obtained over a long period of time. Studies have shown that the progress of ASR-induced expansion is greatly affected by such factors as seasonal changes in atmospheric temperature. It is therefore necessary to use investigation results obtained from investigations conducted over a period of at least one year.

(ii) Method using accelerated curing tests on core samples

The possibility of expansion of concrete is estimated by storing core samples taken from a structure in an environment conducive to ASR and measuring the amount of expansion in that accelerated curing environment. A number of accelerated curing test methods have been proposed, and different accelerate curing environments are used in different test methods. From the experiences with past projects in Japan, many have concluded that concrete with an expansion as determined by accelerated curing testing of 0.1% or more might expand in a harmful manner in future to cause degradation in serviceability and durability. Many have also concluded that concrete with an expansion as determined by accelerated curing testing of less than 0.05% is unlikely to expand in a harmful manner in future. Conclusions are divided, however, about concrete with expansions of 0.05 to 0.1%, and it is difficult to evaluate the possibility of expansion.

What is to be kept in mind here is that the amount of expansion obtained by the method using accelerated curing tests on core samples is a result obtained in an accelerated curing environment specified by each test method, and that result is not necessarily the same as the actual amount of expansion in future in the real-world environment. In other words, what can be done through accelerated curing tests is merely to predict the possibility of the structure's moving onto the next stage of deterioration (in this example the acceleration stage) sometime in future, and predicting the time of such transition is difficult under the present circumstances. It is also difficult to estimate the rate of expansion occurring at a real structure from the results of accelerated curing tests. Care should be taken, therefore, when trying to predict the amount of ASR-induced expansion of concrete by this method and decide what to do in connection with repair or reinforcement.

13.3.3.3 Prediction of steel corrosion

The progress of steel corrosion due to ASR shall be predicted properly considering the influence of ASR-induced defect and the environment in which the structure is in service.

[Commentary] Deterioration due to ASR may cause cracking and other adverse effects on the structure due to the expansion of concrete, but ASR-induced deterioration itself does not directly affect steel corrosion. It has also been reported that the influence of ASR-induced cracks on steel corrosion is smaller than that of cracks caused by other factors mainly because cracks are filled up with alkali–silica gel. It has also been reported, however, that in regions prone to chloride attack, severe steel corrosion resulted under the influence of chloride ions that have infiltrated through cracks. The influence of ASR-induced defect on steel corrosion must be studied, taking into consideration all relevant factors including the locations and degrees of defect and the environmental conditions under which the structure is used.

13.3.3.4 Prediction of steel damage

The occurrence of ASR-induced damage to the reinforcing steel in a structure shall be predicted in due consideration of the influence of the quality of concrete, reinforcement patterns, the type and shape of structural members and the environmental conditions under which the structure is used.

[Commentary] If ASR causes severe deterioration, steel damage (yielding, cracking, fracture) may result. It is difficult to detect steel damage or estimate the possibility of future steel damage simply by observing the outside appearance of the structure. It is nevertheless necessary to be very careful because steel damage is highly likely to affect the load-carrying capacity of the structure.

According to damage reports, all reported cases of reinforcing bar fracture occurred at bends in reinforcing bars. It has been inferred, therefore, that the fractures were caused by fine cracks that may have occurred in the inner region at a bend in a reinforcing bar formed when reinforcing bars conforming to a now-defunct standard, which specified material and rib configuration requirements that differ from the requirements under the current standard, were bent. In many cases, fracture occurred in poorly reinforced regions, such as beams of T-shaped piers and the upper surfaces of footings, where reinforcing bars had to span 10 mm or wider cracks along longitudinal reinforcement.

In a structure that has deteriorated severely because of ASR, therefore, it is good practice to evaluate the possibility of occurrence of steel damage with reference to investigation results for similar structures, conduct an appropriate nondestructive testing and, if necessary, investigate possible damage regions by chipping away the cover concrete to expose the reinforcing bars.

13.3.3.5 Modification of prediction

If the state of deterioration determined in an investigation differs from a predicted state of deterioration, the cause of the difference shall be identified and the prediction shall be revised accordingly. If necessary, the maintenance planning should be altered.

[Commentary] If the state of deterioration determined in an investigation differs from a predicted state of deterioration, an appropriate investigation must be conducted with reference to the deterioration prediction methods described in Section **13.3.3.2**, "Prediction of ASR-induced Expansion of Concrete," and Section **13.3.3.3**, "Prediction of Steel Corrosion," Section 13.3.3.4, "Prediction of Steel Damage" and Table C13.3.2 in Section **13.3.2.5**, "Detailed Investigation," to identify the cause of the difference from the prediction and revise the prediction accordingly. The results of a number of investigations conducted are useful for identifying the cause of the difference and revising the prediction. It is also important to reconsider such details as the frequency of investigation in view of the revised prediction and alter the maintenance planning if necessary.

13.3.4 Evaluation and judgment

(1) The evaluation of performance and judgment as to whether remedial measures need to be taken based on the results of the investigation in initial, routine and regular assessment shall be made in accordance with Part 1 and Item (2) and subsequent items in this section.

(2) The performance of a structure subject to ASR shall be evaluated by appropriately selecting performance attributes to be evaluated in view of the stage of deterioration of the structure.

(3) The evaluation of performance attributes at the time of investigation and at the end of the planned service period of the structure should be made by a quantitative method.

(4) If Item (3) is difficult to achieve, the evaluation of performance attributes at the time of investigation and at the end of the planned service period of the structure may be made by a semi-quantitative grading-based method.

(5) Judgment as to whether remedial measures need to be taken shall be made in view of the degree of performance degradation due to ASR, the degree of importance of

the structure, category of maintenance, and the remaining service life.

[Commentary] (1) The evaluation of performance and judgment of necessity for remedial measures in initial, routine and regular assessment are frequently more or less the same regardless of the deterioration mechanism. For details, refer to **Part 1**. The evaluation of performance and judgment of necessity for remedial measures for structures in which deterioration may have or has progressed vary according to the deterioration mechanism. When discussing the performance degradation due to ASR, the descriptions in this chapter should be consulted.

(2) In the case of a structure subject to ASR, performance attributes affected by deterioration vary depending on the stage of deterioration (initiation stage, propagation stage, acceleration stage or deterioration stage). Performance attributes to be evaluated, therefore, need to be selected appropriately for each stage of deterioration.

Basically, evaluation and judgment concerning a structure subject to ASR must be made through investigations of cracks in the structure and accelerated curing tests on core samples. ASR-induced cracks are usually as deep as concrete cover, and few cracks are deeper than the reinforcing steel. It is generally said that if reinforcing bars are arranged appropriately in the concrete, the influence of ASR on the load-carrying capacity of the concrete structure is small. If cracks in the concrete exist only in the cover concrete zone, in many cases degradation in serviceability, hazads for third party and appearance causes problems such as cracking-induced steel corrosion, cracking and discoloration. Recent investigations of structures that had undergone excessive expansion due to ASR revealed decreases in concrete strength and bond between steel and cover concrete, and damage in bent steel bar regions. In these cases, the load-carrying capacity of the structure needs to be evaluated.

(3) The performance of a structure at the time of investigation and at the end of the planned service period needs to be evaluated quantitatively after the state of deterioration of the constituent materials of the structure, namely, the concrete protection materials, concrete and steel, is evaluated quantitatively. For example, in the performance evaluation at the time of investigation, safety and serviceability may be checked by determining load-carrying capacity, the amount of deflection and the amount of deformation by substituting the dynamic properties obtained from investigation results in the structural calculation equations. It is also possible to verify appearance by evaluating cracks, the extent and density of scaling and spalling, etc. By these verification methods, it may be possible to evaluate performance in a relatively straightforward manner at the time of investigation. It is difficult, however, to evaluate performance at the end of the planned service period with sufficient accuracy. A reasonable method, therefore, is to supplement such evaluation by verifying durability through deterioration prediction based on the rate of progress of ASR with reference, for example, to the method described in Section 13.3.3, “Method for Predicting Performance Degradation of Structures”. In this case, not only the accuracy of the performance verification method used at the time of investigation but also the accuracy of the deterioration prediction method are important considerations. Prediction methods, therefore, need to be carefully selected, and it is important to allow for a reasonable factor of safety.

(4) In the performance verification type design system, structural performance should ideally be evaluated quantitatively. At present, however, there is no established method of quantitative estimation. As a practical method, the performance of a structure can be evaluated semi-quantitatively, with reference to Table C13.3.5, by performing appearance grading in accordance with Table C13.3.4.

The purpose of grading is to classify the present degree of deterioration of a structure semi-quantitatively instead of predicting and evaluating the degree of deterioration in future. It is also possible, however, to predict the performance of a structure at the end of the planned service period in accordance with Table C13.3.4 by estimating the stage of deterioration at the end of the planned service period on the basis of investigation results such as the rate of crack propagation. The method of estimating the degree of deterioration at a certain point of time in future by constructing a deterioration grade model based on a stochastic theory such as a Markov model has also been proposed.

If detailed maintenance records for a similar structure (type of structure, materials, construction, environment, state of use) are available and the progress of deterioration thus far of the structure of interest is similar to that of the similar structure, then the evaluation results for that structure provide useful information.

Table C13.3.4 Grades of appearance of structures and typical performance degradation

<table>
<tr><th>Grade of appearance of structure</th><th>Safety</th><th>Serviceability</th><th>Hazards for third party</th><th>Aesthetic appearance and landscape</th></tr>
<tr><td>I (initiation stage)</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>II (propagation stage)</td><td>-</td><td rowspan="3">Decrease in watertightness
· Cracking
Steel corrosion
· Cracking
Displacement/deformation of structure
· Deflection
· Relative displacement
· Localized surface unevenness</td><td rowspan="3">Hazards for third party
・Scaling
・Spalling</td><td rowspan="3">Degradation in appearance
・Cracking
・Discoloration
・Bleeding of alkali–silica gel</td></tr>
<tr><td>III (acceleration stage)</td><td rowspan="2">Decrease in ductility
・Steel corrosion
Decrease in load-carrying capacity
・Detailed verification: load-carrying capacity
Simple verification: decrease in concrete strength, decrease in bond with steel, steel damage</td></tr>
<tr><td>IV (deterioration stage)</td></tr>
</table>

(5) Because judgment is the act of deciding whether remedial measures need to be taken on the basis of structural performance evaluation results, there is no difference depending on deterioration factors. Therefore, refer to Part 1.

13.4 Remedial Measures

13.4.1 Selection of remedial measures

(1) If it has been judged that remedial measures need to be taken in connection with performance degradation of a structure subject to ASR, remedial measures by which the corrected structure meets the required performances shall be selected.

(2) If it is difficult to select remedial measures for a structure on the basis of performance verification, remedial measures may be selected from the measures corresponding to the grade of appearance.

[Commentary] (1) If it has been judged, as a result of evaluation, that remedial measures need to be taken, it is necessary to select one or more of the following measures: (i) intensified investigation, (ii) repair, (iii) strengthening, (iv) functional improvement, (v) restriction in service or (vi) dismantling/removal. Basically, decisions as to which measures to take should be made by the maintenance manager of the structure, but it is good practice to refer to **Part 1** for information on typical relationships between evaluation and judgment results and remedial measures.

(2) If it is difficult to select remedial measures for a structure through quantitative evaluation or judgment, remedial measures are selected from the measures corresponding to the deterioration grade of the structure. Remedial measures to be taken vary depending on the type of structure, the degree of importance of the structure, deterioration rate and the category of maintenance, but recommended standard measures are shown in Table C13.4.1.

Table C13.4.1 Grades of appearance of structure and remedial measures

Grade of appearance of structure	Intensified investigation	Repair	Strength -ening**	Functional improvement	Restriction in service	Dismantling /removal
I (initiation stage)	**O**	**O****	**X**	**X**		
II (propagation stage)	**O**	**OO**	**X**	**X**		
III (acceleration stage)	**OO**	**OO**	**X**	**X**	**O**	
IV (deterioration stage)	**OO**	**OO***	**X**	**X**	**OO**	**OO**

OO: Standard remedial measures (**OO*:** Including the restoration of mechanical performance), **O:** Remedial measures in some cases**, O**:** Preventive measure, **X:** Remedial measure taken based on other criterion than the grade of appearance.

Strengthening**: Enhancing the mechanical performance above the initiation level

13.4.2 Repair and strengthening

Methods and materials for the repair or strengthening of a structure shall be selected taking into consideration the performance degradation of the structure due to ASR and life cycle cost, so that the required effect can be achieved.

[Commentary] In cases where repair or strengthening is carried out as a remedial measure, it is necessary to define the expected effect of repair or strengthening and the required performance (what level of performance to be maintained for how many years?). Ideally, it is desirable that remedial measures be taken after constructing a deterioration formula (for repair) or structural calculation formula (for strengthening) in view of such factors as the properties of the materials used and verifying the calculation results obtained from those formulas. In this case, it is also important to take life cycle cost into consideration according to the remaining planned service period.

Repair and reinforcement methods for structures deteriorated by ASR can be classified, according to expected effects, as shown in Table C13.4.2.

Table C13.4.2 Expected effects and methods of repair or strengthening

Expected effect	Examples of methods
Control of progress of ASR	Water control (cutoff, drainage), crack injection, surface treatment (covering, impregnation)
Restraining of ASR-induced expansion	Prestressing, steel/PC/FRP jacketing
Removal of deteriorated portion	Cross-sectional restoration
Steel corrosion control	Crack injection, crack filling, surface treatment (covering, impregnation)
Elimination of third party impact	Prevention of spalling
Restoration/enhancement of load-carrying capacity	Steel plate/FRP sheet bonding, prestressing, overlay, steel/PC/FRP jacketing, external tendon

In order to control the progress of ASR, it is important to control water (cutoff, drainage) so that water is not supplied to the structure from an outside source. Among the regions involved in ASR, namely, reactive aggregate, alkalis and water, the regions other than reactive aggregate (i.e., alkalis and water) exist in the concrete from the beginning, and they are also supplied from the environment through, for example, the back side of the structure. It is therefore difficult, even if the supply of water and alkalis can somehow be cut off, to completely stop the progress of ASR when water and alkalis are present in quantities needed to cause ASR in the concrete. It is necessary to keep this characteristic of ASR in mind.

When deciding on which method to use, it is necessary to take into consideration the present state of performance degradation of the structure concerned besides Table C13.4.2. For the correspondence between appearance deterioration grades and repair and reinforcement methods, refer to Table C13.4.3. Many of the repair and reinforcement methods in use today were developed in recent years, and some of them have not been field-tested extensively. Those methods might fail to prevent the recurrence of deterioration or achieve the required performance because of factors that could not be expected at the design stage. It is desirable, therefore, that precautionary measures such as increasing investigation frequency be taken after repair or reinforcement work is done. In the event of the recurrence of deterioration, repair or reinforcement measures need to be taken again. In such cases, it is important to carefully investigate the extent, state, cause, etc., of re-deterioration and select appropriate control measures and materials. For example, when applying the electrochemical corrosion control method (electrochemical desalination, electrochemical so notification) to a concrete structure that has been obviously affected by ASR, care needs to be taken so as not to accelerate ASR.

Table C13.4. 3 Appearance degradation grades of structure and examples of standard repair/reinforcement methods

Grade of structural appearance	Expected expansion	Standard repair/reinforcement method
I (initiation stage)	-	Water control (cutoff, drainage)*
II (propagation stage) III (acceleration stage)	Small	Water control (cutoff, drainage), crack injection, surface treatment (covering, impregnation), prevention of spalling
	Large	Water control (cutoff, drainage), crack injection, surface treatment (covering, impregnation), prevention of spalling, cross-sectional restoration, prestressing, steel plate/FRP sheet bonding, overlay, steel/PC/FRP jacketing, external tendon
IV(deterioration stage)	Small	Water control (cutoff, drainage), cross-sectional restoration, surface treatment (covering), prevention of spalling, prestressing, steel plate/FRP sheet bonding, overlay, steel/PC/FRP jacketing, external tendon

*: Preventive method

For details of various repair and reinforcement methods, refer to, for example, the Report of the Subcommittee on Alkali–Aggregate Reaction Control (Japan Society of Civil Engineers), Recommendations for Concrete Repair and Surface Protection of Concrete Structures (Japan Society of Civil Engineers), Recommendations for Strengthening of Concrete Structures (Japan Society of Civil Engineers), Report of JCI Committee on Rehabilitation of Concrete Structures (Japan Concrete Institute) and the Guideline for Electrochemical Corrosion Control Methods Considering ASR (The Society of Materials Science, Japan).

Considerations in selecting repair and reinforcement methods and materials are as follows:

(i) Progress of ASR and appearance grades

The rate of progress of ASR does not necessarily correspond to the appearance grade of the structure. As shown in Fig. C13.1.1, if the quantity of reactive minerals contained in the aggregate is relatively small, the amount of expansion due to ASR may be relatively small so that deterioration does not progress very much for many years. When making decisions on repair or reinforcement, therefore, it is important to take into consideration both the present rate of progress of ASR and the appearance grade of the structure. The rate of progress of ASR is judged from the results of regular assessment of the structure or residual expansion results obtained from accelerated curing tests on core samples. If the appearance grade of the structure is at the propagation stage or the acceleration stage and a considerable amount of expansion is expected in future, it is necessary to think of taking measures such as water control (cutoff, drainage), surface treatment (covering, impregnation), crack injection, prevention of spalling, cross-sectional restoration and measures to provide restraint against expansion such as prestressing and steel/PC/FRP jacketing.

(ii) Water control (cutoff, drainage)

Before selecting repair/reinforcement methods and materials, it is necessary, as a basic approach, to take water control (cutoff, drainage) measures so that water is not supplied to the structure from external sources. Because these measures are important in order to control the progress of ASR, they must be implemented regardless of the appearance grade of the structure. If there is a deteriorated bridge pier or abutment, possible sources of water such as expansion devices, drainage pipes, deck slab drainage pipes, etc., are investigated. If water from such sources has been found, water control measures, such as making expansion joints non-draining and drainage end treatment (drainage treatment) measures for drains and drain pipes, must be implemented in a reliable manner. It is also necessary to take such precautionary measures as sloping and draining the top faces of piers and abutments to prevent water from collecting there. In regions where deicing agents are used, these measures are particularly important in order to prevent deterioration due to the combined effects of water and other deterioration factors such as freeze–thaw cycles or chloride attack. If drains in structural parts or members such as abutments or retaining walls that are under the influence of backside water are clogged, the drainage holes must be cleared, and additional drainage holes must be installed on an as-needed basis.

(iii) Repairs related to hazards for third party or appearance

Structures whose performance has been degraded by ASR are prone to not only cracking but also bleeding of alkali–silica gel. If alkali–silica gel is polluted by vehicle exhaust gases, surface discoloration may also occur to ASR-affected structures. Repairs may be carried out, therefore, for reasons related to the appearance of concrete structures. Repairs may also be carried out in view of impacts on third parties such as scaling or spalling of concrete.

(iv) Performance of surface lining materials

Performance attributes required of surface lining materials used for structures deteriorated by ASR include crack bridging ability, impermeability, water vapor permeability, weather resistance, alkali resistance, bondability with concrete, carbon dioxide impermeability, oxygen impermeability, freeze–thaw resistance and chloride impermeability. Among these, crack bridging ability, water impermeability and water vapor impermeability are particularly important. Since, however, deterioration due to the combined effects of deterioration factors related to other attributes such as freeze–thaw cycles and chloride attack may result depending on the environmental conditions surrounding the ASR-affected structure, it is also necessary to carefully consider other performance attributes.

(v) Surface lining materials expected to contribute mainly to water impermeability

In the case of a structure whose performance has been degraded by ASR, ASR-induced expansion can be controlled by preventing the intrusion of water from external sources or by adjusting the water content of concrete by dissipating water from internal sources. Surface lining materials expected to contribute mainly to water impermeability are effective in controlling ASR if the concrete is in a dry state or if water intrusion from an outside source is expected. In this case, it is necessary to completely cover the structural members. If the water content of the concrete is high or the members cannot be covered completely, the use of surface lining materials might not only fail to achieve the expected repair effect but also cause water to be confined and accumulated in the structure. It is therefore necessary to carefully study the state of the structure such as the presence of backside water and, if necessary, install drainage holes. If it is difficult to judge whether the surface treatment method using surface lining materials is appropriate, it is good practice to make combined use of the surface treatment method using a silane impregnation agent mentioned in Item (iv) and the crack injection method and observe the state of the structure after the surface treatment measures are taken.

(vi) Silane surface impregnant agents expected to contribute mainly to water repellency

This method is a very effective ASR control method if the environmental conditions are such that water intrusion can be prevented and water in the concrete can be dissipated. Water intrusion through cracks is prevented by means of crack injection or crack filling. It is important to use a surface lining material that does not hamper water dissipation to cover the surface impregnant material.

(vii) Lithium nitrite or other surface impregnant agents

ASR can be controlled by impregnating concrete with lithium ions in a quantity corresponding to the quantity of alkali metal ions in the concrete. When applying this method, it is necessary to study details such as the quantity of lithium ions to be used for impregnation, the depth and extent of impregnation and impregnation methods. After impregnation, it is necessary to cover the surface to prevent lithium ions and nitrite ions from being washed out by rainwater, etc. It is necessary to pay careful attention to the outflow of nitrite ions during construction work as well as before and after it.

(viii) Repair and reinforcement to achieve safety and serviceability goals

It has been generally believed that ASR-induced cracks in a structure do not affect the load-carrying capacity of the structure. There are cases, however, in which repair or reinforcement was carried out for a structure in which excessive expansion occurred because of ASR. Also, in cases where expansion occurs over a long period of time and excessive expansion of concrete occurs during that period, large tensile forces act on the reinforcing bars used to restrain the concrete against expansion. Consequently, in a structure always under the influence of water and with a low steel ratio, reinforcing steel damage (yielding, cracking, breaking) may occur in the bent-bar zones. Repair or reinforcement is necessary in these cases, too.

In cases where measures are taken to enhance the mechanical performance of an existing structure, usually large-scale construction work needs to be carried out because scaffolding and heavy construction equipment are used. It is possible, therefore, to conduct a detailed investigation during that construction period and decide on and carry out large-scale repair or reinforcement against ASR on the basis of the investigation results. Even if the purpose is to enhance mechanical performance, repair or reinforcement must be carried out, taking into consideration not only the mechanical performance but also ASR-induced deterioration, so that the required performances can be met throughout the specified service period. For example, in cases where steel jacketing is carried out for the purpose of seismic strengthening, the water impermeability of the steel plates enhances the effectiveness of steel jacketing as an ASR control method.

13.5 Recording

(1) Investigation, deterioration estimation, evaluation and judgment, and remedial measures shall be recorded in accordance with Part 1.

(2) Items relevant to ASR shall be recorded.

[Commentary] As a general rule, the results of investigations, deterioration estimations, evaluations and remedial measures must be recorded in accordance with **Part 1**. Items relevant to ASR require careful attention, particularly with respect to record keeping. Items to be recorded are indicated in Section **13.3.2** “Investigation in Assessment" and the evaluation items indicated in Section **13.3.4** “Evaluation and Judgment.”

CHAPTER 14　MAINTENANCE OF REINFORCED CONCRETE SLABS SUBJECT TO FATIGUE

14.1 General

(1) This chapter provides standard methods for maintenance planning, assessment, remedial measures and recording for reinforced concrete slabs whose performance has deteriorated or is likely to deteriorate because of fatigue. The items common to all deterioration mechanisms are shown in Part 1.

(2) This chapter shall be applied to structures of the maintenance category A (preventive maintenance) and B (corrective maintenance).

[Commentary] (1) Reinforced concrete slabs for road bridges (hereafter referred to as "slabs") are thin for their span lengths (girder spacings). Because slabs are members that directly support wheel loads, they are representative structures whose performance is degraded by fatigue caused by cyclic loading.

Because bending moment is a governing factor in the design of slabs, inspection is made by the allowable stress method based on the elastic thin plate bending theory, and it has generally been believed that slabs are sufficiently safe against cyclic loads. Cracking of the underside of the slab and spalling of concrete, however, began to be seen in the first half of the 1970s, and in some cases concrete slabs caved in even though the reinforcing bars were in a sound condition. Studies have shown that the main cause of slab fatigue was the passing of overloaded vehicles. It has also been shown, however, that deterioration is accelerated by the combined effect of a number of factors, such as the infiltration of rainwater into the slabs because of the lack of waterproof layers and the nonconformity of existing structures to the current design standard (e.g., thin slab thickness, large span length) until the slabs fail in punching shear. Today, various types of slabs that are highly durable against fatigue are already in use. Since, however, the fatigue resistance of slabs has improved, it is now possible that fatigue-induced deterioration occurs in steel materials and joints with girders instead of in concrete. In order to prevent fatigue-induced deterioration in these parts of structures, therefore, structural details and joints that are highly durable against fatigue have been put to practical use. When managing slabs, it is necessary to pay attention to these vulnerable parts of structures.

On the basis of examples of slabs severely deteriorated because of fatigue and the results of studies on the causes of such deterioration, the process of fatigue-induced deterioration of slabs can be divided into the initiation stage, propagation stage, acceleration stage and the deterioration stage as shown in Fig. C14.1.1 and Table C14.1.1. The performance of a structure is affected differently at different stage of deterioration, and the degree of performance degradation due to deterioration also varies among different deterioration stages. Methods, therefore, for assessment (investigation, deterioration prediction, evaluation and judgment), remedial measures and recording varies among different deterioration stages.

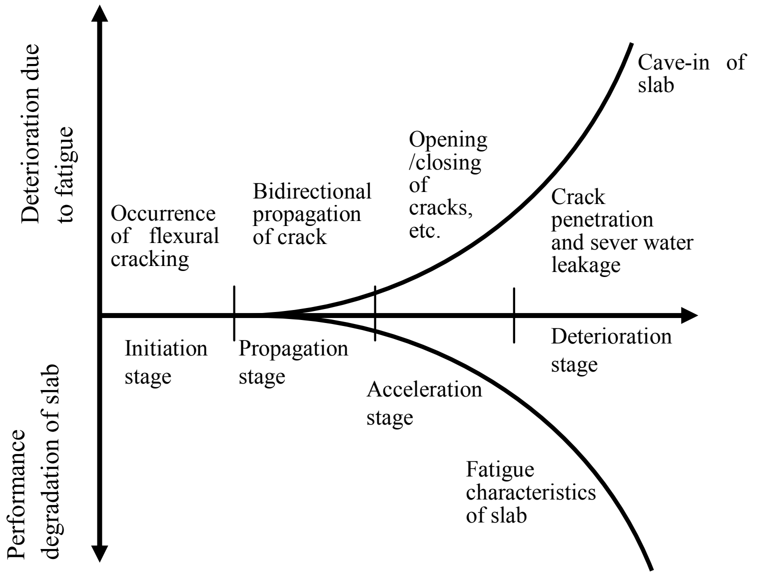


Fig. C14.1.1 Conceptual view of deterioration progress due to fatigue of concrete slab

Table C14.1.1 Definitions of deterioration stages

Stage of deterioration	Definition	Factor determining the stage
Initiation stage (state I)	Several unidirectional cracks along the main reinforcement due to drying shrinkage and loading can be seen. Depending on the girder restraint conditions, cracks perpendicular to the bridge axis may develop because of drying shrinkage or changes in girder temperature.	Applied design standards: slab thickness, amount of distribution reinforcement, slab span length Construction: drying shrinkage Service conditions: traffic volume, vehicle weight (axle load), vehicle location
Propagation stage (state II)	Flexural cracks along the main reinforcement grow, and at the same time cracks along the distribution reinforcement begin to grow and map cracking occurs. Crack density visibly increases considerably, but the continuity of the reinforced slab (tow way plate) has not yet been lost.	
Acceleration stage (state III)	Interconnection of cracks into fine networks increases, and opening/closing of cracks and crack surfaces begin to rub one another. After cracks form slits and corners fall, the resistance of the concrete cross section is no longer dependable. Consequently, the punching shear capacity of the concrete slab begins to decrease.	In addition to the factors mentioned above: Environmental conditions: influence of seepage water Remedial measures taken: bridge deck waterproof membrane; repair/strengthening
Deterioration stage (state IV)	The occurrence of penetrating cracks in the cross section of the slab causes the continuity of the slab to be lost, and the resultant beam-like members separated by the penetrating cracks have to resist wheel loads. The ultimate strength of the member is affected by such factors as penetrating crack spacing, concrete strength	All factors mentioned above

	and the amount of reinforcement steel.	

(2) The performance of the slabs of an existing bridge varies mainly with the environment in which the structure is placed (e.g., load history, rainfall and snowfall) and the design standards applied. In cases where a bridge has no bridge deck waterproof membrane, the effects of fatigue are unavoidable, so maintenance category B is applied to many slabs. If waterproofed slabs are properly constructed, performance degradation due to fatigue is not likely to become a problem for about 50 years. Maintenance category A can also be applied if traffic loads (axle loads), vehicle locations on the bridge, cracks, etc., can be monitored. This chapter, therefore, applies to structures in the maintenance category A and B.

Matters to consider when deciding on the maintenance category for a slab that has deteriorated or is likely to be deteriorated because of fatigue are described in **14.2.2** "Determination of Maintenance Category." Important considerations for different types of maintenance are also described in this chapter.

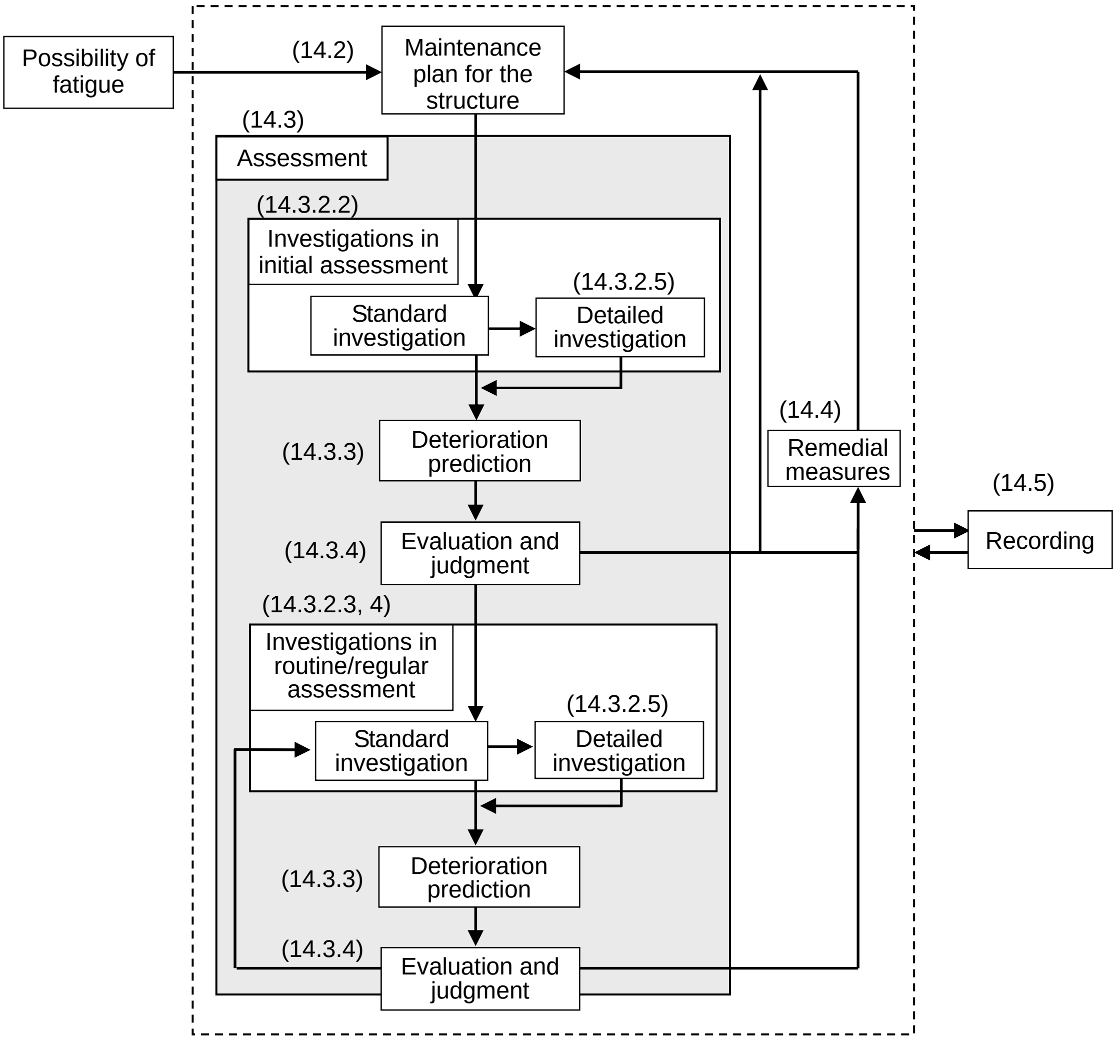


Fig. C14.1.2 Standard maintenance procedure of reinforced concrete slabs under fatigue stress

14.2 Maintenance Planning

14.2.1 Basis of planning

In order to maintain reinforced concrete slabs under fatigue stress, the maintenance category shall be selected, the service period planned, and a maintenance planning for activities including assessment, remedial measures and recording drawn up in advance in view of the service conditions such as the magnitude and frequency of live loads and the environmental conditions such as the supply of rainwater.

［**Commentary**］ When drawing up a maintenance planning for reinforced concrete slabs under fatigue stress, it is necessary to cover such details as check items and procedures for the initial assessment and check items, procedures, timing and frequency for routine and regular assessment, evaluation and judgment methods, actions to be taken in the event of deterioration, and recording methods, taking into consideration the service conditions such as the type of structure, applicable standards, degree of importance, planned service period, maintenance category, large vehicle traffic volume and vehicle locations, the environmental conditions such as the supply of rainwater to the upper surface of the slab, and other factors such as the quality of materials and the existence or nonexistence of a bridge deck waterproof membrane.

It is usually difficult, at the stage of maintenance planning, to accurately predict the state of a structure during its service period. It is therefore good practice to draw up a maintenance planning with reference to the deterioration of a similar structure or a structure in a similar environment.

14.2.2 Determination of maintenance category

The maintenance category of reinforced concrete slabs under fatigue stress shall be selected in view of the degree of importance of the structure, the type of structure, hazards for third party, the planned service period and the characteristics of deterioration due to fatigue.

[Commentary] The determination of the maintenance category is very important because maintenance planning vary widely depending on the maintenance category. The progress of deterioration and performance degradation of reinforced concrete slabs due to fatigue is conceptually illustrated in Fig. C14.1.1.

In order to apply maintenance category A (preventive maintenance), it is necessary to perform maintenance at the initiation stage, in which map cracking has not yet occurred, in order to prevent the performance degradation of the structure due to fatigue. This makes it necessary to investigate the state of the structure as accurately as possible and carry out the following:

(i) Quantitative evaluation and prediction of the axle weight of passing vehicles, total weight, the number of loading cycles, vehicle location, etc.

(ii) Determination of the influence of water such as rainwater

If maintenance category A is applied, in many cases large-scale repair and reinforcement can be avoided so that the maintenance cost can be kept low.

If maintenance category B (corrective maintenance) is applied, it is necessary to conduct investigation relying mainly on visual observation periodically in order to check on the progress of deterioration from the state of cracking at the underside of the slab. To be more specific, some kind of action is taken after the following types of deterioration are found:

(i) Initiation of map cracking at the underside of the slab

(ii) Initiation of opening/closing of cracks and rubbing between crack surfaces

(iii) Penetrating cracks in the slab cross section and occurrence of water leaks or free lime

Even when maintenance category B (corrective maintenance) is applied, it is desirable that repair be carried out at Stage (i). It should be kept in mind that if deterioration reaches Stage (ii) or (iii), large-scale remedial measures need to be taken.

14.2.3 Preparation of maintenance manuals

A maintenance manual describing methods, procedures and frequency requirements should be prepared for each structure in accordance with the maintenance planning, taking the structure-specific conditions into consideration.

[Commentary] The service period of civil engineering structures is long, and maintenance of those structures is performed over a long period of time. It is recommended, therefore, that in order to inform investigators of maintenance concepts and policies, a maintenance manual be prepared so that detailed procedures and methods can be communicated accurately even to newly assigned maintenance engineers.

Under certain circumstances such as in cases where the original maintenance planning is altered because the actual progress of deterioration turned out to differ from that assumed in the original maintenance planning, it is necessary to modify the maintenance manual and take appropriate maintenance measures accordingly.

Manuals such as “Maintenance Manual for Reinforced Concrete Slabs under Fatigue Stress Conforming to Standard Specifications for Concrete Structures: Maintenance” can be used as a reference when preparing a maintenance manual.

14.3 Assessment

14.3.1 General

In the assessment of a reinforced concrete slab whose performance has declined or is highly likely to decline because of fatigue, investigation, evaluation of the present state, deterioration prediction and judgment of necessity for remedial measures shall be appropriately conducted in accordance with the maintenance planning.

[Commentary] In order to maintain concrete structures appropriately, this specification requires three types of assessment: initial assessment, regular assessment and extraordinary assessment. Because the initial and periodic assessments are essential for the maintenance of reinforced concrete slabs under fatigue stress, this chapter stipulates that those assessments must be conducted. Extraordinary assessments are regarded as assessments to be conducted on an as-needed basis and are therefore not dealt with in this chapter. By conducting periodic assessments during the maintenance period, defects in appearance of structures can be discovered before they occur or in early stages, and remedial measures including preventive measures and repairs can be taken systematically.

14.3.2 Investigation in assessment

14.3.2.1 General

Investigations in initial, routine and regular assessment of a reinforced concrete slab under fatigue stress shall be conducted appropriately according to the maintenance category required for the structure. Prior to investigation, check items, methods, frequency and scope of standard investigation shall be determined appropriately. For each type of assessment, detailed investigation shall also be conducted on an as-needed basis.

[Commentary] It is important to select check items, methods, frequency and scope of investigation appropriately according to the purpose of investigation in accordance with the maintenance planning.

Defects peculiar to the fatigue of slabs include the map cracking of the underside of the concrete slab and map crack densification. If defects of these types have been found, the slab has been deteriorated because of fatigue. Check items and checking methods in investigation of a slab, therefore, consist mainly of a visual observation of defects in appearance. Table C14.3.1 lists main check items at each stage of fatigue-induced deterioration of slabs. If evaluation or judgment based on defects in appearance or the road surface condition is difficult, it is necessary to conduct investigation for items such as crack behavior, cross-sectional quantities, load-carrying capacities and traffic characteristics. Table C14.3.2 lists main investigation methods for different check items.

Investigation concerning the service conditions and environmental conditions that affect the fatigue of slabs are also important. For example, the degree of fatigue increases as the number of passing large vehicles increases. Even among identical structures, if large vehicles are allowed to pass, through lanes are more prone to fatigue than passing lanes. If the slab concrete surface is in a wet condition as in rainy regions, fatigue is accelerated. In areas under the influence of seawater such as coastal areas or in cold regions where deicing agents are applied to roads on a daily basis in winter, it is necessary to take into consideration not only fatigue-induced deterioration but also deterioration due to chloride attack.

Table C14.3.1 Main check items in investigation

Stage of Deterioration	Defects in appearance	Road surface defects	Crack behavior	Cross-sectional quantities	Load-carrying capacity	Traffic characteristics	Monitoring
Initiation stage	O	▲	▲	▲*	▲*	▲*	▲
Propagation stage	O	▲*	▲	▲*	▲*	▲*	▲
Acceleration stage	O	▲*	▲*	▲*	▲*	▲*	▲*
Deterioration stage	O	O	O	▲*	▲*	▲*	▲*

O:priority check item,▲:item preferably to be checked,▲*:item to be checked on an as-needed basis

Table C14.3.2 Investigation methods of reinforced concrete slab

Investigation item		Investigation Method
Defects in appearance	State of crack (direction, density, width, corner falls), water leakage, free lime, discoloration of concrete	Visual observation, simple measurement, photography
	Abnormal sound	Sounding
Road surface defects	Crack, cave-in	Visual observation, photography
Crack behavior	Depth, opening/closing, surface unevenness	Contact gauge, etc.
Cross-sectional quantities	Concrete strength	Test hammer, core test
	Rebar arrangement	Electromagnetic radar method, ultrasonic radar method, etc.
	Slab thickness	Ultrasonic method, etc.
Load-carrying capacity	Deflection	Loading test
Traffic characteristics	Traffic volume, large vehicle percentage, lane-by-lane traffic volume percentages, type of vehicle, axle load	Traffic volume survey, load measurement

14.3.2.2 Investigation in initial assessment

(1) In initial assessment, appropriate check items for standard investigation shall be selected for newly constructed structures, existing structures, large-scale repairs and strengthened structures.

(2) If deterioration prediction, evaluation or judgment is difficult to make through a standard investigation alone, a detailed investigation shall be conducted.

[Commentary] (1) Investigation in initial assessment is the first investigation conducted when the maintenance of a concrete structure is started. Investigation in initial assessment includes not only the first investigation of a newly constructed structure conducted before it goes into service but also the first investigation of an existing structure or a structure for which remedial measures have been taken in response to deterioration. Investigation items may vary from structure to structure.

In the case of a newly constructed slab, it is necessary to record, as part of investigation results, not only records on the quality of materials and construction such as the quality of concrete, slab thickness and concrete cover but also records on initial defects such as drying shrinkage and defective construction joints and remedial measures taken in connection with those initial defects. In the case of an existing slab or a slab for which remedial measures have been taken, records on quality control and investigation at the construction stage may not exist, and the load history to date may not be clear, either. For these types of slabs, therefore, the investigation conducted after fatigue-induced deterioration is discovered is usually regarded as the investigation in initial assessment. In such cases, standard investigation items need to be determined with reference to **14.3.2.5 "**Detailed Investigation."

(2) If evaluation and judgment cannot be made with high accuracy by standard investigation alone or if a highly deteriorated part of a structure needs to be investigated, a detailed investigation is necessary. Check items of a detailed investigation are indicated in **14.3.2.5** "Detailed Investigation."

14.3.2.3 Investigation in routine assessment

(1) In routine assessment, standard investigation designed basically to check on concrete surface defects such as cracking, peeling and spalling, rust stain, free lime and discoloration and appearance deterioration such as water leakage, and displacement and deformation shall be conducted.

(2) If deterioration prediction, evaluation or judgment is difficult to make by standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) The purpose of investigation in routine assessment is to detect deterioration at an early stage by checking on defects in the state of a structure over time and, if necessary, take remedial measures while the deterioration is still a minor problem. The determination of details such as the time and place of occurrence also yield information that may be helpful in predicting future deterioration.

Because slabs are always under harsh service conditions, it is necessary to check on changes in the state of slabs on a daily basis and detect the progress of deterioration at the earliest possible stage. Investigation in routine assessment of a slab consists mainly of the investigation of the state of the underside of the slab such as the state of cracks, spalling of concrete, water leaks and free lime.

The purpose of investigation in routine assessment conducted by the manager of slabs is not only to check on the occurrence or signs of occurrence of performance degradation but also to check on serviceability and hazards for third party such as safety of passing vehicles and spalling of concrete. If maintenance category A is applied, monitoring shown in Table C14.3.3 may be conducted as part of investigation in routine assessment.

(2) If high-accuracy evaluation or judgment is difficult by conducting standard investigation alone or if severe deterioration has occurred, detailed investigation is conducted. Check items of detailed investigation are described in detail in **14.3.2.5** "Detailed Investigation."

14.3.2.4 Investigation in regular assessment

(1) The purpose of investigation in regular assessment is to obtain information that is difficult to obtain in routine assessment. In regular assessment, standard investigation consisting of detailed observation of defects in appearance such as cracks shall be conducted as in routine assessment.

(2) If deterioration prediction, evaluation or judgment is difficult through standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) and (2) The purpose of investigation in regular assessment, which is conducted once in one to several years, is to obtain information that is difficult to obtain in a routine assessment. In regular assessment, areas where the progress of deterioration has been identified in routine assessment are investigated in greater detail.

In the investigation in regular assessment of a slab, standard investigation of the slab are conducted at close range to observe the state of the underside of the slab, measure crack density and crack width, check for corner falls, check on crack behavior such as crack opening/closing and displacement, and evaluate the quality of concrete by the sounding method. Regular assessment intervals are determined by the maintenance manager in view of the service conditions and environmental conditions. It is difficult to quantify the state of deterioration by simple investigation methods such as visual observation and sounding. After fatigue-induced deterioration has been detected, therefore, it is good practice to monitor not only the density (direction), width and behavior of cracks, deflection, etc., but also traffic characteristics such as traffic volume and vehicle loads by using such devices as traffic flow monitoring cameras and axle load measurement systems in order to monitor the progress of deterioration and take preventive measures accordingly. Examples of traffic characteristics monitoring are shown in Table C14.3.3.

Table C14.3.3 Examples of monitoring items and methods for traffic characteristics

Monitoring item related to traffic characteristics	Method
Traffic volume survey Traffic volume, large vehicle percentage, lane-by-lane traffic volume percentage, vehicle type surveys, etc.	Traffic volume survey, records by use of traffic flow monitoring system, etc.
Vehicle load survey	Axle load measurement, back analysis of deflection measurement results, etc.

(2) If high-accuracy evaluation or judgment is difficult even after the standard investigation or if deterioration is severe, detailed investigation is conducted. Detailed investigation is described in detail in **14.3.2.5** “Detailed Investigation.”

14.3.2.5 Detailed investigation

Detailed investigation shall be conducted to obtain detailed information on a structure in cases where the deterioration of a reinforced concrete slab deteriorated because of fatigue is difficult to predict, evaluate or judge by standard investigation alone conducted as part of the initial, routine or regular assessment. Check items, methods and location of detailed investigation shall be selected appropriately taking into consideration such factors as the purpose of investigation and the accuracy of obtained results.

[Commentary] Detailed investigation is conducted when the determination of the present state of a structure and the deterioration of the structure are difficult by standard investigation results alone or when anomalous deterioration of a slab has occurred in order to obtain information necessary for purposes such as detailed evaluation of the degree of deterioration, studies on the cause of deterioration, and studies on subsequent progress of deterioration and repair or reinforcement methods to be used.

Main check items and investigation methods for detailed investigation and items that can be evaluated through that investigation are shown in Table C14.3.4.

Table C14.3.4 Examples of evaluation items in detailed investigation

Investigation item		Investigation Method	Evaluation item
Items related to displacement	Deflection	Loading test	Degree of deterioration
	Crack behavior	Loading test	Degree of deterioration
	Crack depth	Ultrasonic method, core sampling	Degree of deterioration
Items related to materials	Concrete strength	Test hammer, core strength test	Prediction of progress of deterioration
	Concrete quality	Laboratory test on core samples	Prediction of progress of deterioration
	Concrete cross section	Core sampling, etc.	Prediction of progress of deterioration
	State of rebar arrangement	Electromagnetic radar method, ultrasonic method, chipping survey	Prediction of progress of deterioration
Items related to traffic characteristics	State of load	Traffic volume survey, vehicle weight (axle load) measurement, etc.	Prediction of progress of deterioration

14.3.3 Methods for predicting performance degradation of structures

14.3.3.1 General

(1) In the maintenance of a reinforced concrete slab under fatigue stress, the performance degradation of the slab shall be evaluated quantitatively at the time of investigation, and future degradation shall be predicted.

(2) In order to predict the performance degradation of a reinforced concrete slab, it is necessary to predict deterioration due to fatigue quantitatively.

(3) If (2) is difficult, an alternative method is to predict performance degradation by predicting the length of the initiation, propagation, acceleration and deterioration stages, taking into consideration the progress of cracking at the underside of the slab.

(4) As a general rule, deterioration shall be predicted on the basis of investigation results.

[Commentary] (1) and (2) In the performance-verification type maintenance method, changes (deterioration) in various performance of a structure are to be predicted. To do that, it is necessary to predict the progress of deterioration of the materials constituting the slab, especially the cracking of concrete, quantitatively. It is also necessary to quantitatively evaluate the performance of the slab and the degree of deterioration of the materials constituting the slab at the time of investigation and at the end of the planned service period on the basis of investigation results. The performance degradation of the structure or the degree of deterioration of the constituent materials at the time of investigation can be evaluated by using an appropriate method on the basis of the investigation results. Performance and the degree of deterioration at the end of the planned service period are predicted on the basis of the regular investigation results by predicting the subsequent progress of deterioration over time.

An example of a method for quantitatively predicting the progress of deterioration of a slab under fatigue stress is to use the S–N relation derived from a punching shear fatigue test using a wheel tracking machine. If the structural conditions of the structure under consideration and the load conditions can be reproduced accurately from the investigation results, quantitative fatigue prediction can be made by using the S–N relation. The actual rate of progress of slab fatigue, however, is affected by many conditions such as design and construction conditions including slab thickness, concrete strength and the amount of distribution steel, service conditions including passing traffic volume, axle loads of large vehicles and vehicle locations and environmental conditions including the supply of rainwater to the upper surface of the slab. It is not easy to identify these conditions. In winter, attention needs to be paid to the progress of steel corrosion, too, because deicing agents may be used. When trying to predict the progress of fatigue of a slab, it is necessary to take into consideration the factors affecting deterioration mentioned above and allow for an appropriate factor of safety.

(3) and (4) In order to predict fatigue-induced deterioration of a slab, it is necessary to identify the environmental conditions, such as cross-sectional performance, axle loads of passing large vehicles, vehicle locations and water, for each structure. Since, however, these conditions are difficult to determine by the prediction methods in use today, predictions are inherently uncertain.

Deterioration may be predicted semiquantitatively, therefore, from the visually observed state of the underside of the slab and factors affecting the progress of deterioration. As shown in Fig. C14.3.1, fatigue-induced cracks at the underside of the slab can be classified, according to the stage of deterioration, into the initiation stage, at which unidirectional flexural cracks occur at the underside of the slab, the propagation stage, at which cracks become bidirectional, the acceleration stage, at which cracks begin to open and close, and the deterioration stage, at which penetrating cracks and considerable water leaks occur, and the punching shear resistance of the slab decreases. At the deterioration stage, bleeding of white powdery substance may be seen at the pavement surface as a precursor of falling of blocks. Also, the deterioration of the cover concrete along the upper surface of the slab may result in the occurrence of pot holes at the pavement surface. These stages of slab deterioration and factors determining their duration of each stage are summarized in Table C14.1.1.

It is relatively easy to identify the stage of deterioration of a slab by observing the state of cracking at the underside of the slab with reference to the descriptions shown above. Since, however, crack density may not increase beyond a certain limit, it is risky to try to determine the duration of a stage of deterioration according to the amount of cracking alone. In this case, it is necessary to observe the width and depth of cracks, crack behavior such as the amount of crack opening, closing and faulting, water leaks, bleeding of free lime, road surface defects, etc.

State I	State II	State III	State IV
(initiation stage)	(propagation stage)	(acceleration stage)	(deterioration stage)
Unidirectional cracking	Bidirectional cracking	Densification of cracks and corner falls	Cave-in of slab

Fig. C14.3.1 Progress of cracking at underside of reinforced concrete slab

14.3.3.2 Modification of prediction

If the state of deterioration determined in investigation differs from a predicted state of deterioration, the cause of the difference shall be identified and the prediction shall be revised accordingly. If necessary, the maintenance planning shall be altered.

[Commentary] When the deterioration confirmed in investigation is different from the prediction, appropriate investigation should be conducted with reference to the deterioration prediction methods described in **14.3.3.1** "General," and the explanation table in **14.3.2.5** "Detailed Investigation," to identify the cause of the difference from the prediction and revise the prediction accordingly. It is also important to reconsider such details as the frequency of investigation in view of the revised prediction and alter the maintenance planning if necessary.

14.3.4 Evaluation and judgment

(1) The evaluation of performance and judgment as to whether remedial measures need to be taken based on the results of the investigation in initial, routine and regular assessment shall be made in accordance with Part 1 and Item (2) and subsequent items in this section.

(2) The performance of a reinforced concrete slab under fatigue stress shall be evaluated by appropriately selecting performance to be evaluated in view of the stage of deterioration of the reinforced concrete slab.

(3) The evaluation of performance at the time of investigation and at the end of the planned service period of the reinforced concrete slab should be made by a quantitative method.

(4) If Item (3) is difficult to achieve, the evaluation of performance at the time of investigation and at the end of the planned service period of the reinforced concrete slab may be made by a semiquantitative grading-based method.

(5) Judgment as to whether remedial measures need to be taken shall be made in view of the degree of performance degradation of the reinforced concrete slab due to fatigue, the degree of importance of the structure, maintenance category, and the remaining service life.

[Commentary] (1) The evaluation of performance and judgment of necessity for remedial measures in initial, routine and regular assessment for structures in which little progress of deterioration has been recognized are frequently more or less the same regardless of the deterioration mechanism. For details, refer to **Part 1**. The evaluation of performance and judgment of necessity for remedial measures for structures in which deterioration may have or has progressed vary according to the deterioration mechanism. When discussing the performance degradation of a reinforced concrete slab due to fatigue, the descriptions in this chapter should be consulted.

(2) In the case of a slab under fatigue stress, performance affected by deterioration and the degree of performance degradation vary depending on the stage of deterioration (initiation stage, propagation stage, acceleration stage or deterioration stage). Performance to be evaluated at each stage of deterioration, therefore, needs to be selected on the basis of the state of cracking at the underside of the slab as shown in Fig. C14.3.1. For example, at the initiation or propagation stage, serious problems related to safety or serviceability do not occur, but it may be necessary to evaluate steel protection performance, which is a durability-related performance attribute because regions causing steel corrosion may enter through cracks depending on the environment in which the structure is placed. At the propagation stage, appearance begins to be a performance attributes to be evaluated. At the acceleration stage, hazards for third party associated with peeling, spalling, etc., also needs to be evaluated in addition to appearance because cracks begin to form slits and corners begin to fall. Safety and serviceability also need to be evaluated because the dynamic properties of concrete cross sections begin to decline. At the deterioration stage, map cracks grow into

penetrating cracks and, depending on the circumstances, the slab may caves in. Because of these forms of degradation associated with safety, serviceability and hazards for third party, the evaluation of these performances is very important.

(3) and (4) Under the present conditions, quantitative evaluation to determine to what extent the performance of a slab declines since the initiation of maintenance and when the allowable limit state is reached is difficult. For example, safety can be evaluated by checking on load-carrying capacity through a loading test conducted at the time of investigation, but safety in future is difficult to predict. There are also performances that are difficult to evaluate quantitatively at the time of investigation. An alternative, therefore, is semiquantitative evaluation made by the method described below. As the first step, the stage of deterioration at the time of investigation is determined from the state of the underside of the slab by using Table C14.1.1. At the same time, the stage of deterioration at the end of the service period is estimated through deterioration prediction, and the stage of deterioration and the appearance grade are related. The degree of performance degradation of the structure can be judged or estimated to some extent from the appearance of the structure with reference to Table C14.3.5. If, therefore, the stage of deterioration can be determined or predicted by using these tables, the performance of the structure can be evaluated semiquantitatively.

(5) Because judgment is the act of deciding whether remedial measures need to be taken on the basis of the results of performance evaluation of slabs, there is no difference depending on deterioration factors. Therefore, refer to **Part 1**.

Table C14.3.5 Structural appearance grading and typical performance degradations

<table>
<tr><th>Structural appearance grade</th><th>Safety performance</th><th>Serviceability performance</th><th>Hazards for third party Appearance</th></tr>
<tr><td>State I
(initiation stage)</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>State II
(propagation stage)</td><td>—</td><td>—</td><td>—</td></tr>
<tr><td>State III
(acceleration stage)</td><td>Decrease in shear stiffness
•Slit formation by cracks, corner falls</td><td>—</td><td rowspan="2">Degradation in appearance
• Cracking
• Free lime
• Cave-in of concrete surface
Hazards for third party
• Peeling
• Spalling</td></tr>
<tr><td>State IV
(deterioration stage)</td><td>Decrease in load-carrying capacity
• Penetrating cracks
• Infiltration of rainwater
• Steel corrosion</td><td>Road surface damage due to fatigue
• Cracking and cave-in of road surface</td></tr>
</table>

14.4 Remedial Measures

14.4.1 Selection of remedial measures

(1) If it has been judged that remedial measures need to be taken in connection with performance degradation due to fatigue, remedial measures shall be taken so that the structure after the measures meets the required performances.

(2) If it is difficult to select remedial measures on the basis of performance verification, remedial measures may be selected from the measures corresponding to the appearance grade for the fatigue of a slab.

[Commentary] (1) If it has been judged, as a result of evaluation, that remedial measures need to be taken, it is necessary to select one or more of the following measures: (i) intensified investigation, (ii) repair, (iii) strengthening, (iv) functional improvement, (v) restriction in service or (vi) dismantling/removal. Basically, decisions as to which measures to take should be made by the maintenance manager of the structure, but it is good practice to refer to **Part 1** for information on typical relationships between evaluation and judgment results and remedial measures.

(2) If it is difficult to select remedial measures through quantitative evaluation or judgment, remedial measures are selected from the measures corresponding to the grade of fatigue-induced deterioration of the slab. Remedial measures to be taken vary depending on the type of structure, the degree of importance of the structure, deterioration rate and the maintenance category, but recommended standard measures are shown in Table C14.4.1. Measures related to functional improvement are not shown in the table because it is not related to the grade of fatigue-induced deterioration.

At the initiation or propagation stage, at which the degree of deterioration of the slab due to fatigue is relatively low, intensified investigation suffices. At and after the acceleration stage, however, appropriate repair or strengthening measures need to be selected, taking into consideration the service conditions and the environmental conditions. An alternative is to select a number of remedial measures or take remedial measures by stages in view of the service conditions of the slab and the environmental conditions. Because the fatigue of slabs is greatly affected by water, it is desirable that remedial measures be taken in conjunction with bridge deck waterproofing. If remedial measures are taken for the underside of a slab, bridge deck waterproofing should be carried out first before other remedial measures are taken. The reason is that if remedial measures for the underside of the slab are taken first, rainwater and other water retained in the slab would have adverse effects on fatigue and other deterioration mechanisms (chloride attack, freeze–thaw damage, alkali–silica reaction).

Because of the possibility of recurrence of deterioration, investigation in routine and regular assessment need to be conducted even after remedial measures are taken. In one example, after the steel plate adhesion method and the overlay method were applied to a deteriorated slab, the cracks in the slab grew because of increases in traffic volume and in the number of overloaded vehicles, and the required performance was not maintained until the end of the of the structure.

Table C14.4.1 Appearance grades of reinforced concrete slabs and remedial measures

Appearance grade of reinforced concrete slab	Intensified investigation	Repair	Strengthening**	Restriction in service	Dismantling/removal
I(initiation stage)	O	(O)	X		
II(propagation stage)	OO	OO	X		
III(acceleration stage)	OO	OO*	X		
IV(deterioration stage)	O	OO*	X	O	O

OO:standard measures(OO*:including restoration of mechanical performance）,O:measures to be taken under certain circumstances,

(O):preventive measures, Strengthening**:designed to achieve performance level higher than initial level,

X:measures taken in accordance with criteria other than appearance grade

14.4.2 Prevention measures

If a reinforced concrete slab is at high risk of performance degradation due to fatigue, deterioration shall be prevented by installing a bridge deck waterproof membrane over the upper surface of the reinforced concrete slab so that water such as rainwater does not enter the slab.

[Commentary] If a reinforced concrete slab is at high risk of performance degradation due to fatigue, installing a bridge deck waterproof membrane over the upper surface of the slab is effective in preventing the progress of fatigue due to abrasion resulting from the intrusion of rainwater or other water into the slab. From many types of bridge deck waterproof membrane, an appropriate type needs to be selected in view of the waterproofing effect, constructibility, economy and the degree of contact with the asphalt pavement. In cases where a waterproof membrane with a high waterproofing effect is used, the space between the asphalt pavement and the waterproof membrane is easily infiltrated by water. It is therefore necessary to carefully consider ways to drain such water.

14.4.3 Repair and strengthening

Methods and materials for the repair or strengthening of a reinforced concrete slab shall be selected taking into consideration performance degradation due to fatigue and life cycle cost, so that the required effect can be achieved.

[Commentary] In cases where repair or strengthening is carried out as a remedial measures, it is necessary to define the expected effect of repair or strengthening and the required performance (what level of performance to be maintained for how many years?).

Repair or strengthening methods can be classified, according to expected effects, as shown in Table C14.4.2.

When deciding on which method to use, it is necessary to take into consideration the present state of performance degradation of the structure concerned besides the expected effect. For the correspondence between appearance deterioration grades and standard repair and strengthening methods, refer to Table C14.4.3. The repair or strengthening methods listed in the table are well-proven methods. If poorly field-tested materials are used, it is desirable that investigation frequency be increased after the repair or strengthening is done.

For details of various repair or strengthening methods, refer to, for example, “Recommendations for Strengthening of Concrete Structures,” “Report of the Committee on Repair Methods for Concrete Structures (I, II and III) (Japan Concrete Institute)” and “Report of JCI Committee on Rehabilitation of Concrete Structures (Japan Concrete Institute).”

Many of the repair or strengthening methods in use today were developed in recent years, and some of them have not been field-tested extensively. Those methods might fail to prevent the recurrence of deterioration or achieve the required performance because of factors that could not be expected at the design stage. In the event of the recurrence of deterioration, repair or strengthening measures need to be taken again. In such cases, it is important to carefully investigate the extent, state, cause, etc., of re-deterioration, select appropriate control measures and materials and carry out repair or strengthening again.

Table C14.4.2 Examples of repair or strengthening methods and expected effects

Expected effect	Example of repair/strengthening method
Improvement in terms of hazards for third party and appearance	Surface treatment (lining)
Improvement in fatigue durability achieved by eliminating the influence of water	Installation of bridge deck waterproof membrane
Improvement in fatigue durability achieved by controlling crack opening	FRP sheet adhesion, prestressing
Restoration of cross-sectional stiffness achieved by installing members at extreme tension fiber	Adhesion of steel plates, etc., on underside of slab, overlay to enlarge cross section of reinforced concrete, installation of additional girders
Improvement of fatigue durability achieved by improving shear stiffness of compression zone of cross section	Overlay on upper surface of slab

Table C14.4.3 Appearance grades of slabs deteriorated by fatigue and examples of standard repair/strengthening methods

Appearance grade of slab	Standard repair/strengthening method
I (initiation stage)	Bridge deck waterproof membrane*
II (propagation stage)	Bridge deck waterproof membrane, Steel plate/FRP sheet adhesion, overlay on upper surface, overlay on underside, additional girder
III (acceleration stage with	Bridge deck waterproof membrane, steel plate

influence of water)	adhesion, overlay on upper surface
III (acceleration stage without influence of water)	Bridge deck waterproof membrane, steel plate adhesion, overlay on upper surface, additional girder
IV (deterioration stage)	Restriction in service, dismantling/removal

*:preventive maintenance method

14.5 Recording

(1) Investigation, deterioration prediction, evaluation and judgment, and remedial measures shall be recorded in accordance with Part 1.

(2) Items relevant to the fatigue of reinforced concrete slabs shall be recorded.

[Commentary] As a general rule, the results of investigation, deterioration prediction, evaluation and remedial measures must be recorded in accordance with **Part 1**. Items relevant to fatigue require careful attention, particularly with respect to record keeping. Items to be recorded are indicated in **14.3.2** "Investigation in Assessment" and **14.3.4** "Evaluation and Judgment."

CHAPTER 15 MAINTENANCE OF REINFORCED CONCRETE BEAMS SUBJECT TO FATIGUE

15.1 General

(1) This chapter provides standard methods for maintenance planning, assessment, remedial measures and recording for reinforced concrete beams whose performance has deteriorated or is likely to deteriorate because of fatigue. The items common to all deterioration mechanisms are shown in Part 1.

(2) This chapter shall be applied to structures of the maintenance category A (preventive maintenance) and B (corrective maintenance).

[Commentary] (1) Failure of a material resulting from cyclic applications of loads usually smaller than the static strength of the material is referred to as "fatigue" or "fatigue failure." Fatigue of a concrete structure refers to the phenomenon in which the performance of the structural members of a concrete structure deteriorates as cracks occur in the reinforcing steel (e.g., reinforcing bars, prestressing tendons) or concrete constituting the structure because of cyclic loading, and eventually the structure fails under normal loads.

This chapter provides standard methods of maintaining beams that are highly likely to be subjected to cyclic application of relatively large variable loads.

Fatigue-induced performance degradation of beams occurs in various forms including (1) decrease in safety due to fatigue breaking of tensile reinforcing steel, (2) decrease in safety due to compression fatigue failure of concrete, (3) decrease in stiffness or degradation in terms of hazards for third party or appearance due to propagation or enlargement of flexural cracks, (4) decrease in safety due to shear fatigue failure (propagation of diagonal cracks) of concrete and (5) decrease in safety due to fatigue breaking of shear reinforcing bars.

Because of typical service conditions (loading effects) for a structure and its cross-sectional details, investigation and evaluation of the fatigue of beams focus mainly on decreases in stiffness due to fatigue breaking of tensile and shear reinforcing steel and propagation and enlargement of flexural cracks and shear cracks in concrete and hazards for third party due to spalling, etc., of cracked concrete. This chapter, therefore, provides maintenance methods for beams whose durability is determined by fatigue breaking of reinforcing steel. Maintenance methods for beams whose durability is determined by fatigue of concrete must be determined separately in due consideration of the environmental conditions and other factors.

In one recent incident, flexural cracks in the concrete of a girder of an express railway bridge grew past the neutral axis of the member because of resonance. In another incident, severe cracking of a road bridge was caused by large vehicles passing the bridge. In recent years, however, there has been no reported incidence of structural member failure caused by the fatigue of reinforcing steel even in the case of a long-used structure. Likely reasons are that actual loads are usually smaller than design loads, and actual loads in reinforcing steel are reduced to levels smaller than design values by the dissipation of loads in the beams, the contribution of nonstructural members to the stiffness of girders and the bearing of part of tensile stress by concrete. For example, it has been reported that actual stresses measured at rapid transit bridge girders were smaller than half of the design values. Another likely reason is that design values for fatigue strength contain a margin of safety. The investigation and evaluation provided in this chapter may be omitted if it can be clearly judged, on the basis of a sufficient amount of information, that even members subjected to cyclic loading are highly unlikely to be subject to fatigue. In prestressed concrete members, the amplitude of stress in prestressing steel due to variable loads is very small unless cracking occurs. In cases where prestressing steel are bonded to concrete, studies on fatigue may be omitted unless cracking of concrete occurs. Depending on the circumstances, however, prestressed concrete members with unbonded prestressing steel may require investigation and evaluation paying attention to anchorage zones.

Fig. C15.1.1 illustrates the relationship between the deterioration stages of a beam under fatigue stress and performance degradation. Table C15.1.1 lists definitions of each stages of deterioration in the load-carrying capacity of members and factors determining the stage of deterioration.

Fig. C15.1.2 shows a standard procedure for fatigue-related maintenance of beams.

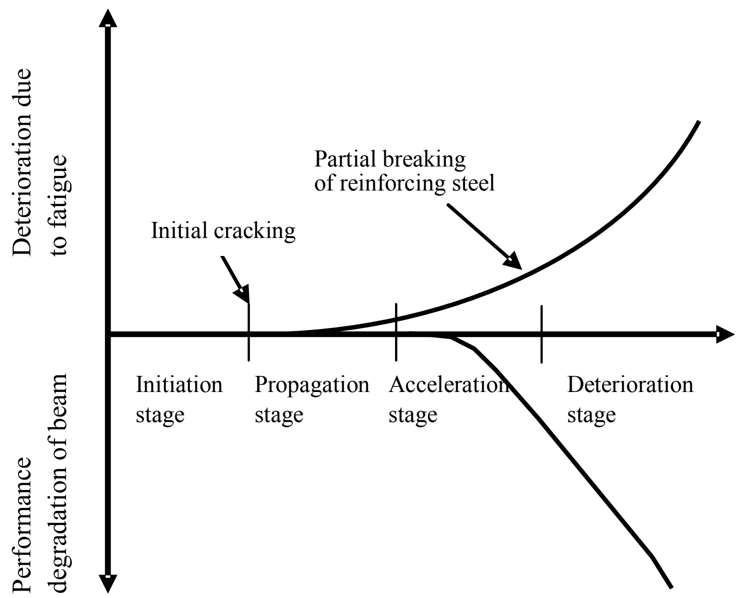


Fig. C15.1.1 Conceptual view of deterioration progress due to fatigue-induced of beam

Table C15.1.1 Definitions of deterioration stages

Stage of deterioration	Definition	Factor determining the stage
Initiation stage	• Stage at which metallic crystal level slip is occurring in the reinforcing steel because of cyclic loading, but usually detectable initial cracks have not yet occurred	Fatigue crack propagation rate
Propagation stage	• Stage at which initial cracks occur in the reinforcing steel, and early-stage cracks become large enough to be detected by magnetic particle investigation • Stage at which crack propagation occurs at a rate dependent on the material composition of steel • Stage at which the loss of cross section due to fatigue cracking of the steel is minor and has little impact on load-carrying capacity	
Acceleration stage	• Stage at which fatigue cracks in the steel become close to critical crack length, part of the steel is on the verge of fatigue breaking, and load-carrying capacity might decrease	
Deterioration stage	• Stage at which fatigue breaking of the reinforcing steel in the beam occurs locally, and stresses are redistributed in the reinforcing steel to induce further fatigue breaking	

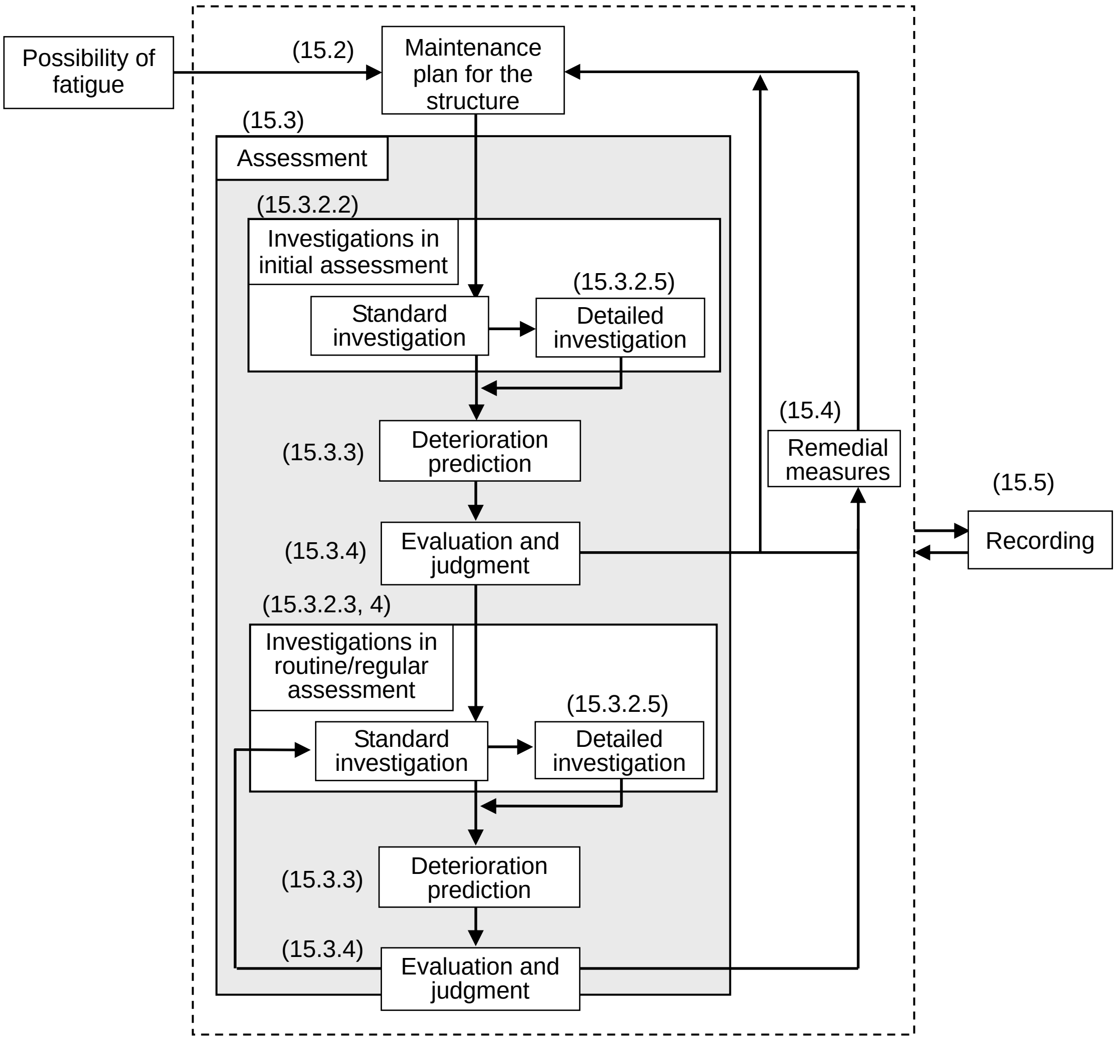


Fig. C15.1.2 Standard maintenance procedure of beam under fatigue stress

(2) This chapter applies to beams in the maintenance category A and B.

As mentioned earlier, in the case of a normally designed structure, studies on fatigue may be omitted if there is no anomaly. Although not clearly known because no information is available on examples of fatigue failures of beams, initial cracking of reinforcing steel does not occur immediately after an anomaly in appearance occurs. Instead, the member fails only after a certain amount of time has passed following the initial breaking of steel. It has also been reported that even after initial cracking of reinforcing steel occurs, a number of reinforcing bars placed in the beam break sequentially instead of all at once.

These indicate that maintenance category A may be applied to a beam to be maintained before fatigue cracking of reinforcing steel occurs. It is difficult, however, to detect initial cracking of reinforcing steel by nondestructive testing. It is recommended, therefore, that in cases where the width of cracks (e.g., cracks caused by other factors, flexural cracks allowed for at the design stage) in the concrete exceeds the critical value considered at the design stage or in cases where cracks or deflections are too large, fatigue-related maintenance be performed indirectly by ascertaining through measurement, etc., that reinforcing steel strains are not greater than the critical strain for cracking.

If cracking of reinforcing steel has already occurred, maintenance category B is applied.

15.2 Maintenance Planning

15.2.1 Basis of planning

In order to maintain beams under fatigue stress, the maintenance category shall be selected, the service period planned, and a maintenance planning for activities including assessment, remedial measures and recording drawn up in advance in view of the service conditions such as the magnitude and frequency of variable loads.

［**Commentary**］When drawing up a maintenance planning, it is necessary to cover such details as check items and procedures for the initial assessment and check items, procedures, timing and frequency for routine and regular assessment, evaluation and judgment methods, actions to be taken in the event of deterioration, and recording methods, taking into consideration the type of structure, the degree of importance of the structure, planned service period, maintenance category, service conditions and the quality of materials.

It is usually difficult, at the stage of maintenance planning, to accurately predict the state of a structure during its service period. It is therefore good practice to draw up a maintenance planning with reference to the deterioration of a similar structure or a structure in a similar environment.

15.2.2 Determination of maintenance category

The maintenance category of beams under fatigue stress shall be selected in view of the degree of importance of the structure, the type of structure, hazards for third party, the planned service period and the characteristics of deterioration due to fatigue.

[Commentary] The determination of the maintenance category is very important because maintenance plannings vary widely depending on the maintenance category. The progress of deterioration and performance degradation of beams due to fatigue is conceptually illustrated in Fig. C15.1.1.

In order to apply maintenance category A (preventive maintenance) to a structure, it is necessary to perform maintenance at the initiation stage, in which initial cracking of the steel in the concrete has not yet occurred, in order to prevent the performance degradation of the structure. This makes it necessary to investigate the state of the structure as accurately as possible and carry out the following:

(i) Quantitative evaluation of concrete surface crack width

(ii) Quantitative evaluation and prediction of the magnitude of variable loads, the number of loading cycles, load locations, etc.

(iii) Amplitude of stress in reinforcing steel

Structures to which maintenance category B (corrective maintenance) is applied need to be maintained so that structural performance does not fail to meet the required performances. For example, maintenance is performed so that deterioration can be prevented until the deterioration stage if attention is paid to safety and until the latter half of the acceleration stage if attention is paid to serviceability. In this case, some kind of action is taken after the following deterioration is identified:

(i) Initial cracking of steel has been observed.

(ii) Fatigue cracks in steel are close to critical crack length.

(iii) Breaking of steel has been observed.

It is desirable that repair is done at Stage (i) or Stage (ii) mentioned above even in the case of a structure to which maintenance category B (corrective maintenance) is applied. Large-scale remedial measures need to be taken if deterioration make progress to Stage (iii). In investigation, therefore, checks must be made on not only the service conditions (e.g., load conditions and frequency) and changes in appearance such as the state of cracks but also other details such as (a) fatigue cracks, (b) length of fatigue cracks in reinforcing steel and (c) amplitude of stress in reinforcing steel.

15.2.3 Preparation of maintenance manuals

A maintenance manual describing methods, procedures and frequency requirements should be prepared for each structure in accordance with the maintenance planning, taking the structure-specific conditions into consideration.

[Commentary] The service period of civil engineering structures is long, and maintenance of those structures is performed over a long period of time. It is recommended, therefore, that in order to inform investigators of maintenance concepts and policies, a maintenance manual be prepared so that detailed procedures and methods can be communicated accurately even to newly assigned maintenance engineers.

Under certain circumstances such as in cases where the original maintenance planning is altered because the actual prediction of deterioration turned out to differ from that assumed in the original maintenance planning, it may be necessary to modify the maintenance manual and take appropriate remedial measures accordingly.

15.3 Assessment

15.3.1 General

In the assessment of a beam whose performance has declined or is highly likely to decline because of fatigue, investigation, evaluation of the present state, deterioration prediction and judgment of necessity for remedial measures shall be appropriately conducted in accordance with the maintenance planning.

[Commentary] In order to maintain concrete structures appropriately, this specification requires three types of assessment: initial assessment, periodic assessment and extraordinary assessment. Because the initial and periodic assessments are essential for the maintenance of beams under fatigue stress, this chapter stipulates that those assessments must be conducted. Extraordinary assessments are regarded as assessments to be conducted on an as-needed basis and are therefore not dealt with in this chapter. By conducting periodic assessments during the maintenance period, changes in appearance of structures can be discovered before they occur or in early stages, and remedial measures including preventive measures and repairs can be taken systematically.

15.3.2 Investigation in assessment

15.3.2.1 General

Investigation in initial, routine and regular assessment of a beam under fatigue stress shall be conducted appropriately according to the maintenance category required for the structure. Prior to investigation, check items, methods, frequency and scope of standard investigation shall be determined appropriately. For each type of assessment, detailed

investigation shall also be conducted on an as-needed basis.

[Commentary] It is important to select check items, methods, frequency and scope of investigation appropriately according to the purpose of investigation in accordance with the maintenance planning.

In order to evaluate the fatigue-induced deterioration of a beam and accurately predict the deterioration, it is necessary, for example, to measure the amplitude of reinforcing steel stresses under variable loads with strain gauges attached to the beam and checking for fatigue cracks in the reinforcing steel. These can be done, however, only by removing the cover concrete and using precision measuring instruments. If there are many beams under similar conditions, it is possible to determine the relationship between deflections, etc., of relatively easy-to-measure beams under variable loads and the amplitude of reinforcing steel stresses in advance and estimate, by using the relationship thus determined, the amplitude of stresses in the reinforcing steel in the members to be maintained. This is an indirect method of estimation but it is useful in deterioration prediction with relatively high accuracy.

In general, investigation vary depending on the stage of deterioration. Table C15.3.1 lists main check items at each stage of fatigue-induced deterioration. The state at the initiation stage can be roughly evaluated mainly by referring to the design drawings and specifications and conducting visual observation. If the design conditions and service conditions indicated in the drawings and specifications can be identified through monitoring, sampling, etc., the information thus obtained is useful for deterioration prediction. At and after the propagation stage, investigation that make it possible to directly determine the prediction of fatigue of the reinforcing steel are necessary.

If the state of the structure cannot be identified appropriately through standard investigation, detailed investigation must be conducted.

Table C15.3.1 Main check items in investigation

Stage of Deterioration	Design conditions	Service conditions (load,frequency)	State of cracking	Crack opening width	Member deflection	Steel stress amplitude	Fatigue crack (scan)	Concrete strain	Monitoring
Initiation stage	O	O	O	▲*	▲*	▲*	▲*	▲*	▲*
Propagation stage	▲	O	O	O	O	▲	▲	▲*	▲*
Acceleration stage	▲*	O	O	O	O	O	O	▲	▲*
Deterioration stage	▲*	O	O	O	O	O	O	▲	▲*

15.3.2.2 Investigation in initial assessment

(1) In initial assessment, appropriate check items for standard investigation shall be selected for newly constructed structures, existing structures, large-scale repairs and strengthened structures.

(2) If deterioration prediction, evaluation or judgment is difficult to make through standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) Investigation in initial assessment is the first investigation conducted when the maintenance of a concrete structure is started. Investigation in initial assessment includes not only the first investigation of a newly constructed structure conducted before it goes into service but also the first investigation of an existing structure or a structure for which remedial measures have been taken in response to deterioration. Investigation items may vary from structure to structure.

Information needed to predict the progress of fatigue of a beam includes the amplitude of stress acting on the reinforcing steel and the number of loading cycles. When selecting investigation items in initial assessment, it is necessary to take into consideration the service conditions for the member and the relationship with the investigation items in routine or regular assessment .

When conducting the investigation in initial assessment of a newly constructed structure, it is possible to predict the deterioration from the information obtained from the design drawings and specifications. The goal here is to check whether the load conditions are not more severe than the design assumptions and whether the applied loads are not too large in view of the state of cracking, etc. It is also important to identify the members to monitor at the subsequent stages.

In cases where the investigation in initial assessment of an existing structure is conducted, deterioration can be predicted as in the case of a newly constructed structure if the design drawings and specifications exist and the service conditions, etc., have been identified through monitoring. If the design drawings and specifications are not available and the service conditions, etc., are not clearly known, it is necessary to estimate the load history by investigating the service conditions or measuring the amplitude of stress in the reinforcing steel directly or indirectly. If such investigation are conducted, it is advisable to obtain data necessary for deterioration prediction indicated in **15.3.3.2** “Prediction of Fatigue,” with reference to **15.3.2.5** “Detailed Investigation.”

In cases where investigation in initial assessment of a structure for which remedial measures have been taken is conducted, usually a study on the mechanical aspects of the structure has already been conducted, and therefore necessary data are available from the drawings and specifications used for the study. If the remedial measures taken are not related to fatigue, it is good practice to predict the deterioration by a method similar to the method used for a newly constructed structure.

Table C15.3.2 Typical investigation items in initial assessment

Inspection item	Inspection Method	Necessity
Service conditions (e.g., load conditions, frequency)	Design drawings and specifications or monitoring	O
State of cracking	Visual inspection	O
Crack opening amplitude	Measurement by use of π gauge	▲
Member deflection	Measurement by use of displacement meter	▲
Reinforcing steel stress	Measurement by use of strain gauge	▲

(2) If high-accuracy evaluation or judgment is difficult to make by conducting standard investigation alone or if severe deterioration has already occurred, detailed investigation is conducted. Check items of detailed investigation are described in **15.3.2.5** "Detailed Investigation."

15.3.2.3 Investigation in routine assessment

(1) In routine assessment, standard investigation designed basically to check on appearance deterioration such as the state of cracking shall be conducted.

(2) If deterioration prediction, evaluation or judgment is difficult to make by standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) It is difficult to predict the fatigue of reinforcing steel from changes in appearance such as the state of cracking. If, however, the deterioration is predicted with sufficient accuracy at the time of the initial assessment and it is judged that the initiation stage is sufficiently long compared with the design service period or the planned service period, the present state of the structure can be identified through appearance investigation on the state of cracking, etc., conducted during investigation in routine assessment. In such cases, the identification of the state of deterioration in appearance is the basic purpose of standard investigation. In investigation in routine assessment, however, of a structure to which maintenance category A is applied, it is good practice to conduct monitoring in order to indirectly or directly check on the service conditions such as the magnitude and frequency of working loads, the amplitude of stress in the reinforcing steel, etc., depending on the circumstances.

Table C15.3.3 Typical investigation items in routine assessment

Investigation item	Investigation method	Necessity
Service conditions (e.g., load conditions, frequency)	Monitoring	▲
State of cracking	Visual inspection	O

(2) If high-accuracy evaluation or judgment is difficult by conducting standard investigation alone or if severe deterioration has occurred, detailed investigation is conducted. Check items of detailed investigation are described in detail in **15.3.2.5** "Detailed Investigation."

15.3.2.4 Investigation in regular assessment

(1) The purpose of investigation in regular assessment is to obtain information that is difficult to obtain in routine assessment. In regular assessment, standard investigation consisting of detailed observation of defects in appearance such as cracks shall be conducted as in routine assessment.

(2) If deterioration prediction, evaluation or judgment is difficult through standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) Investigation in regular assessment is conducted for the purpose of obtaining information that is more detailed than the information obtainable from a routine assessment. Members that have been identified as requiring attention in the initial or routine assessment need to be investigated intensively.

Check items consist mainly of appearance items such as the state of cracking as in a routine assessment, but it is good practice to combine those check items with other check items depending on the stage of deterioration on an as-needed basis so that the stage of deterioration can be identified with higher accuracy.

Table C15.3.4 lists typical check items of investigation conducted as part of a regular assessment of a beam under fatigue stress. Intervals between regular assessment must be determined appropriately by the maintenance manager in view of the service conditions.

In cases where the deterioration needs to be predicted with high accuracy through regular investigation of a structure to which maintenance category A is applied, it is good practice to select check items by which the amplitude of stress in the reinforcing steel can be determined directly or indirectly from the check items of detailed investigation.

Table C15.3.4 Typical investigation items in regular assessment

Inspection item	Inspection method	Necessity
Service conditions (e.g., load conditions, frequency)	Design drawings and specifications or monitoring	▲
State of cracking	Visual inspection	O
Crack opening amplitude	Measurement by use of π gauge	▲
Member deflection	Measurement by use of displacement meter	▲

O:priority check item,▲:item to be checked on an as-needed basis

(2) If high-accuracy evaluation or judgment is difficult even after standard investigation or if deterioration is severe, detailed investigation is conducted. Detailed investigation is described in detail in **15.3.2.5** “Detailed Investigation.”

If deterioration such as rapid propagation or enlargement of cracks due to fatigue of reinforcing steel has been found by visual observation, detailed investigation needs to be conducted urgently because the fatigue of the reinforcing steel is thought to be at an advanced stage.

15.3.2.5 Detailed investigation

Detailed investigation shall be conducted to obtain detailed information on a structure in cases where the deterioration of a beam under fatigue stress is difficult to predict, evaluate or judge by standard investigation alone conducted as part of the initial, routine or regular assessment. Check items, methods and location of detailed investigation shall be selected appropriately taking into consideration such factors as the purpose of investigation and the accuracy of obtained results.

[Commentary] Detailed investigation is conducted when the determination of the present state of a structure and the deterioration of the structure are difficult by standard investigation results alone in order to obtain information necessary for those purposes. In detailed investigation of a beam subject to fatigue stress, direct determination of the amplitude of stress acting on the reinforcing steel and checking on fatigue cracks at the steel surface are important for accurate prediction of the progress of fatigue. It is also good practice to quantitatively relate the investigation items checked during routine and regular assessment with the amplitude of stress acting on the reinforcing steel.

Loads considered in connection with stress amplitude measurement are in many cases loads that are acting under normal conditions. If it is difficult to measure the magnitude of loads accurately or if high-accuracy measurement needs to be conducted, it is good practice to take measurements by letting controllable, predetermined loads (e.g., test vehicle, loading apparatus) act. Table C15.3.5 shows detailed investigation items and methods for a beam under fatigue stress. Table C15.3.6 lists important considerations in measuring the amplitude of stress in the reinforcing steel and checking for fatigue cracks at the steel surface.

Table C15.3.5 Detailed investigation items and methods

Investigation item	Investigation method
Service conditions (e.g., load conditions, frequency)	Design drawings and specifications or monitoring
State of cracking	Visual inspection
Crack opening amplitude	Measurement by use of π gauge
Member deflection	Measurement by use of displacement meter
Reinforcing steel stress	Measurement by use of strain gauge
Checks for fatigue crack	Magnetic particle inspection method, fluorescent penetrate method, eddy current method, ultrasonic method, radiation method
Steel arrangement	Electromagnetic radar method, electromagnetic induction method
Quality of concrete	Core sampling, surface hardness method, ultrasonic method

Table C15.3.6 Investigation methods and important considerations

Investigation item	Method and considerations
Amplitude of stress in reinforcing steel	To measure stress in the reinforcing steel of a simple beam, a high-stress region such as a center span region is selected, the cover concrete in an appropriate section is removed, and a strain gauge is bonded to the steel surface for strain measurement. If steel stress cannot be measured directly because exposing reinforcing steel would create a maintenance problem, the steel arrangement and concrete cover are investigated by an appropriate method, concrete strain is measured, and steel stress is calculated by an appropriate method.
Fatigue cracking of in reinforcing steel	To check for fatigue cracks in the reinforcing steel, a high-stress region is selected as in the stress amplitude measurement, the cover concrete in an appropriate section is removed, and inspection is conducted by a nondestructive testing method such as the magnetic particle inspection method.

15.3.3 Methods for predicting performance degradation of structures

15.3.3.1 General

(1) In the maintenance of a beam under fatigue stress, the performance degradation of the beam shall be evaluated quantitatively at the time of investigation, and future degradation shall be predicted.

(2) In order to predict the performance degradation of a beam, it is necessary to predict deterioration due to fatigue quantitatively.

(3) If (2) is difficult, an alternative method is to predict performance degradation by predicting the length of the initiation, propagation, acceleration and deterioration stages, taking into consideration the progress of fatigue of the reinforcing steel.

(4) As a general rule, deterioration shall be predicted on the basis of investigation results.

[Commentary] (1) and (2) In the performance-verification type maintenance method, changes (deterioration) in various performance of a structure are to be predicted. To do that, it is necessary to predict the progress of deterioration of the materials constituting the beam, especially the prediction of fatigue of the reinforcing steel, quantitatively. It is also necessary to quantitatively evaluate the performance of the beam and the degree of deterioration of the materials constituting the beam at the time of investigation and at the end of the planned service period on the basis of investigation results. The performance degradation of the beam or the degree of deterioration of the constituent materials at the time of investigation can be evaluated by using an appropriate method on the basis of the investigation results. Performance and the degree of deterioration at the end of the planned service period are predicted on the basis of the periodic assessment results. Since, however, deterioration prediction results do not necessarily agree with the actual progress of deterioration, it is important to review the prediction method on the basis of the results of two or more investigation conducted subsequently.

(3) In cases where high-accuracy measurement is conducted continuously in a laboratory or

other controlled environment, it is possible to determine the process of deterioration through appearance observation, but in the case of a real structure, that is not possible except at the final stage of the deterioration process. If, however, attention is paid to the fatigue process of the reinforcing steel, which is a main factor contributing to the fatigue failure of the member, the process leading to the fatigue breaking can be divided, as in other deterioration predictions, into the initiation, propagation, acceleration and deterioration stages.

There is a crack propagation law based on destruction dynamics is a steel crack propagation model. The relationship between fatigue crack length and the number of loading cycles is illustrated in Fig. C15.3.1.

By using this model, the deterioration process can be divided into the initiation stage, which is the period until the occurrence of the first visible crack, the propagation stage, which is the period during which fatigue cracks grow relatively stably, the acceleration stage, which is the period in which openings of cracks begin to appear at the fracture sides until breaking occurs, and the deterioration stage, which is the period in which part of the reinforcing steel in the beam begins to break and the load-carrying capacity of the beam decreases. The relationship between the deterioration stages and performance degradation is shown in Fig. C15.1.1, and the factor determining the deterioration stages and their durations is indicated in Table C15.1.1. The amplitude of stress in a structure tends to be relatively small, and the initiation stage is usually longer than the other stages.

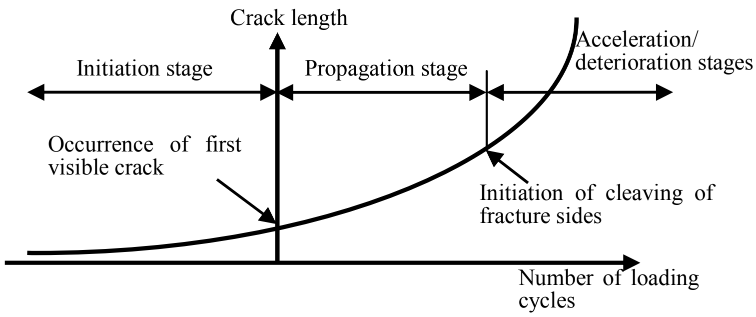


Fig. C15.3.1 Model of fatigue crack propagation in reinforcing steel

(4) Investigation results include data related to the state of the investigated members and the service conditions of the structure. As a general rule, deterioration prediction must be made on the basis of those investigation results. If, however, such investigation results are not available because prediction is to be made at the planning stage or for members of an existing structure, it is necessary to make conservative predictions, taking uncertain factors into consideration. The factor of safety to be used in this case should be determined with reference to, for example, the “Design” volumes of the Standard Specifications. It is also possible to refer to investigation results or the state of deterioration of similar members under identical environmental conditions.

15.3.3.2 Prediction of fatigue

(1) The progress of fatigue of a beam shall be predicted in due consideration of the influence of the design conditions and the service conditions.

(2) The progress of fatigue of a beam may be predicted by applying the crack propagation law for reinforcing steel or the linear cumulative damage law.

[Commentary] The prediction of fatigue of a beam is affected by the variable load (stress amplitude) level and the number of stress cycles. In order to predict the progress of fatigue, therefore, it is important to allow for the service conditions and the design conditions such as cross-sectional details and the quality of reinforcing steel appropriately. With respect to service conditions, in the case of a railway bridge, it may be possible to predict working loads and their history with relatively high accuracy. In the case of a road bridge or an offshore structure, working loads vary widely, so monitoring should be conducted to enhance prediction accuracy.

Because stress waves in a structure are irregular instead of repetitions of constant stresses, those waves need to be converted to repetitions of independent stress waves. There are many conversion methods, and it is necessary to select an appropriate method depending on load conditions and characteristics of the structure. The range pair method and the rainflow method are often used for railway bridges, and the zero-up crossing method is widely used for offshore structures. From independent waves obtained by these methods, the equivalent number of cycles corresponding to a constant stress amplitude by using, for example, the modified Miner's rule. Stresses due to not only variable loads but also permanent loads occur in beams. If stresses due to permanent loads are taken into account, tools such as the figure of Goodman relations are used.

(2) There is no established method of predicting the fatigue of beams. There are simple methods, however, using laws such as the crack propagation law, which uses fatigue crack length in reinforcing steel, a main factor contributing to the fatigue failure of a member, as an indicator, and the linear cumulative damage law as described below.

(i) Prediction based on the crack propagation law

According the crack propagation law, the relationship between the fatigue crack propagation rate (da/aN) in reinforcing steel and stress can be expressed as

$$\frac{da}{dN} = C \cdot \Delta K^m \qquad \text{(Eq.C15.3.1)}$$

where

a: crack length

N: number of stress cycles

ΔK: stress intensity factor ($= \Delta\sigma\sqrt{\pi \cdot a}$)

$\Delta\sigma$: stress amplitude

C, m: coefficients (usually determined by the properties of reinforcing steel)

On the basis of the relation shown above, the crack length a_N after N loading cycles at a stress amplitude of $\Delta\sigma$ can be calculated from the equation shown below Eq. (C15.3.2) to estimate the fatigue crack length in the reinforcing steel.

$$a_N = \sqrt[\frac{1}{\frac{m}{2}-1}]{\left[\frac{1}{a_i^{\frac{m}{2}-1}} - N \cdot C \cdot \left(F \cdot \Delta\sigma \cdot \sqrt{\pi}\right)^m \cdot \left(\frac{m}{2}-1\right)\right]^{-1}} \qquad \text{(Eq.C15.3.2)}$$

where

a_i: initial crack length

F: correction factor (for example, 1.12 for a surface crack)

If the reinforcing steel in the beam is exposed in investigation and crack length is measured by, for example, the magnetic particle inspection method, the prediction of fatigue cracking after the investigation can be estimated by replacing the initial crack length with the measured crack length.

(ii) Prediction based on the linear cumulative damage law

The method using degree of cumulative fatigue damage expressed in Eq. (C 15.3.3) is a simple method for predicting the fatigue.

$$M = \sum_i \frac{n_i}{N_i} \qquad \text{(Eq.C15.3.3)}$$

where

M: degree of cumulative fatigue damage

n_i: number of stress cycles with amplitude of S_{ri}

N_i: fatigue life due to stress with amplitude of S_{ri}

Unlike the crack propagation law described in (i) above, the degree of cumulative fatigue damage is not designed for direct evaluation of fatigue-induced deterioration. The progress of deterioration, however, can be predicted qualitatively by determining thresholds for identifying deterioration stages. Table C15.3.7 shows examples of relationship of deterioration stages with fatigue crack length and degree of cumulative fatigue damage. Although varying depending on the investigation method, the initial crack length ranges roughly from 0.05 mm to 0.5 mm. Critical crack length varies depending on the reinforcing steel diameter, working stress and strength (destruction ductility). The thresholds for the deterioration stages based on degree of cumulative fatigue damage shown in the table are reference only values based mainly on structural soundness grading for the maintenance of steel railway bridges. Thresholds, therefore, should be determined appropriately in view of such factors as the service conditions and the method and frequency of investigation.

Table C15.3.7 Stages of fatigue-induced deterioration and prediction of deterioration

State	Stage of deterioration	Crack length a	Degree of cumulative fatigue damage M
I	Initiation stage	$a \leq a_i$	$M \leq 0.8$
II	Propagation stage	$a_i < a \leq a_f$	$0.8 < M \leq 1$
III	Acceleration stage	$a > a_f$	$M > 1$
IV	Deterioration stage		

a_i:initial crack length, a_f:critical crack length

15.3.3.3 Modification of prediction

If the state of deterioration determined in investigation differs from predicted state of deterioration, the cause of the difference shall be identified and the prediction shall be revised accordingly. If necessary, the maintenance planning shall be altered.

[Commentary] When the deterioration confirmed in investigation is different from the prediction, appropriate investigation should be conducted with reference to the deterioration prediction methods described in**15.3.3.2** "Prediction of Fatigue," and Table 15.3.5 in **15.3.2.5** "Detailed Investigation," to identify the cause of the difference from the prediction and revise the prediction accordingly. For example, if predictions for degree of cumulative fatigue damage differ from detailed investigation results, the deterioration stages may be modified on the basis of fatigue crack length predictions. It is also important to reconsider such details as the frequency of investigation in view of the revised prediction and alter the maintenance planning if necessary.

14.3.4 Evaluation and judgment

(1) The evaluation of performance and judgment as to whether remedial measures need to be taken based on the results of the investigation in initial, routine and regular assessment shall be made in accordance with Part 1 and Item (2) and subsequent items in this section.

(2) The performance of a beam under fatigue stress shall be evaluated by appropriately selecting performance to be evaluated in view of the stage of deterioration of the beam.

(3) The evaluation of performance at the time of investigation and at the end of the planned service period of the structure should be made by a quantitative method.

(4) If Item (3) is difficult to achieve, the evaluation of performance at the time of investigation and at the end of the planned service period of the structure may be made by a semiquantitative grading-based method.

(5) Judgment as to whether remedial measures need to be taken shall be made in

view of the degree of performance degradation due to fatigue, the degree of importance of the structure, maintenance category, and the remaining planned service period.

[Commentary] (1) The evaluation of performance and judgment of necessity for remedial measures in initial, routine and regular assessment for structures in which little progress of deterioration has been recognized are frequently more or less the same regardless of the deterioration mechanism. For details, refer to **Part 1**. The evaluation of performance and judgment of necessity for remedial measures for structures in which deterioration may have or has progressed vary according to the deterioration mechanism. When discussing the performance degradation of a reinforced concrete beam due to fatigue, the descriptions in this chapter should be consulted.

(2), (3) and (4) In the case of a beam under fatigue stress, performance affected by deterioration vary depending on the stage of deterioration (initiation stage, propagation stage, acceleration stage or deterioration stage). Performance to be evaluated at each stage of deterioration, therefore, need to be selected appropriately. For example, it can be said that at the initiation stage and the propagation stage, little performance degradation occurs in safety performance, serviceability, hazards for third party or appearance. At and after the acceleration stage, fatigue cracks occur in the reinforcing steel and some of the reinforcing bars may come into a state close to breaking in fatigue or actually break. As a result, safety and serviceability deteriorate as load-carrying capacity, stiffness, etc., decrease because the cross section of the reinforcing steel becomes smaller. These performance, therefore, need to be evaluated.

There is as yet no established method, however, for quantitatively evaluating various performances of beams under fatigue stress. A more realistic approach, therefore, may be to evaluate the performance of a structure semiquantitatively by performing grading as shown in Table C15.3.8 for appearance grades of beams.

Table C15.3.8 Appearance grades, degree of cumulative fatigue damage and typical performance degradations

Appearance grade of beam	Classification by degree of cumulative fatigue damage	Classification by appearance	Safety performance	Serviceability performance	Hazards for third party Appearance
State I–1 (initiation stage)	$M < 0.2$	Cracking has occurred, but there is no visible anomaly in appearance.	—	—	—
State I–2 (initiation stage)	$0.2 < M < 0.5$	〃	—	—	—
State I–3 (initiation stage)	$0.5 < M < 0.8$	〃	—	—	—
State II (propagation stage)	$0.8 < M < 1.0$	〃	—	—	—
State III (acceleration stage)	$M > 1.0$	Crack propagation can be seen.	Decrease in load-carrying capacity •Decrease in cross-sectional area due to fatigue cracks in reinforcing steel	Decrease in stiffness •Crack propagation	Degradation in appearance •Crack propagation
State IV (deterioration stage)		Crack propagation and growth can be seen.	Decrease in load-carrying capacity •Fatigue breaking of some of the reinforcing bars in the beam	Decrease in stiffness •Breaking of reinforcing steel	Hazards for third party •Scaling and spalling of concrete near broken reinforcing bars

15.4 Remedial Measures

15.4.1 Selection of remedial measures

(1) If it has been judged that remedial measures need to be taken in connection with the performance degradation of a beam due to fatigue, remedial measures shall be taken so that the structure after the measures meets the required performances.

(2) If it is difficult to select remedial measures on the basis of performance verification, remedial measures may be selected from the measures corresponding to the appearance grade for the fatigue of a beam.

[Commentary] (1) If it has been judged, as a result of evaluation, that remedial measures need to be taken, it is necessary to select one or more of the following measures: (i) intensified investigation, (ii) repair, (iii) strengthening, (iv) functional improvement, (v) restriction in service or (vi) dismantling/removal. Basically, decisions as to which measures to take should be made by the maintenance manager of the structure, but it is good practice to refer to **Part 1** for information on typical relationships between evaluation and judgment results and remedial measures.

(2) If it is difficult to select remedial measures through quantitative evaluation or judgment,

remedial measures are selected from the measures corresponding to the grade of deterioration of the structure. Remedial measures to be taken vary depending on the type of structure, the degree of importance of the structure, deterioration rate and the maintenance category, but recommended standard measures are shown in Table C15.4.1.

Table C15.4.1 Appearance grades of beams and remedial measures

Appearance grade of reinforced concrete beam	Intensified investigation	Repair	Strengthening **	Functional improvement	Restriction in service	Dismantling/ removal
I-1(initiation stage)			X	X		
I-2(initiation stage)	O		X	X		
I-3(initiation stage)	O	O**	X	X	O	
II(propagation stage)	OO	O*	X	X	O	
III(acceleration stage)	OO	OO*	X	X	OO	
IV(deterioration stage)	OO	OO*	X	X	OO	O

O:standard measures （OO*:including restoration of mechanical performance）

O:measures to be taken under certain circumstances,(O):preventive measures

Strengthening**:designed to achieve performance level higher than initial level

＊: measures taken in accordance with criteria other than appearance grade

15.4.2 Repair and strengthening

Methods and materials for the repair or strengthening of a reinforced concrete beam shall be selected taking into consideration performance degradation due to fatigue and life cycle cost, so that the required effect can be achieved.

[Commentary] In cases where repair or strengthening is carried out as a remedial measure, it is necessary to define the expected effect of repair or strengthening and the required performance (what level of performance to be maintained for how many years?). Ideally, it is desirable that remedial measures be taken by constructing a deterioration formula (for durability) or structural calculation formula (for load-carrying capacity and stiffness) in view of such factors as the properties of the materials used and verifying the calculation results obtained from those formulas. In this case, it is also important to take life cycle cost into consideration according to the remaining service life.

In cases where preventive remedial measures are taken for a structure to which maintenance category A (preventive maintenance) is applied, it is necessary to select an appropriate method in due consideration of the effect expected of the method.

Repair or strengthening methods for beams deteriorated by fatigue can be classified, according to expected effects, as shown in Table C15.4.2. When deciding on which method or material to use, it is necessary to take into consideration the present state of performance degradation of the members concerned. For the correspondence between appearance grades and remedial methods, refer to Table C15.4.3.

In cases where a beam whose performance has deteriorated because of fatigue is to be repaired or strengthened, it must be ascertained in advance that the repair or strengthening method and materials to be used are sufficiently safe under cyclically applied loads that will act on the beam after the repair or strengthening is carried out. For details of various repair and strengthening methods, refer to, for example, “Recommendations for Strengthening of Concrete Structures,” “Recommendations for Repair and Strengthening of Concrete Structures with Continuous Fiber Sheets,” “Recommendations for Concrete Repair and Surface Protection of Concrete Structures (Japan Society of Civil Engineers)” and “Report of JCI Committee on Rehabilitation of Concrete Structures (Japan Concrete Institute).”

Table C15.4.2 Expected effects and methods of repair or strengthening

Expected effect	Example of repair/strengthening method
Restoration of safety (improvement of load-carrying capacity)	Steel plate/FRP sheet adhesion, additional girder, external cable
Restoration of serviceability (improvement of stiffness)	Steel plate adhesion, additional girder
Elimination of hazards for third party	FRP sheet adhesion

Table C15.4.3 Appearance grades and methods of repair or strengthening

<table>
<tr><th>Appearance grade of beam</th><th>Standard repair/strengthening method</th></tr>
<tr><td>I-1(initiation stage)</td><td>—</td></tr>
<tr><td>I-2(initiation stage)</td><td>—</td></tr>
<tr><td>I-3(initiation stage)</td><td>Steel plate/FRP sheet adhesion</td></tr>
<tr><td>II(propagation stage)</td><td>Steel plate/FRP sheet adhesion</td></tr>
<tr><td>III(acceleration stage)</td><td rowspan="2">Steel plate/FRP sheet adhesion, additional girder, external cable</td></tr>
<tr><td>IV(deterioration stage)</td></tr>
</table>

15.5 Recording

(1) Investigation, deterioration prediction, evaluation and judgment, and remedial measures shall be recorded in accordance with Part 1.

(2) Items relevant to the fatigue of reinforced concrete beams shall be recorded.

[Commentary] As a general rule, the results of investigation, deterioration prediction, evaluations and remedial measures must be recorded in accordance with **Part 1**. Items relevant to fatigue require careful attention, particularly with respect to record keeping. Items to be recorded are indicated in **15.3.2** “Investigation in Assessment,” and **15.3.4** “Evaluation and Judgment.”

CHAPTER 16　MAINTENANCE OF STRUCTURES SUBJECT TO ABRASION

16.1 General

(1) This chapter provides standard methods for the maintenance planning, assessments, remedial measures and recording for structures that have been or are highly likely to be subject to performance degradation due to abrasion. The items common to all the deterioration mechanisms are shown in Part 1.

(2) This chapter shall be applied to structures of the maintenance categories A (preventive maintenance) and B (corrective maintenance).

[Commentary] (1) Abrasion means a phenomenon in which concrete cross section is gradually reduced due to the friction caused by water flowing or wheels. Firstly, in the structures subject to abrasion, coarse aggregate is exposed owing to the reduction of mortar. With the progress of deterioration, coarse aggregate falls off and steel is exposed or corrodes and the cross sections of steel and concrete are reduced.

Abrasion is a problem in such structures as pavements, floors, underwater bridge piers, ports and hydraulic facilities including dams and channels. In pavements and floors, abrasion occurs due to wheel loads. In underwater bridge piers, ports or channels, abrasion occurs due to flow and impact of water or waves. Concrete cracking, peeling and spalling sometimes occur at a certain level of impact. Structures near the coastlines may be subject to abrasion due to come flying sand. In cold areas, floating masses of ice sometimes induce the abrasion of offshore structures.

This chapter refers to unreinforced concrete, reinforced concrete, prestressed concrete and steel-concrete composite structures subject to abrasion and the description focuses on concrete structures that are deteriorated by flowing water. Descriptions concerning pavements and floors subject to abrasion due to abrasion by wheels are given in “Standard Specifications for Pavements.”

If abrasion progresses extraordinarily, steel is exposed, corroded and reduced its cross section as described earlier, however, in actual case few structures can be left until such a deterioration stage without any remedial measures. This chapter refers, therefore, to the maintenance before the deterioration reaches the deterioration level in which steel is affected. As shown in Fig.C16.1.1 and Table C16.1.1, the deterioration progress due to abrasion is divided into four stages such as, initial stage which up to the occurrence of abrasion, propagation stage which up to the exposure of coarse aggregate, acceleration stage which up to the falling of coarse aggregate, and deterioration stage in which the cross section is greatly reduced and outstanding performance degradation occurs. This chapter focuses on concrete members. In cases where only the surface coating materials for preventing concrete abrasion including protective concrete and mortar are subject to abrasion, it is determined that deterioration is in the initial stage. In each stage, deterioration has varying influence on the performance of the structure. The assessment (investigation, deterioration prediction, evaluation or determination), and the remedial measures vary in respective deterioration stages. Deterioration due to abrasion affects such performance attributes as serviceability and aesthetic appearance and landscape because of the reduction of discharge owing to the increase of roughness coefficient. Safety that is determined by load bearing capacity or other factors is not seriously affected except for members of small cross section. Fig.C16.1.1 therefore shows performance degradation focusing on serviceability and aesthetic appearance and landscape.

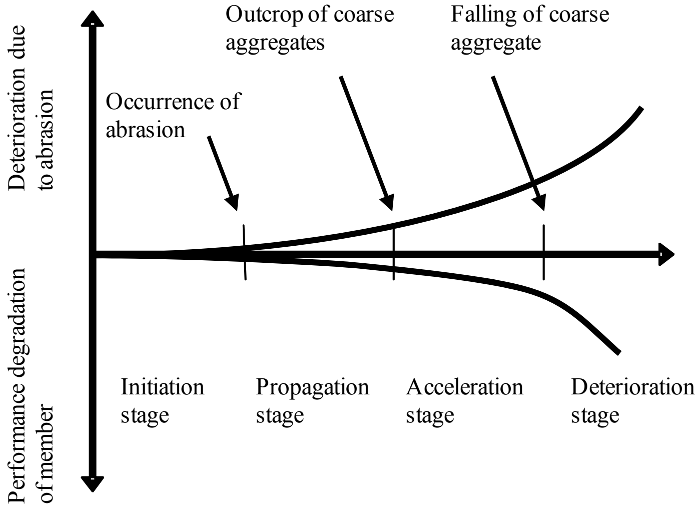


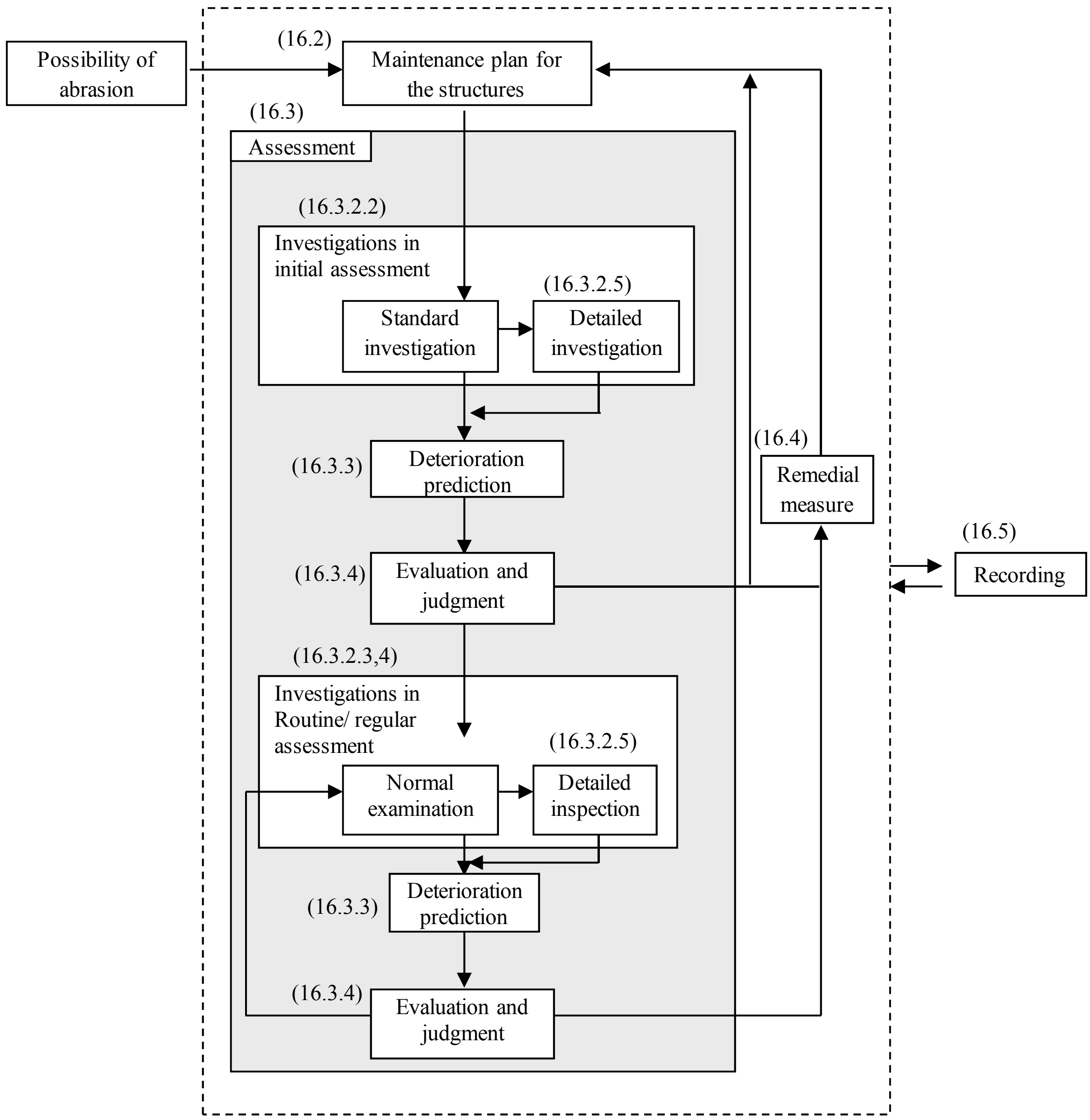
Fig. C16.1.1 Conceptual view of deterioration progress due to abrasion

Table C16.1.1 Definition of deterioration stages

Stage of deterioration	Definition	Major factor determining duration
Initiation stage	Until the occurrence of abrasion of concrete	Abrasion rate
Propagation stage	From the occurrence of abrasion to the exposure of coarse aggregate	
Acceleration stage	From the exposure to the falling of coarse aggregate	
Deterioration stage	Outstanding degradation of performance due to the reduction of cross section caused by abrasion	

(2) Maintenance category B (corrective maintenance) has been designated for numerous existing structures. In the future, maintenance category A (preventive maintenance) is expected to be designated for more structures. In maintenance category A, remedial measures are taken early before performance degradation due to deterioration in view of the life-cycle cost. This chapter therefore mainly discusses structures to which maintenance category A or B is applied. Structures to which maintenance category C (observation-based maintenance) is applied should also be maintained by a basic method described in this chapter wherever possible.

For the matters that should be considered when determining the maintenance category for structures that have been or are expected to be subject to deterioration due to abrasion, refer to **16.2.2** "Determination of Maintenance Category." Special matters to be considered for respective maintenance categories are also described in this chapter.



Figures in the parentheses indicate the related section or paragraph of this chapter.

Fig.C16.1.2 Standard maintenance procedure against abrasion

16.2 Maintenance Planning

16.2.1 Basics of planning

In order to maintain a structure subject to abrasion, the category of maintenance shall be selected, the service period planned, and a maintenance planning for activities including assessment, remedial measures and recording drawn up in advance in view of the service and environmental conditions such as the flowing water.

[Commentary] When drawing up a maintenance planning, it is necessary to cover such details as check items and procedures for initial assessment and check items, procedures, timing and frequency for the investigations in routine and regular assessment, evaluation and judgment methods, actions to be taken in the event of deterioration, and recording methods, taking into consideration the type, degree of importance and planned service period of the structure, category of maintenance, and the quality of materials.

The type of structure, size and environmental conditions of concrete structures vary from structure to structure. A maintenance planning must be optimized for each structure. The progress of deterioration of structures subject to abrasion is greatly affected by the flow velocity, sediment content in flowing water and the quality of concrete. An appropriate maintenance planning needs to be drawn up, therefore, in view of these factors.

It is usually difficult, at the stage of maintenance planning, to accurately predict the state of a structure during its service period. It is therefore good practice to draw up a maintenance planning with reference to the deterioration of a similar structure or a structure in a similar environment.

16.2.2 Determination of maintenance category

The category of maintenance of a structure subject to abrasion shall be selected in view of the degree of importance of the structure, the type of structure, hazards for third party, the planned service period and the characteristics of deterioration due to abrasion.

[Commentary] The determination of the category of maintenance is very important because maintenance planning varies widely depending on the category of maintenance. The progress of deterioration and performance degradation due to abrasion is conceptually illustrated in Fig. C16.1.1.

Structures to which maintenance category A (preventive maintenance) is applied should be maintained so that they might be placed under the condition during the initiation stage with deterioration only of the protection layers or concrete abrasion not yet starting, to prevent performance degradation. The state of the structure should therefore be identified as accurately as possible. Requirements include the following.

(i) Identification of the effects of abrasion factors on the structure surface

(ii) Quantitative evaluation and prediction of the abrasion of the protection layer

Elimination of large-scale repair or strengthening is also important objective.

Structures to which maintenance category B (corrective maintenance) is applied should be maintained so as to prevent the performance of the structure from failing to meet the requirements. Structures should be maintained to prevent deterioration from reaching the deterioration stage to ensure safety, the propagation stage to achieve serviceability or to keep aesthetic appearance and landscape. Certain actions should be taken when any of the following types of deterioration has been detected.

(i) Abrasion of concrete surface

(ii) Exposure of coarse aggregate

(iii) Falling of coarse aggregate

For structures to which maintenance category B is applied, remedial measures should be taken in phase (i) or (ii) above because it is extremely difficult to stop the progress of abrasion once started. It should be noted that large-scale measures will be required if deterioration reaches phase (iii) .

One maintenance category is generally applied to one structure. In cases where the environmental conditions vary from region to region or from member to member, however, applying different maintenance categories to different regions or members may sometimes be effective. For example, in a channel, maintenance category A (preventive maintenance) is applied to the invert, which is vulnerable to abrasion and category B (remedial maintenance) is applied to side walls.

16.2.3 Preparation of maintenance manuals

A maintenance manual describing methods, procedures and frequency requirements should be prepared for each structure in accordance with the maintenance planning, taking the structure-specific conditions into consideration.

[Commentary] The service period of civil engineering structures is long, and maintenance of those structures is performed over a long period of time. It is recommended, therefore, that in order to inform investigators of maintenance concepts and policies, a maintenance manual be prepared so that detailed procedures and methods can be communicated accurately even to newly assigned responsible engineers.

Under certain circumstances such as in cases where the original maintenance planning is altered because the actual progress of deterioration turned out to differ from that assumed in the original maintenance planning, it is necessary to modify the maintenance manual and take appropriate maintenance measures accordingly.

16.3 Assessment

16.3.1 General

In the assessment of a structure whose performance has declined or is highly likely to decline because of abrasion, investigation, evaluation of the present state, prediction of deterioration and judgment of necessity for remedial measures shall be appropriately conducted in accordance with the maintenance planning.

[Commentary] In order to maintain concrete structures appropriately, this specification requires three types of assessment: initial assessment, periodic assessment and extraordinary assessment. Because the initial and periodic assessments are essential for the maintenance of structures subject to abrasion, this chapter stipulates that those assessments must be conducted. Extraordinary assessments are regarded as assessments to be conducted on an as-needed basis and are therefore not dealt with in this chapter. By conducting periodic assessments during the maintenance period, change of appearance of structures can be discovered before they occur or in early stages, and remedial measures including preventive measures and repairs can be taken systematically.

16.3.2 Investigation in assessment

16.3.2.1 General

Investigations in initial, routine and regular assessment of a structure subject to abrasion shall be conducted appropriately according to the category of maintenance required for the structure. Prior to investigation, check items, methods, frequency and scope of standard investigation shall be determined appropriately. For each type of assessment, detailed investigation shall also be conducted on an as-needed basis.

[Commentary] It is important to select check items, methods, frequency and scope of investigation appropriately according to the purpose of investigation in accordance with the maintenance planning.

The major parameters that should be identified in investigations of structures subject to abrasion are the degree of abrasion (depth and area) and the abrasion rate. In cases where deterioration has progressed considerably, investigations should be conducted to directly evaluate performance. Here, the abrasion rate means the progress rate of sectional reduction depth from the concrete surface.

The items to be examined in investigations vary according to the degree of deterioration. In cases where it has been determined or assumed that the deterioration was in the initiation stage, investigations should be conducted mainly to identify the progress of change of appearance. In cases where it has been determined or assumed that the deterioration was in or beyond the propagation stage, investigations should be conducted mainly to identify the progress of abrasion. Table C16.3.1 shows major items to be examined in the respective stages. Data on the items related to deterioration prediction such as the degree of abrasion and the environmental action (e.g. flow velocity, sediment content and head) should be collected in as early a stage as possible.

The frequency and range of investigation should be determined considering the maintenance category, environmental conditions, structural format and the state of deterioration for the structure. Abrasion is likely to occur at the points of cross-sectional change, in curves where velocity changes or at locations subject to impact loads due to high head. Intensive investigation should be made at these points as well as investigations throughout the structure.

Regardless of the category of maintenance, it is important to go through the design drawings and specifications, construction records, investigation results and the repair history prior to the investigation of a structure.

If the state of a structure cannot be judged appropriately by standard investigation, detailed investigation must be conducted.

Table C16.3.1 Main check items in investigation

Stage of Deterioration	Initiation	Propagation	Acceleration	Deterioration
Change of appearance	O	O	O	O
Degree of abrasion	▲	O	O	O
Environmental action	▲	▲*	▲*	O
Concrete strength	▲	▲	▲	▲*

O : Items to be investigated on a priority basis

▲ : Items that should preferably be investigated

▲* : Items to be investigated on an as-needed basis

16.3.2.2 Investigation in initial assessment

(1) In initial assessment, appropriate check items for standard investigation shall be selected for newly constructed structures, existing structures, large-scale repairs and strengthened structures.

(2) If deterioration prediction, evaluation or judgment is difficult to make through a standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) Investigation in initial assessment is the first investigation conducted when the maintenance of a concrete structure is started. Investigation in initial assessment includes not only the first investigation of a newly constructed structure conducted before it goes into service but also the first investigation of an existing structure or a structure for which remedial measures have been taken in response to deterioration. Check items for the investigation may vary from structure to structure. Basic check items for standard investigations in initial assessment of a newly constructed structure are the document search on the design drawings and specifications and construction records and observation. It is good practice to check on such details as concrete cover, the state of steel and porosity through nondestructive testing on an as-needed basis. When investigating a structure for which remedial measures have been taken, it is also important to check for problems in repaired or reinforced parts of the structure. These should be included in check items of standard investigation. When an existing structure is investigated, check items are similar to those for a newly constructed structure if design drawings and specifications and construction records exist. If there is no such document or record, it is necessary to select check items of standard investigation with reference to **16.3.2.5** “Detailed Investigation.” In cases where a prediction needs to be made with high accuracy about a structure to which maintenance category A (preventive maintenance) is applied, it is necessary to conduct investigations concerning the parameters used for the method described in **16.3.3** “Methods for Predicting Degradation of Performance Degradation of Structures.”

Extremely important items in the investigation in initial assessment of a structure subject to abrasion are listed below.

(i) Environmental and loading conditions

(ii) Concrete strength (or water-cement ratio)

(iii) Type and volume of the additive

(iv) Initial defect

(v) Condition of abrasion (depth and area)

(vi) Condition of repaired or strengthened sections

Item (i) is essential to the prediction of progress of abrasion. Identifying the flow velocity, sediment content and head is required. Items (ii) and (iii) are important when evaluating the abrasion resistance of concrete, or the abrasion rate. Item (v) greatly affects the durability of structures regardless of abrasion. Detecting this item in the investigation in initial assessment is important. In sections with poor concrete filling in particular, the velocity of abrasion increases and the performance of the structure is greatly affected.

When investigating an existing structure, identifying the degree of abrasion (depth and area) (item (v)) in addition to items (i) through (iv) is important. Investigating the deformation in repaired or strengthened sections and the condition of deformation (e.g. swelling or peeling of surface coating) (item (vi)) is also important.

(2) If evaluation and judgment cannot be made with high accuracy by standard investigation alone, detailed investigation is necessary. Check items of detailed investigation are indicated in **16.3.2.5** "Detailed Investigation."

16.3.2.3 Investigation in routine assessment

(1) In routine assessment, investigation shall be conducted to detect not only the defect of concrete surface such as degree of abrasion (depth and area), cracking in concrete, peeling and spalling of concrete covering but also the deterioration in appearance such as displacement and deformation.

(2) If deterioration prediction, evaluation or judgment is difficult through standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) The purpose of investigation in routine assessment is to detect deterioration at an early stage by checking on defect in the state of a structure over time. The determination of the time at which deterioration began in order to obtain information that is useful for predicting deterioration is another important purpose of the investigation. In the investigation focus should be placed on deterioration phenomena or their indicators such as abrasion, cracking, peeling and spalling of concrete covering, displacement and deformation.

Exclusively inspecting the sections where deterioration was expected to progress as a result of initial assessment is also effective.

(2) If high-accuracy evaluation or judgment is difficult by conducting standard investigation alone or if severe deterioration has already occurred, detailed investigation is conducted. Check

items of detailed investigation are described in detail in **16.3.2.5** “Detailed Investigation.”

16.3.2.4 Investigation in regular assessment

(1) The purpose of investigation in regular assessment is to obtain information that is difficult to obtain in routine assessment. In regular assessment, standard investigation consisting of detailed observation of defects shall be conducted as in routine assessment. Addition to that environmental action should be identified.

(2) If deterioration prediction, evaluation or judgment is difficult through standard investigation alone, detailed investigation shall be conducted.

[Commentary] (1) Investigation in regular assessment is conducted for obtaining the information more detailed than that in routine assessment. Areas where signs of defects or deterioration have been detected in initial or routine assessment need to be examined intensively. The appearance of the structure should basically be examined as in routine assessment. Identifying the locations where abrasion is likely to occur based on the investigation results and preparing a deterioration map are effective for grasping time-based change in deterioration.

In some cases, the service environment or use condition of a structure may change. It is therefore important to regularly identify the changes in discharge and sediment content.

When measuring the depth and area of abrasion in regular assessment, measurements should be taken three or more frequently during the expected stage of deterioration.

For the structures for which maintenance category A (preventive maintenance) is designated, the frequency of measurement should be increased during the expected initiation stage and propagation stage.

(2) If high-accuracy evaluation or judgment is difficult by conducting standard investigation alone or if severe deterioration has already occurred, detailed investigation is conducted. Check items of detailed investigation are described in detail in **16.3.2.5** “Detailed Investigation.”

16.3.2.5 Detailed investigation

Detailed investigation shall be conducted to obtain detailed information on a structure subject to abrasion in cases where the deterioration of the structure is difficult to predict, evaluate or judge by standard investigation alone in initial, routine or regular assessment. Check items, methods and location of a detailed investigation shall be selected appropriately taking into consideration such factors as the purpose of investigation and the accuracy of obtained results.

[Commentary] When the determination of the present state of a structure and the deterioration prediction of the structure are difficult by standard investigation alone, detailed investigation is conducted in order to obtain the information necessary for those purposes. Examples of investigation items for structures subject to abrasion, and of data on the condition of the structure at the time of investigation and those in the future estimated from the investigation results are listed in

Table C16.3.2. The evaluation items estimated from data in the table are evaluated after deterioration is predicted.

Major check items are outlined below. For other measurement items or testing methods than those described below, refer to **4.7** "Investigation."

(i) Degree of abrasion (depth and area)

The depth of abrasion is defined as the variance between the level of concrete surface at the time of construction and that at the time of investigation. The depth from the concrete surface without abrasion to the concrete surface subject to abrasion is measured at several points. The maximum, minimum and mean values are obtained. For obtaining the area of abrasion, the area is recorded using photographs and sketches and the lengths of long and short sides are measured. Before the measurement, the weakened surface portion should be removed until the sound concrete is exposed.

(ii) Environmental action

The progress of abrasion varies greatly according to the environmental actions of flowing water, waves and other factors. Even where concrete of the same quality is used, deterioration progresses slowly under moderate environmental actions and quickly under severe conditions. Factors of actual environmental actions such as flow velocity, discharge, head, sediment content, wave force and height, etc. should be identified for evaluating the performance and predicting the deterioration of the structure.

(iii) Appearance of structures

In cases where performance of structure cannot be evaluated direct from the state of concrete, the defect of appearance provides important data for performance evaluation. The grades of appearance of structures deteriorated due to abrasion are shown in Table C16.3.3.

Table C16.3.2 Examples of evaluation items in detailed investigation

Measurement item	Data obtained by investigation	Evaluation items predicable from obtained data
Degree of abrasion (depth and area)	Degree of abrasion (depth and area) abrasion rate, load carrying capacity, permeability and aesthetic appearance	Degree of abrasion (depth and area), load carrying capacity, permeability and aesthetic appearance
Cracking (width, depth and density)	Cracking (width, depth and density), rate of progress of cracking and aesthetic appearance	Cracking (width, depth and density) and aesthetic appearance
Concrete strength and modulus of elasticity	Concrete strength, stiffness and load carrying capacity	Condition of abrasion (depth and area), stiffness and load carrying capacity
Environmental action (discharge, flow velocity, sediment content and wave condition)	Environmental conditions, abrasion rate and permeability	Condition of abrasion (depth and area) and permeability

Table 16.3.3 Grades of structural appearance and stage of deterioration

Grade of appearance	State of deterioration
I (Initiation stage)	No abrasion of concrete
II (Propagation stage)	exposure of coarse aggregate, but no falling of coarse aggregate
III (Acceleration stage)	Falling of coarse aggregate falls
IV (Deterioration stage)	Coarse aggregate falls remarkably and the cross section is reduced over a wide area.

16.3.3 Methods for predicting performance degradation of structures

16.3.3.1 General

(1) In the maintenance of a structure subject to abrasion the performance of the structure shall be evaluated quantitatively at the time of investigation, and future degradation shall be predicted.

(2) In order to predict the performance degradation of a structure, deterioration due to abrasion shall be predicted quantitatively.

(3) If (2) is difficult, an alternative method is to predict performance degradation by estimating the length of the initiation, propagation, acceleration and deterioration stages, taking the progress of abrasion into consideration.

(4) Deterioration shall be predicted on the basis of investigation results.

[Commentary] (1) and (2) In the performance verification based maintenance system, changes (deterioration) in various performance attributes inherent in the structure should be predicted. To that end, the progress of material deterioration should be predicted quantitatively. The performance of the structure and the degree of deterioration of materials constituting the structure should be evaluated quantitatively at the time of investigation and the end of planned service period. Performance degradation of the structure or the degree of deterioration of materials constituting the structure at the time of investigation may be evaluated quantitatively by an appropriate method based on investigation results. The performance or the degree of deterioration at the end of the planned service period should be predicted quantitatively based on the previous periodic assessments. The prediction of deterioration progress is not always in agreement with actual progress of deterioration. The method of prediction should therefore be reviewed based on the results of investigations to be conducted later.

(3) When evaluating various performance attributes of a structure by combining the results of prediction of deterioration progress of concrete and steel that constitute the structure, quantitative prediction is difficult at the present technological level. Then, predicting the lengths of initiation, propagation, acceleration and deterioration stages considering the progress of concrete abrasion is a realistic approach. The respective stages of deterioration and the factors determining their lengths

are shown in Table C16.1.1. The prediction methods are described in **16.3.3.2** "Prediction of abrasion."

(4) Investigation results are related to either the quality of concrete of the structure or the environment in which the structure is placed while in service. These parameters should be used as a basis for predicting deterioration. If the structure is now being planned or no investigation result is available for the existing structure, investigation results or deterioration conditions of similar structures under the similar environment may be consulted.

16.3.3.2 Prediction of abrasion

(1) The progress of abrasion shall be predicted properly considering the quality of concrete and the environment in which the structure is in service.

(2) The progress of abrasion may be predicted by one of the following methods.

(i) Method based on the degree of abrasion obtained from investigation results

(ii) Method based on the investigation results for a similar structure under the same environment

(iii) Evaluation in an abrasion test

[Commentary] (1) The abrasion rate is determined by the mix proportions and strength of concrete, flow velocity and sediment content, strength and frequency of waves and whether impact is applied or not. Generally, the lower the water-cement ratio of concrete, the more dense and stronger the concrete. Then, abrasion progresses slowly. Surface treatment using materials that densify concrete surface is also expected to increase abrasion resistance. Even for concrete of the same quality, the abrasion rate naturally varies according to the acting load. The higher the flow velocity, the higher the abrasion rate. In cases where the flowing water contains deposit, the abrasion rate increases even at the same flow velocity owing to the force of abrasion. Deterioration may sometimes progresses considerably on an apron of a weir with a head owing to impact loads. When predicting the progress of abrasion, therefore, both the physical properties of concrete and the environmental actions should be evaluated properly.

(2) Three major methods for predicting the progress of abrasion are described below.

(i) Methods based on the degree of abrasion obtained in investigations

In cases where the time-based change in degree of abrasion has been predicted in investigations, the progress of abrasion may be predicted through the regression of the result. Under the same loading conditions, it may be assumed that the abrasion rate is nearly constant and that the degree of abrasion is in proportion to time. The abrasion rate should be estimated based on the measurements taken at three or more ages.

(ii) Method based on the investigation results for a similar structure under the same environment

If no investigation results are available for the structure, the progress of abrasion may be predicted based on the investigation results for a similar structure under the same environment.

(iii) Evaluation in abrasion testing

No method has yet been established for quantitatively predicting abrasion. If no investigation results are available, therefore, the abrasion rate should be predicted in abrasion testing properly considering the concrete mix proportions and environmental actions (e.g. flow velocity and sediment content).

16.3.3.3 Modification of prediction

If the state of deterioration determined in an investigation differs from a predicted state of deterioration, the cause of the difference shall be identified and the prediction shall be revised accordingly. If necessary, the maintenance planning shall be altered.

[Commentary] When the deterioration confirmed in investigations is different from the prediction, appropriate investigations should be conducted using the deterioration prediction methods shown in **16.3.3.2** "Prediction of abrasion" and based on Table C16.3.2 to examine the cause for the difference, and the prediction should be modified. Then, the results of several investigations conducted until that are useful to the examination of causes and the modification of the prediction. Revising the subsequent maintenance plans including a review of investigation frequency based on the modified prediction is also important.

16.3.4 Evaluation and judgment

(1) The evaluation of performance and judgment as to whether remedial measures need to be taken based on the results of the investigation in initial, routine and regular assessment shall be made in accordance with Part 1 and Item (2) and subsequent items in this section.

(2) The performance of a structure subject to abrasion shall be evaluated by appropriately selecting performance attributes to be evaluated in view of the stage of deterioration of the structure.

(3) The evaluation of performance attributes at the time of investigation and at the end of the planned service period of the structure should be made by a quantitative method.

(4) If Item (3) is difficult to achieve, the evaluation of performance attributes at the time of investigation and at the end of the planned service period of the structure may be made by a semi-quantitative grading-based method.

(5) Judgment as to whether remedial measures need to be taken shall be made in view of the degree of performance degradation due to abrasion, the degree of importance of the structure, category of maintenance, and the remaining service life.

[Commentary] (1) The evaluation of performance and judgment of necessity for remedial measures in initial, routine and regular assessment for structures in which little progress of deterioration has been recognized are frequently more or less the same regardless of the deterioration mechanism. For details, refer to **Part 1**. The evaluation of performance and judgment of necessity for remedial measures for structures in which deterioration may have or has progressed vary according to the deterioration mechanism. When discussing the performance degradation due to abrasion, the descriptions in this chapter should be consulted.

(2) In the structures subject to abrasion, the performance attribute to be affected by deterioration varies depending on whether deterioration is in the initiation, propagation, acceleration or deterioration stage. The performance attribute to be evaluated should be properly selected for each stage of deterioration. In the propagation stage for example, the cross section is likely to be reduced with the progress of abrasion. In hydraulic structures, the water permeability capacity determined by the change in roughness coefficient should be evaluated. In the acceleration stage, the cross section is likely to be reduced as coarse aggregate is exposed. Evaluations should be made to verify further deterioration of water permeability capacity due to the increase of roughness coefficient, or aesthetic deterioration. In the deterioration stage, relatively large cross sections are reduced as a result of falling of coarse aggregate. Attention should be paid not only to the items worth noting in the acceleration stage but also to safety that is determined by such factors as load bearing capacity, and to the deterioration of serviceability due to water leakage through the reduced cross section.

(3) The performance of a structure at the time of investigation and at the end of the planned service period should be evaluated after evaluating the deterioration of concrete and steel. For evaluating the performance of a structure at the time of investigation, safety is checked by obtaining the load bearing capacity, etc. by, for example, substituting the dynamic properties of materials obtained from investigation results into a structural calculation formula. Also conceivable is the checking of serviceability by obtaining the discharge and the checking of aesthetic appearance and landscape by examining the exposure of coarse aggregate and the range and density of cracking, peeling and spalling. Performance can be evaluated relatively explicitly at the time of investigation by checking the effects in cases where deterioration is not serious. Evaluating performance at the end of the planned service period fully accurately is, however, difficult. As a supplementary measure, deterioration is generally predicted based on the abrasion rate using the methods shown in **16.3.3** “Methods for Predicting Performance Degradation of Structure”. Then, the accuracy of the deterioration prediction method as well as the accuracy of the performance checking method is important. Prediction methods should therefore be selected carefully. Adequate safety should be guaranteed.

(4) In the performance verification type design system, structural performance should ideally be evaluated quantitatively. At present, however, there is no established method of quantitative estimation. As a practical method, the performance of a structure can be evaluated semi-quantitatively, with reference to Table C16.3.3, by performing appearance grading in accordance with Table C16.3.4.

The purpose of grading is to classify the present degree of deterioration of a structure semi-quantitatively instead of predicting and evaluating the degree of deterioration in future. It is also possible, however, to predict the performance of a structure at the end of the planned service period in accordance with Table C16.3.4 by estimating the stage of deterioration at the end of the planned service period on the basis of investigation results such as the abrasion rate. The method of estimating the degree of deterioration at a certain point of time in future by constructing a deterioration grade model based on a stochastic theory such as a Markov model has also been proposed.

If detailed maintenance records for a similar structure (type of structure, materials, construction, environment, state of use) are available and its progress of deterioration is also similar to that of the evaluated structure, then the evaluation results for the similar structure provide useful information.

(5) Because judgment is the act of deciding whether remedial measures need to be taken on the basis of structural performance evaluation results, there is no difference depending on deterioration factors. Therefore, refer to **Part 1**.

Table C16.3.4 Grades of appearance of structures and typical performance degradation

<table>
<tr><th>Grade of appearance of structure</th><th>Safety</th><th>Serviceability</th><th>Aesthetic appearance and landscape</th></tr>
<tr><td>I
(Initiation stage)</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>II
(Propagation stage)</td><td>-</td><td rowspan="3">Reduction of discharge
-Increase of roughness coefficient
-Leakage</td><td rowspan="3">- exposure of coarse aggregate
-Cracking
-Peeling
-Spalling</td></tr>
<tr><td>III
(Acceleration stage)</td><td>-</td></tr>
<tr><td>IV
(Deterioration stage)</td><td>Degradation of load carrying capacity and ductility

-Reduction cross section of concrete</td></tr>
</table>

16.4 Remedial Measures

16.4.1 Selection of remedial measures

(1) If it has been judged that remedial measures need to be taken in connection with performance degradation of a structure subject to abrasion, remedial measures by which the corrected structure meets the required performances shall be selected.

(2) If it is difficult to select remedial measures for a structure on the basis of performance verification, remedial measures may be selected from the measures corresponding to the grade of appearance.

[Commentary] (1) If it has been judged, as a result of evaluation, that remedial measures need to be taken, it is necessary to select one or more of the following measures: (i) intensified investigation, (ii) repair, (iii) strengthening, (iv) functional improvement or (v) restriction in service. Basically, decisions as to which measures to take should be made by the maintenance manager of the structure, but it is good practice to refer to **Part 1** for information on typical relationships between evaluation and judgment results and remedial measures.

(2) If it is difficult to select remedial measures for a structure through quantitative evaluation or judgment, remedial measures are selected from the measures corresponding to the deterioration grade of the structure. Remedial measures to be taken vary depending on the type of structure, the degree of importance of the structure, deterioration rate and the category of maintenance, but recommended standard measures are shown in Table C16.4.1. Taking remedial measures for structures to which maintenance category A (preventive maintenance) is designated in the initiation

stage in which no outstanding abrasion occurs is important from a preventive viewpoint. It is also important to take remedial measures for structures to which maintenance category B (corrective maintenance) is designated, for preventing deterioration before it becomes outstanding, considering the rate of progress of deterioration.

Table C16.4.1 Grades of appearance of structure and remedial measures

Stage of deterioration	Intensified investigation	Repair	Strengthening **	Functional improvement	Restriction in service
I (Initiation stage)	**OO**	**O***	X	X	
II (Propagation stage)	**O**	**OO**	X	X	
III (Acceleration stage)		**OO**	X	X	
IV (Deterioration stage)		**OO***	X	X	**O**

OO: Standard remedial measures [**OO***: Including the restoration of mechanical performance]
O: Remedial measures in some cases [**OO***: Preventative measures]
X: Remedial measure taken based on other criterion than the grade of appearance
Strengthening** : Enhancing the mechanical performance above the initial level

16.4.2 Repair and strengthening

Methods and materials for the repair or strengthening of a structure shall be selected taking into consideration the performance degradation of the structure due to abrasion and life cycle cost, so that the required effect can be achieved.

[Commentary] In cases where repair or strengthening is carried out as a remedial measure, it is necessary to define the expected effect of repair or strengthening and the required performance (what level of performance to be maintained for how many years?). Ideally, it is desirable that remedial measures be taken after constructing a deterioration formula (for repair) or structural calculation formula (for strengthening) in view of such factors as the properties of the materials used and verifying the calculation results obtained from those formulas. In this case, it is also important to take life cycle cost into consideration according to the remaining planned service period.

When taking preventive measures for a structure to which maintenance category A (preventive maintenance) is applied, an appropriate method should be selected fully considering the effect that should be achieved by the method.

The methods of repair or strengthening for structures subject to performance degradation due to abrasion are listed in Table C16.4.2 by expected effect.

Table C16.4.2 Expected effects and methods of repair or strengthening

Expected effect	Example of method

Control the progress of abrasion	Surface treatment (including coating, adhesion of abrasive-resistant materials and impregnation)
Reduce roughness coefficient	Surface treatment and repair of cross section
Secure member cross section	Surface treatment
Enhance load carrying capacity	Adhesion of steel or fiber reinforced plastic plates, lining and replacing

When selecting the method, Table C16.4.2 and the present performance degradation of the structure should be considered. For the grades of deterioration of appearance and remedial measures, refer to Table C16.4.3.

In the initiation stage, surface treatment may be applied to prevent the abrasion of concrete surface. In the propagation or acceleration stage, repairing the cross section reduced by abrasion is effective. Then, surface treatment may be applied to prevent abrasion in the section of cross section to be repaired. In the deterioration stage, dynamic properties may have been deteriorated in such terms as load bearing capacity and roughness. Then, enhancing the dynamic properties by adhering steel or fiber reinforced plastic plates or applying lining is important. Also in this case, surface treatment for preventing abrasion after the implementation of remedial measures is desirable.

Many of the repair or strengthening methods applied have been developed only recently and few have been applied to actual structures. If such methods are adopted, the structure may be re-deteriorated and its performance may be degraded due to the factors not expected in the design phase. Measures should therefore be taken such as increasing the frequency of investigations after the repair or strengthening.

For details of the methods of repair and strengthening, refer to the "Guidelines for Strengthening Concrete Structures (draft)," "Guidelines for Design and Implementation of Surface Protection (draft)," "Shotcreting Guidelines(draft) - Repair and Strengthening" and other documents.

Table C16.4.3 Appearance grades of structural and standard methods of repair or strengthening

Appearance grade of structure	Example of method
I (Initiation stage)	Surface treatment*
II (Propagation stage)	Repair of cross section and surface treatment*
III (Acceleration stage)	Repair of cross section and surface treatment*
IV (Deterioration stage)	Adhesion of steel or fiber reinforced plastic plates, lining, replacing and surface treatment*

16.5 Recording

(1) Investigation, deterioration estimation, evaluation and judgment, and remedial measures shall be recorded in accordance with Part 1.

(2) Items relevant to abrasion shall be recorded.

[Commentary] As a general rule, the results of investigations, deterioration estimations, evaluations and remedial measures must be recorded in accordance with **Part 1**. Items relevant to abrasion require careful attention, particularly with respect to record keeping. Items to be recorded are indicated in Section **16.3.2** “Investigation in Assessment" and the evaluation items indicated in Section **16.3.4** “Evaluation and Judgment.”

CHAPTER 17 SEISMIC RETROFIT

17.1 General

This chapter provides basic matters concerning the planning, assessments, selection of methods, design, construction, post-retrofit maintenance and recording for seismic retrofit of existing structures.

[Commentary] Seismic design standards for structures stipulate the levels of earthquake motions to be considered and required seismic performance according to the technical level at the time when the standards were established. Seismic design standards have undergone revisions as earthquake motions stronger than the design level frequently damaged structures or caused structures to collapse and new technologies were developed. Each time the standards were revised, the earthquake motions to be considered or seismic required performances for structures and members were upgraded. In the Hyogoken-Nambu Earthquake of 1995, numerous structures were damaged or collapsed. As a result, the levels of earthquake motions to be considered were raised considerably in highway and railway design standards including the "Standard Specifications for Concrete Structures." The structures that were designed before the revision of seismic standards therefore no longer meet the latest seismic standards. The seismic retrofit of non-conforming structures is an important issue in maintenance. Existing structures are in large numbers and many are not in compliance with standards. When applying seismic retrofit, therefore, it is important to prepare a plan for effective retrofit considering the importance of the structure and the level of retrofit.

This chapter provides a basic idea of seismic retrofit for improving the seismic performance of existing structures. The restoration of structures damaged by earthquakes is, however, discussed in **Part 1** because repair or strengthening is applied based on the results of extraordinary assessments conducted after accidental loads are applied.

17.2 Seismic Retrofit Planning

(1) The seismic retrofit plan shall be prepared considering the characteristics of the structure or member to be strengthened, objective of service, available seismic performance, seismic performance to be provided, importance, emergency and cost performance.

(2) The seismic retrofit plan should generally present information concerning the selection of methods of seismic assessment and seismic retrofit, retrofit design, construction and recording.

[Commentary] The seismic retrofit plan should be prepared properly to retrofit a structure or member in conformity with its conditions that are identified in advance. To that end, the characteristics of the structure or member to be strengthened, objective of service, available seismic performance, seismic performance to be provided, importance, emergency and cost performance should be identified. Various types of concrete structures exist such as bridges, port facilities, tunnels and plant facilities and have unique characteristics. Seismic retrofit of ground-level structures is relatively easy. On the other hand, retrofit is not so easy for underwater structures such as piers and other port facilities, and bridge piers installed in rivers, or underground structures such as tunnels and foundations because the building of a coffer dam or large-scale excavation is involved. When preparing a seismic retrofit plan, these points and social impacts described below should be taken into consideration.

(i) The suspension of service due to the damage to a structure or collapse of a structure impacts the escape, relief and rescue activities during a disaster and the prevention of secondary disasters. The delay of restoration influences the regional life and economic activities. Not only the difficulty in restoration and the construction cost but also the social impacts of structural damage should be considered.

(ii) In cooperation with a plan for escape and relief activities during a great earthquake, developing a plan for retrofit emergency required important structures such as the key transportation hubs like airports and seaports and channels between these facilities is important.

(iii) Infrastructure systems such as highways, railways, and water and power supply systems function as a network. Infrastructure can keep working if an alternative route is available to compensate for the suspension of a route. In view of such a condition, structures should be prioritized for seismic retrofit.

(iv) The leakage of the contents of oil or gas tanks at the time of serious damage to the facilities during an earthquake has great influences in the vicinity. Seismic retrofit of the structures involving high risk or facilities required for power generation or gas supply should be given a high priority.

17.3 Seismic Assessment

17.3.1 General

When planning seismic retrofit, the seismic performance of the structure shall be evaluated properly considering the importance of the structure, emergency and cost performance for the purpose of identifying the currently available seismic performance of the structure and judging the necessity for seismic retrofit.

[Commentary] When planning seismic retrofit, seismic performance of the structure should be evaluated to judge seismic performance before seismic retrofit. In simple assessment, seismic performance is estimated based on the design concept at the time of design and construction of the structure. Detailed assessment is conducted based on the results of directly investigation of the structure. Seismic performance should be judged fully considering the importance of the structure, emergency and cost performance, and the opinions of the responsible or professional engineer.

17.3.2 Investigation for seismic assessment

Literature surveys shall be basically conducted to evaluate seismic performance. In cases where available data are inadequate or insufficiently accurate, or the structure has been deteriorated, detailed investigation shall be conducted.

[Commentary] For evaluating the present seismic performance of a structure or member, the equation for evaluation used in structural design is generally employed. Then, data such as the dimensions of members, arrangement of reinforcing bars and the strength of members is required. In the inspections for seismic performance evaluation, surveying literature such as design drawings and completed building drawings is a basic practice.

Detailed investigation should be conducted to evaluate seismic performance in the following cases.

(i) Where evaluating seismic performance is difficult because of a lack of design or completed building drawings

(ii) Where the structure has been deteriorated

In case (i), the arrangement of reinforcing bars should be verified by nondestructive or small scale destructive testing. The shape of the hook at the anchorage of reinforcement, arrangement of shear reinforcement and whether the main reinforcement has intermediate anchorages or not influence the ductility or flexural strength of members, which is important to seismic performance. Detailed investigation should be conducted if details of reinforcing bar arrangement are unknown.

In case (ii), detailed investigation should be conducted to examine whether or not the equation for evaluating the seismic performance of sound members used in design is applicable to deteriorated structures, and to collect quantitative data for input into the equation. In cases where detailed investigation have been conducted in routine or other assessment to identify the condition of deterioration, the results may be used for evaluating seismic performance. In cases where no outstanding deterioration has been found by visual observation but initial deterioration has or may have occurred, detailed investigation should be conducted. Then, whether detailed investigation are required or not should be judged by a responsible or professional engineer considering the importance of the structure, cost performance and other factors.

17.3.3 Evaluation of seismic performance and judgment of necessity for seismic retrofit

(1) In principle, seismic performance of a structure should be evaluated and the necessity for seismic retrofit should be judged in accordance with Chapter 6 "Evaluation and Judgment" and (2) below.

(2) In cases where no outstanding deformation of a structure due to deterioration is found, seismic performance may be evaluated and the necessity for seismic retrofit may be judged using the method for inspecting seismic performance stipulated in the "Design" volumes of the Standard Specifications.

[Commentary] (1) Seismic performance of a structure should be evaluated and the necessity of seismic retrofit should be judged quantitatively by the methods of structural performance evaluation and judgment of the necessity of remedial measures based on the investigation results shown in **Chapter 6** "Evaluation and Judgment."

(2) In cases where no outstanding deformation of a structure due to deterioration is found, seismic performance may be evaluated and the necessity of seismic retrofit may be judged using the method for inspecting seismic performance shown in the "Design" volumes of the Standard Specifications." The standards for specific types of structures may be applied at the discretion of the responsible engineer, e.g. "Specifications for Highway Bridges: Seismic Design," "Design Standards for Railway Structures: Seismic Design" and "Technical Standards for Port and Harbor Facilities." The performance evaluation equation used in design is oriented toward sound members and applicable to cases with no outstanding deterioration of an existing structure or member. The performance evaluation equation used in design is inapplicable to cases with the corrosion of reinforcing bars and cracking along the bars because the strength and expansibility of reinforcing bars are deteriorated and because the bond between reinforcing bars and concrete is reduced. The performance evaluation equation is applicable to cases where structural requirements are met in such terms as concrete cover, shape of the hook of reinforcement, and arrangements of joints and hoops. Whether structural requirements are met or not should therefore be verified. Unless the requirements are met, the seismic performance calculated should be reduced according to the condition or other measures should be taken.

In cases of outstanding deterioration, repair or strengthening in response to deterioration is required as well as seismic retrofit.

17.4 Selection of Seismic Retrofit Method

The seismic retrofit method shall be selected properly considering the present seismic performance of the structure or member to be strengthened and the seismic performance to be achieved, importance of the structure, cost performance, environment in which the structure is placed in service, and the site conditions.

[Commentary] Methods for improving seismic performance include improving the strength of the member, improving ductility and reducing the inertial force during an earthquake. Various seismic retrofit methods have been executed such as the increase of member thickness, jacket with reinforced concrete or steel plates, application of reinforcement, adhesion of steel or fiber reinforced plastic plates and installation of dampers. An appropriate method of seismic retrofit should be selected considering the present seismic performance of the structure or member to be strengthened and the seismic performance to be achieved, importance of the structure, cost performance, environment in which the structure is placed while in service and site conditions. Seismic retrofit methods should be selected in accordance with **Chapter 7** "Remedial Measures" because seismic retrofit methods have much in common with ordinary retrofit methods.

Existing structures to be retrofitted have generally been in service such as railways, highways, ports, plants and power or gas supply facilities. In cases where stores or facilities are located under a viaduct, where only narrow space is available in a river or at the construction site, or where enforcing traffic regulations is difficult; large-scale work for removing obstacles, temporary work or security measures are required before the commencement of construction. Methods have recently been developed and put to practical use that enable construction in narrow space, manually apply light-weight reinforcement, enable construction in cases where only small surface of members is exposed, eliminate the construction of a temporary coffer dam in the river or eliminate the need of temporary earth retaining or excavation. These methods may be selected considering the construction conditions. Described below are typical retrofit methods for structures.

(i) Seismic retrofit of reinforced concrete rigid frame viaducts

-Jacket with steel plates

-Jacket with fiber reinforced plastic plates

-Installation of reinforcement or divided steel plates on the outer side of the column

-Adhesion of multiple layers of thin steel plates

-Jacket with concrete segments and steel strands

-Construction on one side of the column using steel plates and reinforcement

-Installation of damper braces

(ii) Seismic retrofit of reinforced concrete bridge piers

-Jacket with reinforced concrete

-Jacket with steel plates

-Jacket with fiber reinforced plastic plates

-Underwater construction using mechanical joints

-Installation of concrete filled steel piles from above the ground

-Jacket by erecting straight sheet piles from above the ground

-Insertion of steel into the frame of bridge pier

(iii) Seismic retrofit of underground box culverts (construction from inside)

-Inner jacket with reinforced concrete

-Inner jacket with steel plates

-Inner jacket with fiber reinforced plastic plates

-Installation of supports

-Insertion of shear reinforcement

17.5 Design of Seismic Retrofit

Seismic retrofit shall be designed by an appropriate method to meet the required seismic performances.

[Commentary] Seismic retrofit should be designed properly following the retrofit design procedure shown in **Chapter 7** “Remedial Measures.” Seismic performance may be inspected after seismic retrofit in accordance with the “Design” volumes of the Standard Specifications. Standards such as the “Specifications for Highway Bridges: Seismic Design,” “Design Standards for Railway Structures: Seismic Design” and “Technical Standards for Port and Harbor Facilities” may be applied at the discretion of the responsible engineer. Details of the retrofit method may be specified, the retrofit method may be selected and the performance of the strengthened member may be inspected in accordance with the “Guidelines for Strengthening of Concrete Structures (draft),” “Guidelines for Repair and Strengthening of Concrete Structures Using Continuous Fiber Sheets” and other documents.

With the increase of strength of bridge piers by retrofit, foundations instead of piers may be damaged. When retrofitting a structure, the sections requiring retrofit should be identified fully considering the balance throughout the structure and performance should be improved properly in the sections. For foundation members, identifying damage or repairing is difficult. Improving ductility rather than strength of piers so as not to cause damage to foundation members facilitates restoration.

17.6 Execution of Seismic Retrofit

(1) Structures shall be retrofitted properly using materials of verified quality.

(2) When retrofitting a structure, an effective verification plan shall be developed and appropriate verification shall be conducted during and after construction to verify seismic retrofit has been constructed so that the designated effect of retrofit may be achieved.

[Commentary] (1) Structures should be retrofitted properly in accordance with **Chapter 7** “Remedial Measures” and using materials of verified quality. For matters unique to retrofit, refer to the “Guidelines for Strengthening of Concrete Structures (draft)” and the “Guidelines for Repair and Strengthening of Concrete Structures Using Continuous Fiber Sheets.”

For seismic retrofit, such methods are frequently adopted as the increase of member thickness, jacket with reinforced concrete or steel plates, application of reinforcement and adhesion of steel or fiber reinforced plastic plates. Drilling is frequently in existing members. Appropriate construction is required to prevent damage to reinforcement by verifying the locations of reinforcement in existing members. In cases where reinforcement is actually located at positions far different from those assumed in design, actions are required including the review of the design. In order to ensure the installation of anchors at appropriate locations and the provision of adequate bond, surface treatment is important at the construction joints between existing and reinforcing concrete or on the surface of adhesion of steel or fiber reinforced plastic plates. To that end, the weak department or adhesion objects to concrete surface shall be removed. Methods have recently been developed for chipping concrete without damaging reinforcement or internal concrete (water jet method) or shotcrete concrete or mortar.

(2) In seismic retrofit, verifications should be conducted to judge whether or not the strengthened structure or member meets the required performances specified in seismic retrofit design. At the end of retrofit, only a limited number of items may be verified, e.g. the surface condition of the structure, dimensions of the member and locations of reinforcement. Appropriate interim verifications shall therefore be conducted in each phase of construction.

The method of verification varies according to the structure to be strengthened or the method of retrofit. In order to ensure efficient and reliable verification , items, method and frequency of verification in each construction phase should be examined and a verification plan should be prepared. The time and cost required for the verification and the reliability of the verification should also be examined in advance. Specific verification items include general items in the construction of concrete structures such as the arrangement of reinforcing bars in sections where member thickness is increased (strength, diameter, location and the degree of fixation of reinforcement), physical properties and thickness of concrete or mortar to be placed, and items unique to seismic retrofit like the strength of anchors to be installed and the bond between existing and reinforcing concrete. For the method of adhering steel or fiber reinforced plastic plates, items such as material strength and adhesion should be verified whether adequate reinforcing effect is provided or not. These verification items should be fully examined when preparing the verification plan.

In verifications, whether construction has been carried out properly or not and whether the strengthened structure provides the designated seismic performance or not are judged. The method of verification and standard of judgment should be objective and stipulated in the special mention specifications prepared at the time of signing the agreement. Strictly conducting tests in accordance with the Japan Industrial Standards and the standards of Japan Society of Civil Engineers is a basis for making objective decisions. Comparison with past construction is facilitated and failure may be prevented based on the results of comparison. Thus, construction is carried out more effectively.

17.7 Maintenance after Seismic Retrofit

A retrofitted structure shall be maintained so that the required performances for the structure are within the allowable range throughout the remaining planned service period.

[Commentary] A retrofitted structure shall be maintained so that the designated performance for the structure may be within the allowable range throughout the planned service period assumed in retrofit design. The retrofitted structure should be maintained by following the maintenance procedure described in this Specification. For seismic retrofit, large-scale remedial measures are frequently taken. In cases where the state of the structure or member changes greatly before and after the retrofit, the maintenance procedure for newly constructed structures should be taken.

17.8 Recording

Data of the retrofit shall be recorded by an appropriate method and stored for a required period.

[Commentary] Records on the planning, design and construction of seismic retrofit not only serves as a basic material for the maintenance of the strengthened structure but also is important for evaluating subsequent seismic retrofit methods or materials to be used. Data shall therefore be recorded in a way that facilitates reference, and kept at least as long as the strengthened structure is in service. For details of recording, refer to **Chapter 8** “Recording.”