Concrete Library 157

Guidelines for Electrochemical Corrosion Control Methods

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Common Part

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Chapter 1 General

1.1 Scope

(1) This publication provides standard guidelines (hereinafter referred to as “the Guidelines”) for the design, implementation, and maintenance of electrochemical corrosion control applied to newly constructed and existing concrete structures. The Guidelines are applicable to the following four methods: cathodic protection, desalination, re-alkalization, and electrodeposition.

(2) The Guidelines cover steel corrosion, among other factors used to verify the durability of structures, based on the fact that the purpose of electrochemical corrosion control is to prevent steel corrosion.

(3) The Guidelines can be used as a means to ensure the durability specified in the "Standard Specifications for Concrete Structures [Design]" published by the Japan Society of Civil Engineers (JSCE).

(4) The Guidelines can be used as a means to repair deterioration due to steel corrosion specified in the “Standard Specifications for Concrete Structures [Maintenance]” published by the JSCE.

(5) For matters not described in this document, refer to the "Standard Specifications for Concrete Structures [Design] and [Maintenance]" and other relevant guidelines.

[Commentary]

(1) Electrochemical corrosion control is used proactively to improve or ensure the durability of concrete structures and also during in-service maintenance to repair deterioration due to steel corrosion and progressive cracking that occurs over time. The Guidelines herein provide standards to ensure that the investigation, design, implementation, and maintenance of corrosion control systems are performed in a rational and appropriate manner. The Guidelines are applicable to concrete structures of maintenance categories A and B as defined in the “Standard Specifications for Concrete Structures [Maintenance]”. The Guidelines can be used as a guide to restore or improve the durability of existing structures, and can be incorporated into maintenance planning during the design stage to ensure the durability of newly constructed structures.

Electrochemical corrosion control uses an electrochemical reaction that occurs on the surface of steel or inside concrete when a direct current is applied between an anode installed on the surface or outside the concrete and the steel inside the concrete, thus preventing corrosion. Despite ongoing technological developments, only a limited number of techniques are available as a practical method that provides the means to assess the effectiveness of corrosion prevention during installation and to perform the in-service inspection required for maintenance. Therefore, the Guidelines cover the following four types of methods that have proven to be reasonably effective and practical as a measure to maintain, restore and improve the durability of concrete structures, or as a means to prevent deterioration due to steel corrosion:

Cathodic protection

It electrochemically controls the corrosion reaction of steel and prevents the progress of corrosion by supplying direct current to the steel in concrete from an anode system installed on the concrete surface.

Desalination

It electrochemically reduces chloride ions present in concrete by supplying direct current to the steel in concrete from a temporary anode system installed on the concrete surface.

Re-alkalization

It electrochemically permeates alkaline solution by supplying direct current to the steel in concrete from a temporary anode system installed on the concrete surface, thus restoring the pH level (re-alkalization).

Electrodeposition

It electrochemically deposits inorganic electrodeposits on cracks and the concrete surface by supplying direct current to the steel in concrete through electrolyte solution from a temporary anode system installed on the concrete surface to close cracks, cover concrete surfaces, and densify surface layers.

As shown in Table 1.1.1, because each of these methods has its own characteristics in terms of the duration and amount of energization, and the methods for measuring effectiveness, the investigation, design, implementation, and maintenance procedures for each method differ. In addition, different methods may be used in combination where appropriate. Therefore, for matters common to all four methods, follow the Common part of the Guidelines; and for method-specific details, follow the Method-Specific Standards part. Note that the Guidelines may be applied to an electrochemical corrosion control method that may be developed in the future, provided that it provides a means to measure the corrosion prevention effect during implementation and to perform the required maintenance inspections, and that it is shown to be sufficiently effective by actual results or appropriate experiments.

Table 1.1.1 Electrochemical Corrosion Control Methods

	Cathodic protection method	Desalination method	Re-alkalization method	Electrodeposition method
Duration of Energization	Continued during corrosion prevention period	About eight weeks	About one to two weeks	About six months
Current density*	0.001-0.03A/m^2	1A/m^2	1A/m^2	0.5-1A/m^2
Current-carrying voltage	1-5V	5-50V	5-50V	10-30V
Electrolyte solution	—	H_3BO_3 and K_2CO_3 Mixed solution, etc.	Na_2CO_3 aqueous solution, etc.	Seawater, etc.
How to measure effectiveness	Measurement of electric potential or potential change	Measurement of chloride ion content in concrete	Measurement of carbonation depth of concrete	Measurement of physical properties related to surface layer quality
When to check effectiveness	Several times per 1-5 years	After energization is completed	After energization is completed	After energization is completed

* Current density: the amount of current flowing per unit area (concrete) to be protected

(2) Durability is a performance indicator that comprehensively determines whether a structure can maintain its performance requirements such as safety, serviceability, and restorability at or above a required level over the planned service period. This means that if the time-based change in these performance factors can be verified with sufficient accuracy, there would be no need to use durability as a performance indicator during the maintenance stage. However, the techniques to predict deterioration or evaluate performance are not practically mature at present. The "Standard Specifications for Concrete Structures [Maintenance]" states that durability, which has been generally used in Japan, has been designated as a parameter that comprehensively indicates these performance factors during the planned service

period, and that verifying durability is considered to serve as an alternative to verifying whether performance requirements are met or not in terms of safety, serviceability, and restorability during the planned service period. From the same viewpoint, the Guidelines consider durability verification as an alternative to verifying performances of structures. In addition, since electrochemical corrosion control methods are designed to prevent steel corrosion to restore or improve the durability of structures, the Guidelines focus on steel corrosion, among other aspects of durability verification for structures. Note that in this document, corrosion control means controlling the state of steel corrosion so that the effectiveness of corrosion prevention is maintained as intended during the design period. Typically, the methods herein are used to control corrosion so that it does not occur or progress, but in some cases they may also be used to prevent corrosion cracking.

(3) To ensure the durability of new concrete structures, it is necessary to design structures that satisfy the durability requirements over the design service period, considering the importance of the structures, the maintenance categories, and the economics in terms of life cycle costs. However, it is sometimes difficult to predict all the factors that may affect the durability of the structures at the design stage. When it is not possible to identify the factors affecting durability in the design stage, or when concrete alone may not be resistant enough to the deterioration factors, it is important to provide redundancy to prevent the deterioration factors from degrading the performance of the structure by implementing back-up or multiple protection measures. In the “Standard Specifications for Concrete Structures [Design]”, electrochemical corrosion control is presented as a standard protection measure to be taken at the design stage for structures that are expected to deteriorate due to steel corrosion. In this regard, the Guidelines assume that electrochemical corrosion control methods may be used as a protective measure to be taken at the design stage of new structures. In such cases, it is important to include possible maintenance scenarios predicted during the design stage in a maintenance plan so that maintenance work can be done accordingly. If an unexpected scenario occurs during maintenance, the maintenance plan must be reviewed and appropriate action taken.

(4) Existing concrete structures must be maintained so that the performance requirements for structures such as safety, serviceability, and restorability are maintained at or above a required level over the planned service period. When deterioration of a structure is apparent and it is determined that measures should be taken in accordance with the approaches described in the "Standard Specifications for Concrete Structures [Maintenance]", it is necessary to define what performance should be achieved, considering the importance of the structure, the maintenance category, the remaining planned service period, the deterioration mechanism, the degree of performance deterioration and other factors; and to determine appropriate measures to be taken, considering the ease and economy of maintenance and environmental friendliness, and then to implement them accordingly. The Guidelines describe how to apply electrochemical corrosion control methods, following the concept presented in the "Standard Specifications for Concrete Structures [Maintenance]" as a way to deal with structures that show deterioration such as steel corrosion and progressive cracking. When creating a maintenance plan, it is worth considering the use of electrochemical corrosion control methods while deterioration is not yet visible, to exclude deterioration factors or prevent the progress of deterioration. Such a preventive practice will subsequently help to reduce the maintenance burden.

(5) Matters not described in the Guidelines shall be addressed in accordance with the “Standard Specifications for

Concrete Structures [General Principles], [Design], [Construction] and [Maintenance]”. Electrochemical corrosion control methods are intended to prevent deterioration in the performance of structures by preventing steel corrosion, and may be used independently where deterioration due to steel corrosion is latent or developing. They may also be used in combination with other repair or strengthening measures at a stage when the deterioration is accelerating. Note that the Guidelines are applicable in cases where electrochemical corrosion control methods are used to restore or improve the durability of structures, and when the methods are used in combination with other measures to restore, maintain, or improve mechanical or other performance, it is recommended to refer to relevant guidelines such as the "Standard Specifications for Concrete Structures [Design] and [Maintenance]" and the "Guidelines for structural intervention of existing concrete structures using cement-based materials (Concrete Library 150)" published by JSCE.

1.2 Principles of Electrochemical Corrosion Control Methods

(1) Electrochemical corrosion control methods are used as measures to satisfy the performance requirements of a concrete structure based on the maintenance category of the structure.

(2) When using the methods, the design corrosion prevention period and the desired effect shall be determined according to the purpose and conditions of the structure.

(3) Electrochemical corrosion control methods must be used with appropriate implementation procedures and workflows.

[Commentary]

(1) and (2) Electrochemical corrosion control methods are used to prevent steel corrosion and subsequent progressive cracking and are implemented to maintain, restore or improve the durability of a concrete structure according to the scenario defined in the maintenance plan based on the maintenance category of the structure. The methods can be applied to both new and existing structures. When using the methods to ensure the durability of a new structure, be sure to define the design corrosion prevention period and the desired effect based on the design service life and the limit state of the structure. When using the methods for repair purposes, be sure to define the design corrosion prevention period and the desired effect based on the target period and performance level specified in the maintenance plan for the structure. Examples of objectives are: “Steel corrosion will not progress during the design corrosion prevention period”, or “Steel corrosion may progress, but harmful cracking due to steel corrosion will not occur during the design corrosion prevention period (or the remaining planned service period).

(3) The electrochemical corrosion control method should be implemented with appropriate investigation, design, implementation, and maintenance to achieve the desired effect over the design corrosion prevention period. It is also necessary to thoroughly examine the organizational, personnel, material, and budgetary requirements in advance. With appropriate implementation procedures in place, the investigation, design, implementation, and maintenance must follow the flowchart shown in Figure 1.2.1. It is also important to follow the PDCA (Plan-Do-Check-Act) cycle for all of these maintenance activities.

As shown in the figure, there are two paths in the flowchart: one path is followed when the method is used as a repair measure in the maintenance of existing structures based on the approaches described in the "Standard Specifications for Concrete Structures [Maintenance]" and the "Guidelines for structural intervention of existing concrete structures using cement-based materials (Concrete Library 150)"; and the other path is followed when the use of the method is considered in the maintenance planning at the design stage to ensure the required durability of a new structure. In both cases, the design, verification, implementation, and maintenance should be carried out according to the specific details given in the Method-Specific Standards section. After the method is implemented, it is important to incorporate method-specific maintenance considerations into the maintenance plan of the structure.

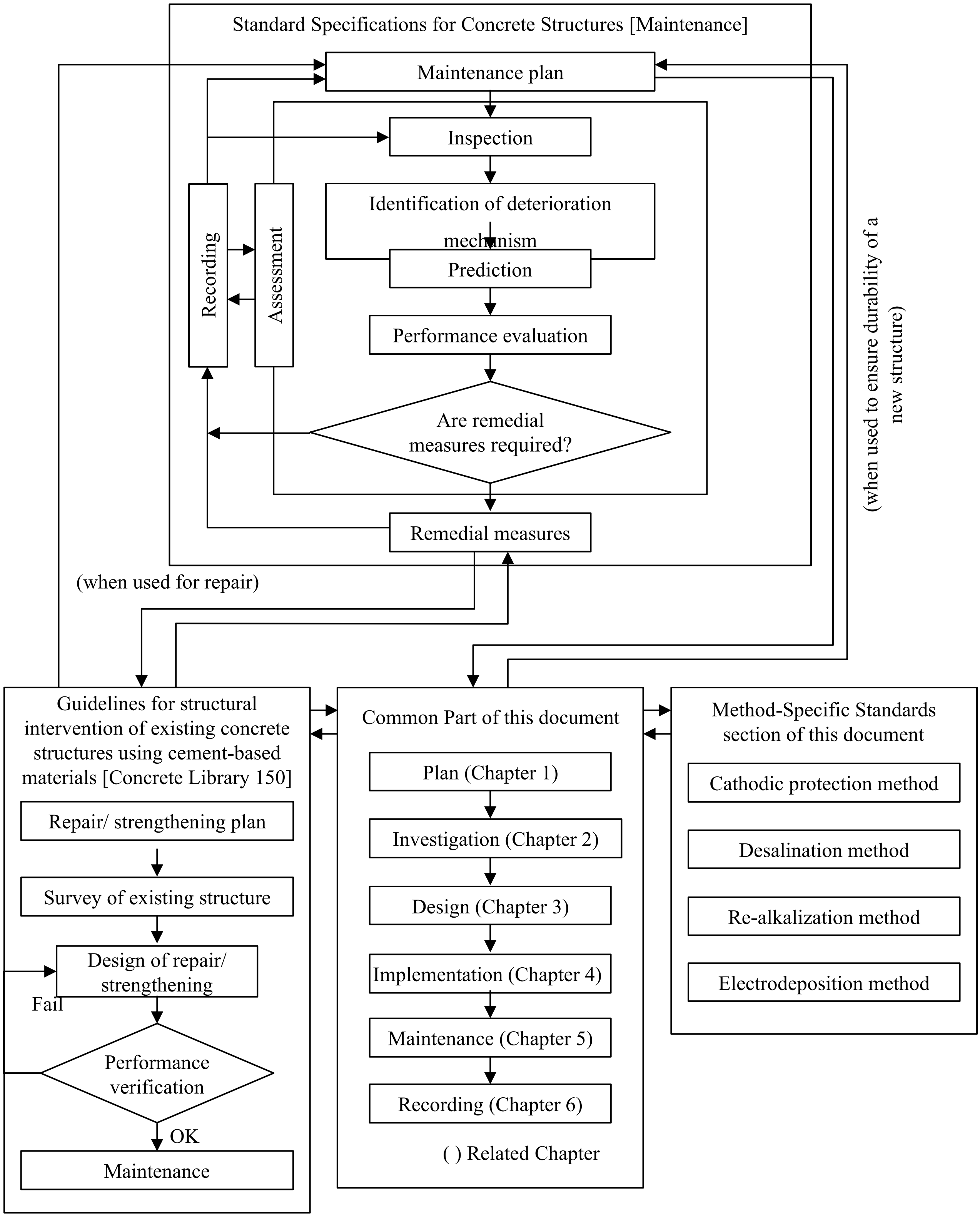


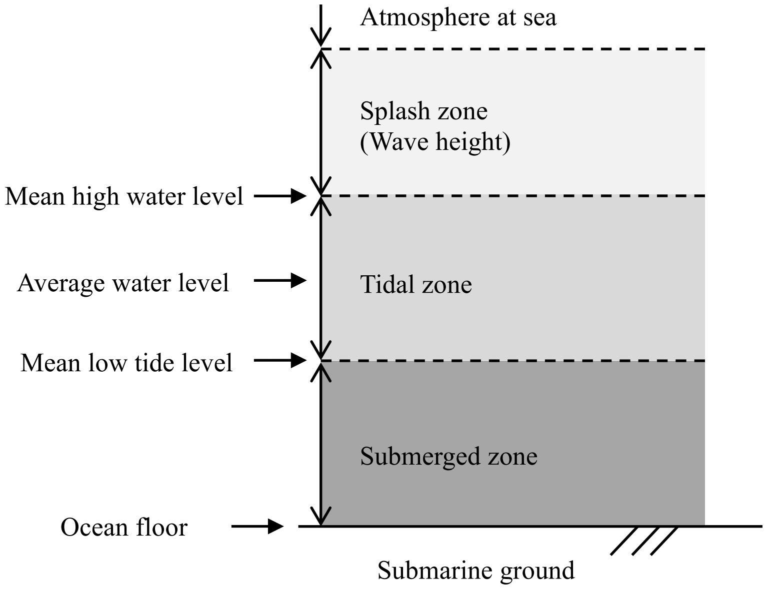
Figure 1.2.1 Structure of the Guidelines and Flowchart of Electrochemical Corrosion Control Procedures

1.3 Terms and Definitions

In the Common part and the Method-specific Standards part of the Guidelines, terms are defined as follows:

(1) Terminology used in the Common part

Tidal zone: The area between high and low water levels, or between respective shoreline positions. For reference, the definitions of levels in the marine environment used in the Guidelines are shown below.



Definitions of levels in the marine environment

Design corrosion prevention period: The period of time estimated in the design process during which the intended corrosion prevention effect must be maintained.

Electrolyte solution: A generic term for electrically conductive solutions containing electrolytes. It constitutes a temporary anode in desalination, re-alkalization, and electrodeposition methods.

Professional engineer of electrochemical corrosion control methods: An engineer who has comprehensive, high-level knowledge and extensive experience in concrete structures and is able to make appropriate technical judgments in the application and maintenance of electrochemical corrosion control methods. Defined for each of the four methods: cathodic protection, desalination, re-alkalization, and electrodeposition.

Corrosion prevention: In a narrow sense, it means the prevention of corrosion of steel in concrete. In the Guidelines, it means controlling the state of corrosion prevention of steel reinforcement to achieve the intended corrosion prevention effect over the design corrosion prevention period. In most cases the practice is used to control corrosion so that it does not occur or progress, but in some cases it is used to prevent corrosion-induced cracking from occurring.

Maintenance criteria for corrosion prevention: Indicators and their levels used in verification during design, quality control during implementation, inspection after implementation, and diagnosis during maintenance, to determine whether the intended corrosion prevention effect can be achieved over the design corrosion prevention period. The indicators are quantitative values such as the amount of polarization of the steel or the grade of appearance, or a combination of both. The corrosion control index is used for cathodic protection, the desalination target for desalination, the re-alkalization target for re-alkalization, and the electrodeposition target for electrodeposition.

Intended corrosion prevention effect: The condition or degree of deterioration (the grade of appearance) of steel that is specified during design and must be maintained for the design corrosion prevention period. In general, it means a state in which corrosion is not occurring or progressing. Based on this condition, appropriate control standards for corrosion prevention are specified for each method.

Anode and anode materials: An electrode and its materials connected to the positive electrode of the DC power supply.

(2) Terminology used in the Method-Specific Standards part

(i) Terminology common to all methods

Anode: An electrode at which an electric current flows toward the electrolyte and an oxidation reaction occurs. In electrochemical corrosion control, the anode is connected to the positive electrode of the DC power supply. In steel corrosion, it is the part where corrosion progresses.

Anodic reaction: Oxidation reactions that occur around steel or anode materials in concrete. Major anodic reactions include:

$Fe \rightarrow Fe^{2+} + 2e^{-}$ (reaction that occurs on the corroded part of the steel)

$4OH^{-} \rightarrow 2H_2O + O_2 + 4e^{-}$ (reaction that occurs around the anode material due to energization)

$2Cl^{-} \rightarrow Cl_2 + 2e^{-}$ (reaction that occurs around the anode due to excessive current flow)

Cathode: An electrode at which current flows from the electrolyte and a reduction reaction occurs. In electrochemical corrosion control, it refers to the steel inside the concrete, and it is connected to the negative electrode of the DC power supply. In steel corrosion, reduction occurs at the cathode.

Cathodic reaction: Reduction reaction that occurs on the surface of the steel in concrete. Major cathodic reactions include:

$2H_2O + O_2 + 4e^{-} \rightarrow 4OH^{-}$ (reaction that occurs on the surface of corroded steel materials when the power is applied.)

$2H_2O + 2e^{-} \rightarrow H2 + 2OH^{-}$ (reaction that occurs around steel due to excessive current flow)

Hydrogen embrittlement: Reduction in toughness of steel materials due to absorbed hydrogen.

Hydrogen generation potential: The potential at which hydrogen gas is generated at the cathode.

Exhaust current: The return of direct current supplied by the DC power supply from the steel materials to the power supply.

Drain terminal: A terminal attached to the steel to connect the negative side of the DC power supply in electrochemical corrosion control.

Drain point: The point of contact between the steel and the wiring when the direct current returns to the DC power supply in electrochemical corrosion control.

(ii) Cathodic protection method

”Instantaneous OFF” potential: The potential of the anode or the steel inside the concrete measured immediately after the cathodic protection current is stopped in a test to verify the corrosion prevention effect. This potential approximates to the true potential without voltage drop (IR drop). Abbreviated as E_{io}.

Off potential: The potential of the anode or the steel inside the concrete measured after sufficient time has elapsed since the cathodic protection current was stopped. Abbreviated as E_{of}.

On potential: The potential of the anode or the steel inside the concrete when the cathodic protection current is applied. This potential includes a voltage drop (IR drop). Abbreviated as E_{on}.

Cathodic polarization: To change the potential of a metal in the negative (base) direction by supplying a protective current (direct current) to the metal.

Cathodic protection: A method of controlling corrosion of steel by changing the potential of the steel to be protected in the negative (base) direction (cathodic polarization) by supplying a protective current (direct current).

Surge absorber: A device that absorbs overvoltage caused by lightning and protects equipment such as DC power supplies.

Backfill material: A material added to the outer surface of the anode to reduce the contact resistance of the anode material or to maintain the performance of the galvanostatic anode system and to facilitate the dissolution of the sacrificial anode.

Anode coating material: A material that protects the anode material and also acts as a backfill material. Cement-based mortar is commonly used.

Sacrificial anode: Anode used in the galvanic anode system. A metal (such as zinc) having greater ionization tendency than the steel inside concrete is used as an anode.

Contact resistance: Resistance generated at the interface between the reference electrode or anode and the anode coating material, and at the interface between the reference electrode and concrete.

Energizing point: Contact point between the wiring and the anode system in cathodic protection.

Constant voltage method: A cathodic protection method in which a constant voltage is applied from a DC power supply to prevent corrosion.

Constant potential method: A cathodic protection method that prevents corrosion by maintaining the potential of steel at a constant level.

Constant current method: A cathodic protection method that prevents corrosion by applying a constant current from a DC power supply.

Voltage drop (IR drop): Voltage drop due to resistance of concrete, anode and wire materials. It is equal to the difference between the on-potential and the ”Instantaneous OFF” potential.

Professional engineer of cathodic protection method: An engineer with specialized knowledge of cathodic protection methods. Refers to an engineer who has comprehensive, sophisticated knowledge and extensive experience in concrete structures, is familiar with the use and maintenance of the cathodic protection systems, and can make appropriate technical judgments. In the area of cathodic protection system maintenance, it also refers to an engineer who has been involved more than once as a leader in the design, implementation, or maintenance of a cathodic protection project.

Measuring terminal: A point of contact between wiring and steel to measure the potential of the steel in a cathodic protection system. No protective current passes through this wiring.

Distributor: Current distribution material used to ensure electrical continuity between anode materials. Generally made of titanium.

Depolarization: A phenomenon in which a change in the potential of the steel occurs when the supply of protective current is stopped.

Depolarization quantity: This is one of the indices of corrosion control in a cathodic protection system and refers to the amount of potential difference between the "Instantaneous OFF" potential E_{io} and the off potential E_{of} of the steel ($\Delta E_d = E_{of} - E_{io}$).

Polarization: A phenomenon in which a change in the potential of the steel occurs when a protective current is supplied.

Polarization quantity: This is one of the indices of corrosion control in a cathodic protection system and refers to the amount of potential difference between the natural potential E_0 and the "Instantaneous OFF" potential E_{io} of the steel ($\Delta E_p = E_0 - E_{io}$).

Corrosion control index: An item and level for controlling the corrosion prevention condition of the steel inside concrete. It corresponds to the maintenance criteria for corrosion prevention defined in the Common part of the Guidelines.

Protective potential: The electric potential required to prevent corrosion of the steel.

Protective current: The electric current supplied to the steel to maintain the corrosion prevention condition.

(iii) Desalination method, re-alkalization method, and electrodeposition method

Liquid-phase reaction: The reaction of ions present in a solution, depending on the stability of the bond. In particular, in the electrodeposition reaction, positive and negative ions in the solution shows a reaction of precipitating and precipitating as poorly soluble salts.

Temporary energizing system: A system consisting of temporary anodes, DC power supplies and wiring materials.

Temporary anode: Collectively refers to anode materials, electrolyte solution and holding materials.

Temporary anode system: A system in which a temporary anode is fixed to the concrete surface. Characteristics vary depending on the materials used and the method of fixing.

Professional Engineer of re-alkalization method: An engineer with specialized knowledge of the re-alkalization process. Refers to an engineer who has comprehensive, sophisticated knowledge and extensive experience in concrete structures, is familiar with the use and maintenance of the re-alkalization process, and can make appropriate technical judgments.

Professional Engineer of desalination method: An engineer with specialized knowledge of the desalination process. Refers to an engineer who has comprehensive, sophisticated knowledge and extensive experience in concrete structures, is familiar with the use and maintenance of the desalination process, and can make appropriate technical judgments.

Professional Engineer of electrodeposition method: An engineer with specialized knowledge of the electrodeposition process. Refers to an engineer who has comprehensive, sophisticated knowledge and extensive experience in concrete structures, is familiar with the use and maintenance of the electrodeposition process, and can make appropriate technical judgments.

Electrodeposits: Inorganic substances such as insoluble calcium carbonate and magnesium hydroxide deposited by cations such as calcium and magnesium ions in electrolyte solution in a temporary anode, seawater, or groundwater.

Crack closure rate: Percentage of crack length blocked by electrodeposit to total length of crack before countermeasure.

Surface coverage: Percentage of the area covered by electrodeposits to the area to be repaired.

Holding material: A material used to hold an electrolyte solution on the concrete surface.

[Commentary]

The above is a list of terms and definitions used in the Guidelines. The explanations are intended to be as simple and understandable as possible for those civil engineers who may not be familiar with electrochemical terms.

Chapter 2 Investigation

2.1 General

An investigation plan shall be developed by considering the investigation items, methods and the implementation system that will serve the purpose of the investigation. The investigation shall be properly conducted according to the plan.

[Commentary]

In order for the application of electrochemical corrosion control to maintain its intended effect for the intended duration, appropriate investigation results are essential for the applicability assessment and method selection, as well as for the design, implementation, and maintenance of the corrosion control system. It is necessary to develop an appropriate investigation plan by selecting investigation items and methods appropriate to the purpose of the investigation and establishing a feasible implementation system. The results of the investigation should be properly recorded and retained as they can be used at every stage of the design, construction, and maintenance of the structure.

2.2 Investigation Plan

2.2.1 General

The overall work plan should be prepared after selecting the investigation methods, considering the investigation items according to the purpose and field conditions. In addition, the implementation system should be determined, taking into account issues such as safety and health management.

[Commentary]

An investigation plan should be prepared with an appropriate selection of investigation items and methods to determine the applicability of electrochemical corrosion control and to obtain information needed for the design and implementation phases. The overall work plan should then be prepared and the implementation system established, taking into account issues such as site safety and hygiene control.

After selecting investigation items, it is necessary to determine the investigation methods and procedures that will efficiently and adequately obtain the required information, and then develop an overall work plan. It is important to develop a plan along with its implementation system by evaluating the environmental conditions in which the concrete structures and the members will be placed, determining if the investigation can be performed while the structures are in service, and investigating if there are any time restrictions on the investigation.

The investigation plan is basically made before the execution of each investigation, but in order to carry out the investigation efficiently, it is important to grasp the investigation items and the investigation method necessary for the implementation of an electrochemical control method as early as possible. Therefore, during the evaluation of the applicability of an electrochemical corrosion control method, it is better to start preparing an investigation plan, including the investigation for the selection of the method and the investigation for the design and implementation, based on the conditions of the target structure and its deterioration mechanism, and so on.

2.2.2 Selection of Investigation Items

Investigation items should be selected appropriately to achieve the purpose of each investigation.

[Commentary]

For electrochemical corrosion control methods, different types of investigation are required: prior investigation to determine the applicability of an electrochemical corrosion control method (hereinafter referred to as the "Prior investigation"); investigation to select an appropriate electrochemical corrosion control method according to the purpose of corrosion prevention ("Investigation for method selection"); and investigation to obtain information necessary for the design and implementation of the selected method ("Investigation for design and implementation"). As shown in Table 2.2.1, these investigations are conducted at different stages. When planning an investigation at each stage, it is important to select the necessary investigation items according to the purpose of the investigation.

The purpose of the Prior investigation is to obtain the information necessary to determine whether electrochemical corrosion control is applicable to the target structure. Such information includes: whether electrochemical corrosion control is applicable to the deterioration mechanism assumed for the structure; whether the supply of direct current to the target steel will not be inhibited; and whether the direct current will not cause any other deformations of the concrete. Therefore, it is necessary to investigate into issues such as the structural types and the materials used for the target members, the environmental conditions in which the members are placed, the main deterioration mechanism, the deterioration conditions such as the grade of appearance, the history of remedial measures, and the methods and materials used in the previous repairs. Examples of causes that inhibit direct current to the steel are the use of corrosion resistant steel (e.g., epoxy-resin coated reinforcing bars) and the application of surface coating materials or surface penetrants to the surface of the structure. In the case of concrete structures in which alkali silica reaction (ASR) may occur, adequate investigation is required because ASR may be promoted by the electrochemical corrosion control. For newly constructed concrete structures, it is desirable to assume the deterioration mechanism. Table 2.2.2 shows examples of Prior investigation items.

The purpose of the Investigation for method selection is to obtain the information necessary for the selection of the method to be applied to the target structure or its members. For this investigation, in addition to the Prior investigation items, it is necessary to select investigation items needed to examine the expected effects of applying the electrochemical corrosion control method, and the persistence of the effects, the service condition of the structure when the method is applied, the scope and numerical data of the implementation (e.g., area to be applied), environmental constraints and considerations, and the economic efficiency such as life cycle cost. Table 2.2.3 shows examples of investigation items. The information already obtained from the Prior investigation can be used for this investigation.

The purpose of the Investigation for design and implementation is to obtain the information necessary for the design and implementation of the selected electrochemical corrosion control method. For this investigation, in addition to the investigation items of the previous stages, the investigation items suitable for the selected electrochemical corrosion control method shall be selected. For existing concrete structures, it is also necessary to obtain information such as the exact location, area and size of cracks or delamination, and measures taken in the past, to determine the pretreatment of concrete and steel required prior to the application of electrochemical corrosion control method. This investigation is generally carried out at the detailed design stage of each method, but it is often appropriate to carry out some additional investigations during the implementation stage, such as an investigation to determine the extent and amount of degradation. Table 2.2.4 shows examples of investigation items for this investigation. The information already obtained from the investigations performed during the previous stages can be used for this investigation.

Table 2.2.1 Purpose and Timing of the Investigation

Name of Investigation	Purpose	Investigation performed during
1) Prior investigation	To gather information necessary to evaluate the applicability of electrochemical corrosion control methods	applicability determination (preliminary examination) stage
2) Investigation for method selection	To gather information necessary to select electrochemical corrosion control methods	method selection (basic design) stage
3) Investigation for design and implementation	To gather information necessary for detailed design and implementation of selected electrochemical corrosion control methods	detailed design stage for each method (some investigations are additionally conducted during the implementation stage)

Table 2.2.2 Examples of Prior Investigation Items

Investigation items		New construction	Existing	Remarks
Structure	Type of structure	○	○	
	Shape and dimensions of members	○	○	
	Shape and type of steel	○	○	
	Site conditions	○	○	
	History of remedial measures (type of remedial measures, etc.)	—	○	
Implementation conditions	Schedule, duration, and time of implementation	○	○	
Hazards for third party	Presence of hazards for third party	○	○	
State of deterioration	Deterioration mechanism, grade of appearance, etc.	△	○	

○:Investigation required △:Investigation recommended -:Investigation not possible or not necessary

Table 2.2.3 Examples of Investigation Items for Method Selection

Investigation items		New construction	Existing	Remarks [1)]
Structure	Type of structure	○	○	Prior
	Shape and dimensions of members	○	○	
	Shape and type of steel	○	○	
	Site conditions	○	○	
	History of remedial measures (type of remedial measures, etc.)	—	○	
Service life	Planned service period	○	—	
	Remaining planned service period	—	○	
Implementation conditions	Presence or absence of commercial power supply	○	○	
	Locations of DC power supplies and enclosures	○	○	
	Schedule, duration, and time of implementation	○	○	Prior
Hazards for third party	Impact on third parties	○	○	

State of deterioration	Deterioration mechanism, grade of appearance, etc.	△	○	
Economy	Material costs, replacement costs, renewal costs, etc.	○	○	

○:Investigation required △:Investigation recommended -:Investigation not possible or not necessary
1) The "Prior" in the remarks column indicates that the information obtained from the Prior investigation may be used.

Table 2.2.4 Examples of investigation items for design and construction

Investigation items		Cathodic protection		Desalination	Re-alkalization	Electrodeposition	Remark [4]
		New construction	Existing				
Target structures	Type of structure	○	○	○	○	○	Prior
	Shape and dimensions of members	○	○	○	○	○	
	Shape and type of steel	○	○	○	○	○	
	Site conditions	○	○	○	○	○	
	History of remedial measures (type of remedial measures, etc.)	—	○	○	○	○	
	Load conditions (traffic volume, upper load, etc.)	△	△	△	△	△	
Service life	Planned service period	○	—	—	—	—	Selection
	Remaining planned service period	—	○	○	○	○	
Environmental conditions	Details of environmental conditions	○	○	○	○	○	
	Spraying of anti-freeze materials	○	○	○	○	○	
Implementation conditions	Presence of commercial power supply	○	○	○	○	○	Selection
	Locations of DC power supplies and enclosures	○	○	○	○	○	
	Water quality of electrolyte solution (concentration of Ca or Mg ions in seawater, brackish water and groundwater, etc.)	—	—	—	—	○	
	Schedule, duration, and time of implementation.	○	○	○	○	○	Prior
Hazards for third party	Impact on third parties	○	○	○	○	○	
Defect	Delamination, Spalling, Honeycomb, Scaling, etc. (Position, Area)	—	○	○	○	○	
	Cracks (Shape, Width, Length)	—	○	○	○	○	
	Strain of Rust (Position, Area)	—	○	○	○	○	
	Water leakage / Water splash (Position, Area)	—	○	○	○	○	
	Exposed metal (Position, Size)	—	○	○	○	○	
History of remedial measures	Surface treatment (Position, Area, Type)	—	○	○	○	○	
	Patching (Position, Area, Type)	—	○	○	○	○	
	Strengthening (Position, Area, Type)	—	○	○	○	○	
Deposits / Incidents	Deposits of marine organisms (Type, Quantity)	—	—	—	—	○	
	Incidental equipment (Existing pipes, Inspection passages, etc.)	—	○	○	○	○	
Quality of concrete	Materials (Type of cement, etc.)	○[1]	○[1]	○[1]	○[1]	○[1]	
	Water to cement ratio	—	—	○[1]	○[1]	—	
	Electrical resistivity	○	○	○	○	○	
	Water permeability	—	—	—	—	△	
	Porosity	—	—	—	—	△	
State of deterioration	Deterioration mechanism, grade of appearance, etc.	△	○	○	○	○	Prior
	Chloride ion concentration	—	△	○	—	△	
	Carbonation depth	—	△	△	○	△	
	Degree of deterioration due to alkali-silica reaction, etc.	—	△[2]	△[2]	△[2]	△[2]	
State of steel	Position of steel (Cover)	○[1]	○[1]	○[1]	○[1]	○[1]	
	Arrangement and quantity of steel	○[1]	○[1]	○[1]	○[1]	○[1]	
	Shape and type of steel	○[1]	○[1]	○[1]	○[1]	○[1]	

	Type and arrangement of sheath	○1)	○	○	○	○	
	Corrosion conditions of steel	—	○	○	○	○	
	Electrical continuity between the steel	○	○	○	○	○	
	Polarization of steel (Cathodic polarization)	—	△3)	—	—	—	
Economy	Material costs, replacement costs, renewal costs, etc.	○	○	○	○	○	Selection

○:Investigation required △:Investigation recommended -:Investigation not possible or not necessary
1) Verify with design and implementation documents.
2) Conduct this investigation when deterioration may be caused by ASR.
3) Conduct this investigation when deemed necessary during the design phase, such as when determining the current density for the cathodic protection method or determining the anode arrangement.
4) "Prior" in the Remarks column indicates that the information from the Prior investigation may be used. Similarly, "Selection" indicates that the information obtained from the Investigation for method selection may be used

2.2.3 Determination of Investigation Methods

Investigations and their implementation system shall be determined based on site conditions and other considerations for the investigation items selected according to the purpose of each investigation.

[Commentary]

It is important to appropriately determine the investigation methods based on the site conditions for the investigation items selected according to the purpose of the investigation at each stage. There are various methods, such as one based on design and relevant documents, one based on on-site measurement, and one based on samples taken from the site. They can be classified into the following five types:

(i) Document search

Information appropriate to the selected electrochemical corrosion control method is obtained from documents such as design and completion documents, maintenance plans, maintenance records, and interviews with related parties.

(ii) Environmental survey

Information on the site conditions of the structure is obtained. It includes environmental conditions, construction conditions, hazards for third parties, and interviews with related parties.

(iii) Appearance inspection

Information on the target existing structure is obtained from documents or site inspection. It includes concrete surface defects such as delamination, spalling and metal exposure, history of remedial measures, and the location, size, area and type of ancillary equipment.

(iv) Inspection of concrete

Information on the quality of the concrete and the cause of deterioration of the target structure is obtained from documents and site inspection.

(v) Inspection of steel

Information on the condition of steel in concrete is obtained by inspecting the design and site conditions.

Note that the required or applicable investigation differs depending on the time of the investigation and the condition of the target structure. The Prior investigation and the Investigation for method selection primarily require (i) and (ii), while the Investigation for design and implementation requires (i) through (v). Items (i) and (ii) are primarily required for newly constructed structures, while items (i) through (v) are required for existing structures.

When planning an investigation, it is necessary to examine the whole work schedule of the investigation and establish an appropriate implementation system that can perform a reliable investigation. Especially, it is important that the Investigation for design and implementation should be carried out by professional engineers who specialize in the selected electrochemical corrosion control method. An on-site investigation must be planned with work safety and environmental considerations in mind. For more details on investigation methods, refer to the Method-Specific Standards part and Appendix 1 (outline of the investigation methods).

2.3 Implementation of the Investigation

The investigation should be conducted as planned to ensure that information is obtained according to the purpose of each investigation.

[Commentary]

The investigation shall be conducted efficiently according to the plan. On-site investigations shall be carried out with work safety and environmental protection measures in place. After each investigation, ensure that the intended information is obtained. Based on the results, review the content of subsequent investigations and, if necessary, revise the investigation plans before proceeding.

Based on the results of the Prior investigation, determine the applicability of an electrochemical corrosion control method. If it is determined to be applicable, conduct the Investigation for method selection, and determine an appropriate electrochemical corrosion control method. The results of the Investigation for design and implementation should be used during the design and implementation stages so that the expected effects of each method can be fully demonstrated. All investigation results shall be recorded and stored.

Chapter 3 Design

3.1 General

(1) An electrochemical corrosion control method shall be selected considering the purpose of corrosion prevention, the expected main effects, and the deterioration mechanism of the concrete structure to be protected.

(2) The applicability of an electrochemical corrosion control method to a newly constructed concrete structure shall be examined in accordance with Chapter 3 “Structural Planning” of the "Standard Specifications for Concrete Structures [Design: General Requirements]".

(3) The applicability of an electrochemical corrosion control method to an existing concrete structure shall be examined based on the "Standard Specifications for Concrete Structures [Maintenance]" and the "Guidelines for structural intervention of existing concrete structures using cement-based materials (Concrete Library 150)".

[Commentary]

(1) When designing an electrochemical corrosion control method, select an appropriate method based on the results of the Investigation for method selection, taking into account the purpose of corrosion prevention, the expected main effects, and the deterioration mechanism of the concrete structure, as shown in Table 3.1.1.

The cathodic protection method can be applied to structures where steel corrosion may occur or has occurred due to chloride attack or carbonation or other causes. It can also be used when steel corrosion has occurred due to multiple deterioration mechanisms and the cause of corrosion has not yet been identified.

The desalination method can be applied to structures suffering from chloride attack in anticipation of the effect of reducing the chloride ion concentration in concrete.

The re-alkalization method can be applied to structures suffering from steel corrosion due to carbonation, in anticipation of the effect of restoring alkalinity in concrete.

The electrodeposition method, which is expected to improve the migration resistance of corrosion factors, can be applied to structures subject to chloride attack and carbonation and structures with nonprogressive cracks.

Table 3.1.1 Purpose of corrosion prevention, expected effects, and applicable deterioration mechanisms

Electrochemical corrosion control method	Purpose of corrosion prevention	Expected main effect	Major deterioration mechanism or deformation to which the method applies
Cathodic protection	To suppress corrosion reaction	Reduction of corrosion reaction rate	Chloride attack*, carbonation*
Desalination	To improve the corrosive environment of steel	Reduction of chloride ion concentration	Chloride attack
Re-alkalization		Recovery of alkalinity	Carbonation
Electrodeposition	To suppress the supply of corrosion factors	Improving the migration resistance of corrosion factors	Chloride attack**, carbonation**, Non-progressive Cracking**

* Includes cases where the main cause of steel corrosion is assumed to be chloride attack or carbonation at the stage of method

selection.
** Can be used as surface coating after the application of desalination method or as crack repair or surface treatment in special working environments.

(2) and (3) With regard to durability, as stated in Section 3.2 (Studies on performance requirements) of Chapter 3 (Structural Plan) of "Standard Specifications for Concrete Structures [Design: General Requirements]", if a highly corrosive, severe environment makes it difficult to ensure the required durability using the permeation resistance of concrete materials, it is recommended to consider the use of a cathodic protection method or an electrodeposition method. In this case, the design corrosion prevention period and the intended corrosion prevention effect should be appropriately determined based on the design service life and the required performance of the structure, and the use of an electrochemical corrosion control method that satisfies these requirements should be examined.

In addition, as described in Section 3.4 (Studies on Maintenance) of the Specifications mentioned above, if it is anticipated that an electrochemical corrosion control method will be used during the in-service stage in order to reduce the life cycle cost of the structure, it is advisable to consider ways to facilitate the use of the method at the time of structural planning. In such a case, refer to the descriptions relating to existing concrete structures in the Guidelines.

When an existing concrete structure requires repair as part of maintenance and an electrochemical corrosion control method is deemed applicable, an appropriate method shall be selected according to the "Standard Specifications for Concrete Structures [Maintenance]" and "Guidelines for structural intervention of existing concrete structures using cement-based materials (Concrete Library 150)". The design corrosion prevention period and the intended corrosion prevention effect shall then be determined based on the target period and the target performance level defined in the maintenance plan of the structure, considering the present conditions of the structure, implementation conditions, ease of maintenance, and other requirements.

3.2 Selection of Electrochemical Corrosion Control Method

(1) To achieve the intended corrosion protection effect, an appropriate electrochemical corrosion control method should be selected, taking into account the implementation process, maintenance procedure, environmental friendliness, and economic efficiency.

(2) As a measure against chloride attack, it is basic to use the cathodic protection method, the desalination method or the electrodeposition method.

(3) As a measure against carbonation, it is basic to use the cathodic protection method, the re-alkalization method or the electrodeposition method.

(4) As a measure against cracking, it is basic to use the electrodeposition method.

[Commentary]

(1) When selecting an electrochemical corrosion control method, consideration should be given to the requirements of the corrosion control method necessary to achieve the intended corrosion prevention effect based on the deterioration state of the target structure, the structure type, and environmental conditions. Consideration should also be given to matters related to the implementation procedure, ease of maintenance, environmental restrictions, economic efficiency, and so on. Examples of these considerations are shown in Table 3.2.1. Since the importance of each item differs for each

structure, it is important to select a corrosion control method considering these issues comprehensively. For a detailed examination of these considerations, it is necessary to refer to Method-Specific Standards part. As a reference, Appendix 2 outlines the method selection flow for each structural manager, Appendix 3 shows the LCC/LCCO$_2$ calculation method and sample calculations, and Appendix 4 provides a case study of the design, implementation, and maintenance of the cathodic protection method.

An appropriate electrochemical corrosion protection method should be selected to maintain the intended corrosion prevention effect on the structure or its members, whether new or existing, over the design corrosion prevention period. For newly constructed structures, the cathodic protection method and the electrodeposition method are used.

Table 3.2.1 Examples of considerations when selecting an electrochemical corrosion control method

Category	Subcategory	Points to note
Deterioration	1) Deterioration state	Deterioration process and appearance grade in the main deterioration mechanism when the method is applied
	2) Occurrence of complex deterioration	Presence or absence of complex deterioration (possibility of multiple deterioration mechanisms) and its status
Structural condition	3) Structural type	Structural type of applicable member (PC member/RC member)
	4) Environmental conditions	Environmental conditions in which applicable components are placed
Performance assurance	5) Expected effects	Expected effects of using the corrosion control method (including recovery of mechanical performance)
	6) Sustainability of the effects	Durability of effect vs. design corrosion prevention period (service life)
Implementation method	7) State of service	Necessity and feasibility of implementation while the structure is in service
	8) Efficiency of implementation	Work process (efficiency) based on the amount of work (including pretreatment), procurement of materials and equipment, necessity of temporary scaffolding, ease of installation, time available for work, etc.
Maintainability	9) Ease of maintenance	Ease of maintenance after implementation
Environmental friendliness	10) Environmental constraints	Restrictions on the generation of dust, noise, etc.
Economic efficiency	11) Cost	Life cycle costs, etc.

(2) For chloride attack, the cathodic protection method, desalination method or electrodeposition method is used based on the results of the durability verification of the structures or the results of the inspection, evaluation, and judgment for the structures. When selecting an electrochemical corrosion control method as a measure against chloride attack on concrete structures, it is necessary to consider various points as shown in Table 3.2.1.

Regarding the 1) Deterioration state, the applicable method differs depending on the deterioration process and the grade of appearance. The applicable method also differs for different 5) Expected effects, such as restoration and improvement of durability, and restoration of mechanical performance. Therefore, it is necessary to consider these factors when selecting an electrochemical corrosion control method. Table 3.2.2 shows examples of appearance grades and applicable methods for chloride attack prevention. Regarding 4) Environmental conditions, the scope of each method differs depending on the environment, such as land, inland, and marine, as shown in Table 3.2.3.

Table 3.2.2 Examples of appearance grades and applicable methods (measures against chloride attack)

Structures	Appearance Grade	Deterioration process	Expected effect	
			Restoration and improvement of durability	Recovery of mechanical performance
Newly constructed	–	–	Surface treatment [1)], cathodic protection [1)]	–

structure				
Existing structures	Grade I	Initiation stage	Surface treatment 1), desalination 1), and cathodic protection 1)	—
	Grade II	Propagation stage	Surface treatment, desalination, cathodic protection	—
	Grade III-1	First half of the acceleration stage	Repair of cross section, desalination, and cathodic protection	—
	Grade III-2	Second half of the acceleration stage	Repair of cross section, desalination 2), and cathodic protection 2)	Cross section repair (if necessary)
	Grade IV	Deterioration stage	Desalination 3), cathodic protection 3)	Cross section repair

1) Preventive measure.
2) Consider using it in combination with other methods (such as external cabling) if necessary.
3) Can be used in combination with other methods (such as external cabling).
Note: Electrodeposition method can be used for the same purpose as the surface treatment shown in the table.

Table 3.2.3 Scope of application for different environments (measures against chloride attack)

Environment \ Method		Electrochemical corrosion control method		
		Cathodic protection method	Desalination method	Electrodeposition method
Land and inland areas		○	○	△
Marine environment	Atmosphere at sea	○	○	△
	Splash zone	○	○	△
	Tidal zone	△	△	△
	Submerged zone	△	△	○

○: Applicable △Careful consideration is required

Table 3.2.4 provides an example of items to consider when selecting a method to restore or improve durability as a measure against chloride attack. The table shows the applicability and considerations of the cathodic protection method, desalination method, and other methods with reference to the items listed in Table 3.2.1. The Guidelines focus on the appropriate selection of an electrochemical corrosion control method, but for reference purposes, the table also provides characteristics of the surface treatment method and the cross section repair method in the other methods column, in comparison with the cathodic protection method and the desalination method. A case where a structure has ASR (alkali-silica reaction) concerns is shown as complex deterioration. It should be noted that the considerations described in this table may not always apply to structures in special conditions; the considerations are intended for concrete structures, such as bridges, which have many proven implementations of electrochemical corrosion control methods.

The cathodic protection method can be applied to both new and existing concrete structures, and can be used for structures in environments ranging from land to inland, and from the atmosphere at sea to underwater. However, when it is applied to existing structures after the acceleration stage, it is necessary to consider using it in combination with other measures such as cross section repair or external cabling, depending on the degree of deterioration of mechanical performance such as cracks and cross section defects of steel. In addition, when it is applied to members in the tidal zone of the marine environment, design considerations such as separating the corrosion prevention circuit from the atmosphere are necessary. When applied to the structure in which ASR is a concern, it is advisable to refer to the Method-Specific Standards part and decide the applicability and implementation procedures. In terms of maintainability, the cathodic protection method has the advantage that the corrosion prevention effect can be quantitatively assessed by appropriate inspections. In addition, when used in conjunction with a remote monitoring system, it can provide continuous monitoring and data collection from remote locations, allowing for more sophisticated, simplified and streamlined maintenance.

The desalination method can be applied to existing concrete structures, but when used after the acceleration stage, it is necessary to consider using it in combination with other measures such as cross section repair and external cabling, just as with the cathodic protection method. When used in the tidal zone, it is necessary to assess the applicability by thoroughly examining the field conditions, because the temporary energizing system can be easily damaged by external forces such as waves. It is common practice to use the surface treatment method together when desalination is applied to concrete structures that are affected by external chloride ions. Even if the desalination treatment is properly performed, experience shows that it is impossible to completely remove chloride ions, and it is common for chloride ions to remain in concrete. The applicability of the desalination method is basically evaluated from the perspective of whether the intended corrosion prevention effect can be maintained over the design corrosion prevention period. When the deterioration of the structure is at or after the propagation stage, it is very important to investigate and evaluate the chloride ion concentration and the state of steel corrosion, which significantly affect the sustainability of the effect. When applying the desalination method to structures where ASR is a concern, consult the Method-Specific Standards part to determine applicability and implementation method.

With its expected effectiveness, the electrodeposition method is applicable to both new and existing structures in the initiation and propagation stages as a measure against chloride attack. As described above, the electrodeposition method can also be used as a surface coating after the desalination method has been used. However, unlike general surface treatment methods, there is not enough quantitative data available on salt shielding effects, making it impossible to quantitatively assess the duration of the effect.

Table 3.2.4 Examples of considerations in the selection of electrochemical corrosion control methods for restoration and improvement of durability (measures against chloride attack)

	Cathodic protection method *	Desalination method*	Other repair methods**
1) State of deterioration	A standard method for all deterioration processes (Table 3.2.2)	Same as on the left	Surface treatment methods are often used before the propagation stage, and the cross section repair method is often used during and after the acceleration stage (Table 3.2.2).
2) Possibility of ASR	Careful consideration is required.	Same as on the left	Careful consideration is required for the surface treatment method and the cross section repair method (see Concrete Library 119 of the Japan Society of Civil Engineers).
3) Structural type	Under general conditions, applicable to both PC members and RC members.	Same as on the left	Careful consideration is required when applying the cross section repair method to PC members.
4) Environmental conditions	It can be used in land and inland areas, atmosphere at sea, and splash zones. Studies required for use in the tidal zone (Table 3.2.3).	It can be used in land and inland areas, atmosphere at sea, and splash zones. Studies required for use in the tidal zoned (Table 3.2.3).	Depends on repair methods and materials used (see Concrete Library 119 of the Japan Society of Civil Engineers)
5) Expected effect	Corrosion reaction rate can be reduced. Mechanical performance cannot be expected to recover.	Chloride ions can be removed. Mechanical performance cannot be expected to recover.	The cross section repair method is also expected to recover mechanical performance.
6) Sustainability of effect	Long-term corrosion prevention effects can be	Long-term corrosion prevention effects can be	The surface treatment method and the cross section repair

	maintained with proper maintenance.	maintained with proper maintenance.	method are expected to be effective in preventing corrosion for the period corresponding to the design conditions.
7) State of service	None	Same as on the left	Because the use of the cross section repair method temporarily reduces the mechanical performance of the structure, prior examination is necessary.
8) Efficiency of implementation	Pretreatment and repair (of cracks and cross section) of members with a lot of delamination and spalling are often time consuming.	Same as on the left	Same as on the left for the cross section repair method (see Concrete Library 119 of the Japan Society of Civil Engineers).
9) Ease of maintenance	The linear/dotted anode method is easy to visually inspect. Corrosion prevention effect can be confirmed quantitatively by monitoring. Inspection by professional engineers on this method is required.	Normal inspection and maintenance are possible. When used with in combination with the surface treatment method, maintenance of surface treatment is necessary.	Surface treatment method and cross section repair method: same as the desalination method.
10) Environmental constraints	Usually, dust, vibration, and noise associated with chipping operations are rarely a problem (unless the chipping area is large).	Same as on the left	Same as on the left for the cross section repair method (see Concrete Library 119 of the Japan Society of Civil Engineers).
11) Cost	Depends on the remaining planned service period. If the area of delamination and spalling is small, the initial repair cost is lower and the LCC is also likely to be lower than that of the cross section repair method.	Same as on the left	Depends on the remaining planned service period. If the area of delamination and spalling is large, the initial cost of the cross section repair method is less than that of the cathodic protection or desalination methods, and the LCC is likely to be lower.

* For further details, refer to the Method-Specific Standards part (cathodic protection method and desalination method) and appendices.

** Other methods here mean the surface treatment method and the cross section repair method. The cross section repair method involves repairing all cross sections (partial cross section repair is not applicable). The table shows only points to be noticed in comparison with the electrochemical corrosion control methods. Note that the electrodeposition method is applicable for the same purpose as the surface treatment method.

(3) As a measure against carbonation, the cathodic protection method, re-alkalization method or electrodeposition method is used based on the result of the durability verification of the structure or the result of the inspection, evaluation and judgment for the structure. When selecting an electrochemical corrosion control method as a measure against carbonation of concrete structures, it is essential to consider various points shown in Table 3.2.1.

Regarding the 1) deterioration state, the applicable method differs depending on the deterioration process and the grade of the appearance. The applicable method also differs for different 5) expected effects, such as restoration and improvement of durability, and restoration of mechanical performance. Therefore, it is necessary to consider these factors when selecting an electrochemical corrosion control method. The table 3.2.5 shows examples of grades of appearance and applicable methods for carbonation prevention. Regarding 4) environmental conditions, the scope of each method differs depending on the environment as shown in Table 3.2.6.

The Table 3.2.7 provides an example of points to consider when selecting a method to restore or improve durability as a measure against carbonation. The table shows the applicability and considerations of the cathodic protection method, re-alkalization method, and other methods with reference to the items listed in Table 3.2.1. The

Guidelines focus on the appropriate selection of an electrochemical corrosion control method, but for reference purposes, the table also provides characteristics of the surface treatment method and cross section repair method in the other methods column, in comparison with the cathodic protection method and the re-alkalization method. A case where a structure has ASR (alkali-silica reaction) concerns is shown as complex deterioration. It should be noted that the considerations described in this table may not always apply to structures in special conditions; the considerations are intended for concrete structures, such as bridges, which have many proven implementations of electrochemical corrosion control methods.

Table 3.2.5 Examples of grades of the appearance and applicable repair methods (measure against carbonation)

Structures	Appearance Grade	Deterioration process	Expected effect	
			Restoration and improvement of durability	Recovery of mechanical performance
Newly constructed structures	—	—	Surface treatment 1) (including anti-spalling 1))	—
Existing structures	Grade I	Initiation stage	Surface treatment 1) (including anti-spalling 1)), Re-alkalization 1)	—
	Grade II	Propagation stage	Surface coating (including anti-spalling), Cross section repair2), re-alkalization, and cathodic protection	—
	Grade III-1	First half of the acceleration stage	Cathodic protection, re-alkalization, and cross section repair	—
	Grade III-2	Second half of acceleration stage	Cross section repair, cathodic protection3), and re-alkalization 3)	Cross section repair (if necessary)
	Grade IV	Deterioration stage	Cathodic protection 4), re-alkalization 4)	Cross section repair

1) Preventive maintenance method.
2) Select this method when the steel corrosion rate is high or the amount of corrosion is large.
3) Consider using it in combination with other methods (such as external cabling) if necessary.
4) Can be used in combination with other methods (such as external cabling).
Note 1: In all deterioration processes, the additional use of water treatment is effective in preventing the progress of steel corrosion.
Note 2: Electrodeposition method is applicable for the same purpose as surface treatment and surface coating shown in the table.

Table 3.2.6 Scope of application for different environments (measure against carbonation)

Method / Environment	Electrochemical corrosion control method		
	Cathodic protection method	Re-alkalization method	Electrodeposition method
Land and inland areas	○	○	△
Marine environment (atmosphere at sea)	○	○	△

○ Applicable △Careful consideration is required

Table 3.2.7 Examples of considerations in the selection of electrochemical corrosion control method for restoration and improvement of durability (measure against carbonation)

	Cathodic protection method*	Re-alkalization method*	Other methods**
1) State of deteriorated state	A standard method used during and after the propagation stage (Table 3.2.5)	A standard for all deterioration processes (Table 3.2.5)	Surface treatment is often used before the propagation stage, and cross section repair is often used during and after the propagation stage (Table 3.2.5).
2) Possibility of ASR	Careful consideration is	Same as on the left	Careful consideration is

	required.		required for the surface treatment method and cross section repair method (see Concrete Library 119 of the Japan Society of Civil Engineers).
3) Structural type	Under general conditions, applicable to both PC members and RC members.	Same as on the left	Careful consideration is required when applying the cross section repair method PC members.
4) Environmental conditions	Applicable to land, inland areas and atmosphere at sea (Table 3.2.5)	Same as on the left	Depends on repair methods and materials used (see Concrete Library 119, Japan Society of Civil Engineers)
5) Expected effect	Corrosion reaction rate can be reduced. Mechanical performance cannot be expected to recover.	Carbonation depth is set to 0 or progress of steel corrosion is reduced. Mechanical performance cannot be expected to recover.	The cross section repair method is expected to recover mechanical performance.
6) Sustainability of effect	Long-term corrosion prevention effects can be maintained with proper maintenance.	The corrosion prevention effect can be maintained for a long term. However, when the surface treatment method is used together in environmental conditions where re-carbonation is a concern, the effect depends on the sustainability of the corrosion prevention effect of the surface treatment method.	The surface treatment method and cross section repair method are expected to be effective in preventing corrosion for the period corresponding to the design conditions.
7) State of service	None	Same as on the left	Because the use of the cross section repair method temporarily reduces the mechanical performance of the structure, prior examination is necessary.
8) Efficiency of implementation	Pretreatment and repair (of cracks and cross section) of members with a lot of delamination and spalling are often time-consuming.	Same as on the left	Same as on the left for cross section repair method (see Concrete Library 119 of the Japan Society of Civil Engineers).
9) Ease of maintenance	The linear/dotted anode method is easy to visually inspect. Corrosion prevention effect can be confirmed quantitatively by monitoring. Inspection by professional engineers on this method is required.	Normal inspection and maintenance are possible. When used with the surface treatment method, maintenance of surface treatment method is necessary.	Surface treatment method and cross section repair method: same as re-alkalization method.
10) Environmental constraints	Usually, dust, vibration, and noise associated with chipping operations are rarely a problem (unless the chipping area is large)	Same as on the left	Same as shown on the left for the cross section repair method (see Concrete Library 119 of the Japan Society of Civil Engineers).
11) Cost	Depends on the remaining planned service period. If the area of delamination and spalling is small, the initial repair cost is lower and the LCC is also likely to be lower than that of the cross section repair method	Same as on the left	Depends on the remaining planned service period. If the area of delamination and spalling is large, the initial cost of the cross section repair method is less than that of the cathodic protection method or the re-alkalization method, and the LCC is likely to be lower.

* For further details, refer to the Method-Specific Standards part (Cathodic protection method and Re-alkalization method) and appendices.

** Other methods here mean the surface treatment method and the cross section repair method. The cross section repair method involves repairing all cross sections (partial cross section repair is not applicable). The table shows only points to be noticed in comparison with the electrochemical corrosion control methods. Note that the electrodeposition method is applicable for the same purpose as the surface treatment method.

The cathodic protection method can be applied to both new and existing concrete structures located in the land and inland areas and in the atmosphere at sea, which are susceptible to carbonation. However, when it is used for existing structures during and after the acceleration stage, it is necessary to consider using it in combination with other methods such as the cross section repair method and the external cabling method, according to the degree of deterioration of mechanical performance based on cracks and cross-sectional defects of steel, and so on. Application to the structure that may be affected by ASR requires considerations similar to those for chloride attack. In terms of maintainability, the cathodic protection method has the advantage that the corrosion prevention effect can be quantitatively assessed by appropriate inspections. In addition, when used in conjunction with a remote monitoring system, it can provide continuous monitoring and data collection from remote locations, allowing for more sophisticated, simplified, and streamlined maintenance.

The re-alkalization method can be applied to existing concrete structures, but when it is applied to existing structures during and after the acceleration stage, it is necessary to consider using it in combination with other methods such as the cross section repair method and the external cabling method, just as with the cathodic protection method. The applicable environmental conditions are the same as for the cathodic protection method. The re-alkalization method generally does not require any surface treatment after application, but it is recommended to perform surface treatment in environments where constant exposure to water may cause the electrolyte solution to leak. The applicability of the re-alkalization method is basically evaluated from the perspective of whether the intended corrosion prevention effect can be maintained over the design corrosion prevention period. The evaluation is made by investigating and checking the carbonation depth of the concrete structure. If the deterioration of the structure is at or after the propagation stage, special attention should be paid to the degree of carbonation depth and steel corrosion, which significantly affect the sustainability of the effect. When applying the re-alkalization method to structures where ASR is a concern, consult the Method-Specific Standards part and determine if the method is applicable.

With its expected effectiveness, the electrodeposition method is applicable to both new and existing structures in the initiation and propagation stages as a measure against carbonation. However, unlike general surface treatment methods, there is not enough quantitative data available on the effectiveness of the method in controlling carbon dioxide and carbonation, making it practically difficult to quantitatively assess the duration of the effect, and thus prior research and investigation is essential.

(4) The electrodeposition method is applicable to non-progressive cracks, for the purpose of improving the migration resistance of corrosion factors, based on the results of inspection, evaluation, and judgment for the structures. Electrodeposition is expected to fill cracks and densify the concrete surface, and produce the side benefit of providing better surface quality and surface coating effect. It can also be used to repair cracks generated during the construction of concrete structures. It is possible to use the method to repair cracks or perform surface treatment on structures located in special environments with many work constraints, such as structures located underwater or underground, and structures located in hot spring environments or radiation controlled areas. However, it is difficult to quantitatively evaluate the duration of the effect of the method, because there is not enough quantitative data available on its effectiveness in improving the resistance to the permeation of materials in cracked closures and surface layers, and thus prior research and investigation is essential.

3.3 Implementation Plan in Design

The designer shall prepare an implementation plan based on the results of the Investigation for design and implementation. The plan should consist of an outline of the implementation method and procedure, taking into account the characteristics of the materials and equipment to be used.

[Commentary]

The implementation plan prepared by the designer is intended to present the implementation method and procedures that will be the basis for Section 3.8 (verification of steel corrosion) of this document. The plan will be the basis for the execution plan prepared by the executing party, but should not prevent the executing party from proposing safe, rational, and efficient execution methods and procedures. When preparing an implementation plan, the designer should consider issues such as the overall process and the implementation method based on the results of the Investigation for design and implementation, taking into consideration the characteristics of the materials and equipment to be used.

3.4 Maintenance Plan

3.4.1 General

In order to maintain the effectiveness of corrosion control for an intended period of time, a maintenance plan shall be formulated. The plan should include information such as appropriate inspection items and methods, timing and frequency of inspections, the evaluation method, and actions to be taken if deterioration is observed.

[Commentary]

This section describes the method-specific maintenance plan to be formulated and incorporated into the maintenance plan for the structure, and Section 3.8 (Verification of steel corrosion) assumes that maintenance is conducted according to the method-specific maintenance plan.

Even in structures to which the electrochemical corrosion control method is applied, steel corrosion may progress due to the penetration of chloride ions from the outside, diffusion of endogenous chloride ions, lowered pH of the steel surface caused by carbonation, or other reasons. Therefore, it is necessary to pay special attention to the penetration of chloride ions, movement of residual chloride ions, and changes in the alkaline atmosphere around the steel when preparing a maintenance plan specific to the electrochemical corrosion control method. Attention should also be paid to indices and their levels that are used as criteria for maintaining structures against corrosion or checking the effectiveness of corrosion control. These indices are sometimes not monitored in the maintenance of ordinary structures, but it is important to focus on them when preparing a method-specific maintenance plan.

In the structure to which the cathodic protection method is applied, it is necessary to ensure that the cathodic protection system is maintained in good condition throughout the design corrosion protection period and that the intended corrosion prevention effect can be achieved. Polarization quantity and depolarization quantity are indices used as criteria for corrosion control according to Section 3.5 (Design and Control Standard for Corrosion Prevention) , but if it is assumed that the corrosion prevention effect cannot be properly evaluated with these indices, other corrosion control indices may be used instead. In such cases, it is necessary to adjust the maintenance plan accordingly (e.g., more frequent inspections).

For structures using desalination, re-alkalization, or electrodeposition methods, it is sufficient to ensure that the intended corrosion prevention effect can be achieved over the design corrosion prevention period.

3.4.2 Inspection

(1) Inspection of structures to which the cathodic protection method is applied shall ensure that the cathodic protection system is in good condition and the intended corrosion prevention effect is maintained.

(2) Inspection of structures to which the desalination, re-alkalization, and electrodeposition methods are applied shall ensure that the intended corrosion prevention effect is maintained.

[Commentary]

(1) When inspecting structures to which the cathodic protection method has been applied, it is necessary to confirm that the cathodic protection system is in good condition and that the intended corrosion prevention effect is maintained. Inspections are performed to determine the soundness of the cathodic protection system and remote monitoring system, as well as the corrosion prevention effect. The cathodic protection system should be visually inspected and measured to determine the operating condition of the DC power supply equipment, the condition of the storage box such as energization and monitoring terminals, the anode system, the reference electrode, and the condition of the piping. The integrity of the remote monitoring system is verified by its operating condition. Standard methods for confirming the corrosion prevention effect include measuring the polarization or depolarization of the steel potential and visually inspecting for deformation such as cracking of the concrete surface. If the remote monitoring system is integrated with the cathodic protection system, the operating status of the DC power supply and the corrosion prevention effects can be checked on a daily basis using the readings from the remote monitoring system.

(2) For the desalination, re-alkalization, and electrodeposition methods, inspections are performed to determine whether the intended corrosion prevention effect is achieved. As part of the design, implementation, and maintenance specified in the Method-Specific Standards, items related to the corrosion control indices may also be investigated. In particular, it is important to obtain the initial values of the indices during the initial inspection, since the indices are required in Section 3.4.3 (Evaluation) to verify the corrosion prevention effect.

For structures where the surface treatment method is used in addition or where the electrodeposition method is used, also refer to the section describing the inspection of the surface treatment method in the "Recommendation for Concrete Repair and Surface Protection of Concrete Structures (Concrete Library 119)" published by JSCE.

3.4.3 Evaluation

The structures to which the electrochemical corrosion control method has been applied shall be evaluated to determine whether the intended corrosion prevention effect can be maintained over the design corrosion prevention period. The evaluation shall be based on the information obtained from the inspections.

[Commentary]

The structures or their members shall be evaluated after the application of the electrochemical corrosion control method to confirm that the corrosion prevention effect is maintained. If the effect decreases over time, due consideration shall be given to ensure that the intended corrosion prevention effect is maintained over the design corrosion prevention period. The structures to which the cathodic protection method is applied shall be comprehensively evaluated based on the results of the inspections to confirm that the operating condition of the cathodic protection system satisfies the requirements to achieve the intended corrosion prevention effect and that the materials and equipment constituting the system are in a sound condition to satisfy the predetermined criteria.

The evaluation of structures to which the desalination, re-alkalization, or electrodeposition methods have been applied shall confirm that the intended corrosion prevention effect is maintained over the design corrosion prevention period. The evaluation shall be performed using items related to the indices defined as the maintenance criteria for corrosion prevention in the design, implementation, and maintenance of the Method-Specific Standards.

3.4.4 Remedial measures

(1) If periodic remedial actions are anticipated for the structure after the electrochemical corrosion control method is applied, the plan for such actions shall be reflected in the maintenance plan.

(2) If the evaluation indicates that the desired corrosion prevention effect has not been achieved, the maintenance plan for the structure shall be reviewed.

[Commentary]

(1) The externally powered cathodic protection system requires periodic maintenance, including replacement of the DC power supply and its components, replacement of anode materials and sacrificial anode materials (in the case of the galvanic anode method), and surface treatment method used in conjunction. These activities should be included in the method-specific maintenance plan as well as the maintenance plan for the structure.

(2) If the desired effect has not been achieved on the structure or its members after the application of the electrochemical corrosion control method, the maintenance plan for the structure should be reviewed. In some cases, repeated remedial actions only on the parts and members to which electrochemical corrosion control has been applied may be sufficient for the performance of the structure at the end of its planned service life to exceed the maintenance control limit or the required performance; while in other cases, some other actions on other parts or members may be necessary. Therefore,

it is necessary to select appropriate remedial measures according to the "Standard Specifications for Concrete Structures [Maintenance]" by referring to the inspection and evaluation results.

If the required performance of the structure can be satisfied by the implementation of remedial measures, the following should be considered: repair and renewal of the cathodic protection system, review and adjustment of the energization quantity, improvement of the energization system, and review of the corrosion prevention management, etc.

3.5 Design and Maintenance criteria for corrosion prevention

(1) Each method shall be designed appropriately to achieve the intended corrosion prevention effect throughout the design corrosion prevention period.

(2) In a design process, the maintenance criteria for corrosion prevention shall be determined as needed based on the design corrosion prevention period and the intended effects.

[Commentary]

(1) Based on the results of various surveys described in Chapter 2 (Investigation), the design of the electrochemical corrosion control method shall basically take into consideration such issues as the deterioration state and structural condition of the concrete structure, the expected effects, the methods of implementation, effect verification, and maintenance methods. For the design details given in the Common Part of this document should be followed. The structure or its member to which the electrochemical corrosion control method is applied shall be designed to achieve the intended corrosion prevention effect during the design corrosion prevention period.

A cathodic protection system must be designed based on the condition of the structure as determined by the investigation. Issues that should be considered include: the characteristics and scope of a cathodic protection method (constant voltage, constant potential, or constant current method) and post-implementation activities such as maintenance inspection and equipment replacement. Based on these considerations, the appropriate method, and anode and other required materials should be selected and the energization system and monitoring system should be designed.

A desalination, re-alkalization, or electrodeposition process should be designed based on the condition of the structure as determined by the investigation. The design process includes determining the energization conditions, selecting the materials and equipment to be used (e.g., anode materials and electrolyte solutions), and arranging the layout of the temporary anode system. The temporary anode system should be designed considering the characteristics and scope of each system.

(2) The following indicators can be used alone or in combination to determine the maintenance criteria for corrosion prevention: numerical values such as the chloride ion concentration of the steel surface, the carbonation depth and the polarization quantity of the steel, any deformation due to corrosion on the surface of the structure, and the grade of appearance of the cathodic protection system. Depending on the indicators to be used, the inspection items and frequency of maintenance inspections will differ. Therefore, it is essential to define the maintenance criteria for corrosion prevention and maintenance plans that can be used to evaluate whether the intended corrosion prevention effect can be maintained over the design corrosion prevention period. The maintenance criteria for corrosion prevention is an index used to confirm

that the formula (3.8.1) used in verification of steel corrosion is satisfied. For example, in the cathodic protection method, the design limit value is set for the corrosion rate of steel (protective current density) and checked by obtaining the design response value. It is an index used to confirm that the value attains 100 mV or higher using the polarization quantity or the depolarization quantity as the prescription. Therefore, for different stages of verification for steel corrosion at the time of design assuming the state immediately after the application of electrochemical corrosion control method, quality control during construction, confirmation of effect immediately after construction (inspection), confirmation of corrosion prevention effect in maintenance (evaluation), maintenance criteria for the same corrosion prevention may be used, or different indices and levels may be used. In any case, when establishing maintenance criteria for corrosion prevention, it is necessary to set appropriate indicators and levels that can confirm that the intended corrosion prevention effect can be achieved over the design corrosion prevention period.

The maintenance criteria for corrosion prevention in the cathodic protection method corresponds to the corrosion control index defined in Section 3.5 Maintenance criteria for corrosion prevention of the Guidelines for the Cathodic Protection Method. An appropriate maintenance plan should be developed according to the corrosion control index to be used, and steel corrosion will be verified on the assumption that maintenance will be performed according to the plan.

As for the desalination, re-alkalization, and electrodeposition methods, it is common practice to remove the temporary energization system after implementation, and the conditions of chloride ion concentration, pH, oxygen, water, and other factors that cause steel corrosion in concrete may change over time. Therefore, when designing a temporary energization system for these methods, it is necessary to set the target to be achieved immediately after implementation, assuming that the intended corrosion prevention effect will be achieved at the end of the design corrosion prevention period. The maintenance criteria for corrosion prevention in the desalination, re-alkalization, and electrodeposition methods are defined in Section 3.5 of the corresponding guidelines for each method. An appropriate maintenance plan should be developed according to the target set for each method and steel corrosion verification will be performed accordingly. From the above, it is essential to develop a maintenance plan to confirm that the intended corrosion prevention effects are achieved during the design corrosion prevention period, because in the maintenance of the structure to which these methods are applied, there are cases where the target set immediately after the construction of the temporary energization system (maintenance criteria for corrosion prevention used in the design assuming conditions immediately after application) is no longer satisfied but the intended corrosion prevention effects are still maintained.

3.6 Materials and Equipment

3.6.1 General

In the application of the electrochemical corrosion control method, materials and equipment of the required quality and performance shall be selected and used to satisfy the intended corrosion prevention effect for the design corrosion prevention period with the required energization.

[Commentary]

It is important that the materials and equipment used have the required quality and performance to achieve the intended corrosion prevention effect on the structure or its members to which the electrochemical corrosion control method is applied, over the design corrosion prevention period. Such materials and equipment include: for new concrete structures, those used for the members to which the corrosion control will be applied; for existing concrete structures, those used for the target members and those used for pretreatment; and for both new and existing concrete structures, those used for new cathodic protection systems and temporary energizing systems. Some members of existing concrete structures may have a history of repairs, and the materials used for such members must also be examined. It is necessary to ensure that the materials and equipment used in each case retain the required performance to deliver the required direct current to the steel in concrete.

Materials and equipment specific to the electrochemical corrosion control method include anodes, wiring, and DC power supply equipment, and should be selected based on their characteristics, design values, and environmental impact. In particular, it is necessary to ensure that the DC power supply equipment is safe for humans and ecosystems, that it does not cause noise or radio wave interference to the surrounding environment, and that its structure is explosion-proof where required.

3.6.2 Materials Composing Members Subject to Corrosion Control

The materials constituting the members subject to corrosion control shall be of a quality that does not significantly inhibit energization.

[Commentary]

In the electrochemical corrosion control method, the steel in concrete is used as the cathode, and direct current is supplied from the anode installed on or near the concrete surface. Therefore, it is necessary to ensure that the materials used for the members do not inhibit energization.

For newly constructed concrete structures, the concrete used for the members should be of quality that does not significantly inhibit energization.

For existing concrete structures, it is necessary to check the quality of the concrete used for the members and the materials used in previous repairs, and if the materials are found to interfere with the expected effects of each method, they should be replaced with appropriate materials. Factors that may inhibit energization include steel on the surface (including exposed reinforcing bars), corrosion-resistant steel (e.g., epoxy-coated reinforcing bars), cross section repair materials and crack injection materials whose electrical resistivity is significantly different from that of the concrete in the area to be protected from corrosion, covering materials and hydrophobic impregnating materials of the concrete surface layer. In addition, for existing concrete structures, it is necessary to pretreat deteriorated areas such as cracks, delamination, spalling of the member. The pretreatment materials shall be of a quality that does not significantly inhibit energization.

3.6.3 Materials and Equipment used in Electrochemical Corrosion Control Methods

Materials and equipment used for the electrochemical corrosion control method shall have sufficient durability according to the energizing conditions of each method such as the energizing period and the energizing current amount, and shall satisfy the intended corrosion prevention effect by the application of each method.

[Commentary]

In the electrochemical corrosion control method, there are specific materials and equipment used for a cathodic protection system and a temporary energization system. These materials and equipment must not inhibit energization for the design corrosion prevention period and must satisfy the designed energization conditions.

In the cathodic protection method, continuous protective current supply is required for the design corrosion prevention period in principle, so the materials and equipment should be selected in consideration of the environment of the structure and the design corrosion prevention period. The materials and equipment include anode materials, distributors, anode covering materials, and the DC power supply equipment. Note that the performance of the anode material can be verified using the accelerated test described in NACE Standard TM0294-2016, Item No. 21225: Testing of Embeddable Anodes for Use in Cathodic Protection of Atmospherically Exposed Steel-Reinforced Concrete; and that the electrical resistivity rate of the repair material used for the anode covering material and pretreatment can be verified using the test described in the Japan Society of Civil Engineers Standard "Test method of measuring resistivity for patching repair materials with four electrodes" (JSCE-K 562). For the materials and equipment whose parts can be easily renewed or replaced, it is effective to perform the renewal or replacement during a periodic inspection based on the maintenance plan for cathodic protection.

In principle, the energization period is limited for the desalination, re-alkalization, and electrodeposition methods. Therefore, the materials and equipment used for these methods should be selected in consideration of the environment of the structure, and the energizing conditions such as the energizing period and the energizing current amount. The materials and equipment used in these methods include anode materials, anode holding materials, electrolyte solution, and a temporary DC power supply. For example, alkaline electrolyte solution containing substances such as H_3BO_3 and K_2CO_3 is used in the desalination method, while alkaline electrolyte solution containing Na_2CO_3, K_2CO_3, or Li_2CO_3 is used in the re-alkalization method. In the electrodeposition method, when the natural water is used as electrolyte solution, it should contain substances capable of precipitating poorly soluble salts, and when the artificial aqueous solution is used, it should contain substances such as magnesium acetate.

Repair materials for pretreatment of existing concrete structures and anode covering materials for cathodic protection should be used with consideration of the aforementioned characteristics and other factors such as usable time and curing time. These characteristics can be evaluated using the methods specified in the relevant Japanese Industrial Standards (JIS) and the Japan Society of Civil Engineers standards.

3.6.4 Material Characteristics

For the materials used in the electrochemical corrosion control method and for the constituent materials of the members to be protected, the characteristic values required for the verification of steel corrosion in each method shall be determined by an appropriate method.

[Commentary]

The characteristic values required for the verification of steel corrosion in structures to which the electrochemical corrosion control method is applied shall be determined appropriately for the materials used for each method and the constituent materials of the members protected from corrosion, based on the environmental and other conditions. Verification for steel corrosion of the structure to which the cathodic protection method is applied, the corrosion rate of the steel in the object member to which the direct current is supplied as an index, for using the protective current density as an equivalent physical quantity as an index, electrical resistivity such as concrete or repair material used to predict the protective current density is a characteristic value. In the desalination method, the chloride ion concentration in the vicinity of the steel is used as an index for verification, so the diffusion coefficient of chloride ion after the application of the method, which is used to predict the penetration of chloride ion, is used as a characteristic value. In the re-alkalization method, the carbonation depth is used as an index for verification, so the rate coefficient of carbonation after the application of the method, which is used to predict the progress of carbonation, is used as a characteristic value. In the electrodeposition method, the hydraulic conductivity of concrete and the diffusion coefficient of chloride ions after the application of the method are used as characteristic values. These characteristic values may be appropriately determined by thoroughly examining the past test results related to each method. For the characteristic values of ordinary materials used in each method and their handling, it is recommended to refer to the Method-Specific Standards part.

3.7 Load

3.7.1 General

(1) For the verification of steel corrosion, appropriate combinations of loads assumed to occur during the implementation stage and the design corrosion prevention period shall be taken into account.

(2) The design load shall be obtained by multiplying the characteristic value of the load by the load factor.

[Commentary]

Since the electrochemical corrosion control is intended to prevent steel corrosion, the Guidelines focus on the prevention of steel corrosion, an indicator used to evaluate the durability of structures. Therefore, the verification focuses mainly on steel corrosion. In the verification for steel corrosion, it is necessary to consider appropriate combinations of all loads that are assumed to affect the development of rust and corrosion reactions in steel during the construction and design corrosion prevention period. When designing using maintenance criteria for corrosion prevention, appropriate combinations of all assumed loads shall be considered according to the maintenance criteria. In principle, the design loads shall be in accordance with "Standard Specifications for Concrete Structures [Design]" when electrochemical control is used together with other methods to maintain, recover, or improve mechanical or other performance and the load factor used in a multiplication formula to obtain a characteristic value of the load shall be in accordance with Chapter 6 Load of the "Standard Specifications for Concrete Structures [Design: General Requirements]". The load factor for environmental actions can generally be assumed to be 1.0.

3.7.2 Loads to be considered in the Design

(1) Appropriate consideration shall be given to the loads occurring on the structure to be treated and on the part to which the electrochemical corrosion control method is applied.

(2) If the actual measured value of the load is known, the characteristic value obtained from the measured value may be used.

[Commentary]

(1) and (2) The loads to be considered in the design of electrochemical corrosion control methods include those that remain unchanged from before application and those that are changed or added after application. These loads must be appropriately considered based on the structure to be protected, and they differ depending on its member, purpose and the methods of application and implementation. Therefore, it is important that each of the loads on the structure is examined separately in each state and that their responses are reasonably combined where necessary. In particular, it is necessary to sufficiently consider the environmental actions likely to occur on the structure and the new actions that may occur due to the application of the corrosion control method. The former include temperature, solar radiation, humidity, supply of moisture, supply of various substances and their concentration, and the latter include re-diffusion of chloride ions and macrocell corrosion, and changes in chemical composition due to energization.

If a more reliable verification or a more rational design is possible by actually measuring the characteristics acting on the structure, the measured values obtained from statistical processing of multiple measurement results can be used as characteristic values. In such cases, the load factors used in the design load should be defined accordingly. For the characteristic values of the standard loads used in each method and their handling, it is recommended to refer to the Method-Specific Standards part.

3.8 Verification of Steel Corrosion

(1) Steel corrosion shall be verified by confirming that the desired corrosion prevention effect can be achieved over the design corrosion prevention period, provided that the established implementation plan and maintenance plans are implemented.

(2) In general, steel corrosion of structures to which the electrochemical corrosion control method is applied shall be verified using the following equation (3.8.1):

$$\gamma i \, Sd \, / \, Rd \leqq 1.0 \qquad (3.8.1)$$

where *Sd*: Design response value

Rd : Design limit value

γi : Structural factor , generally 1.0 to 1.2 may be used.

(3) The established maintenance criteria for corrosion prevention can be used to confirm that the equation (3.8.1) is satisfied for corrosion prevention for each of the following stages: verification at the time of design (verification assuming conditions immediately after the application of the method), post-implementation inspections, and maintenance inspections (confirmation of the corrosion prevention effect).

[Commentary]

(1) and (2) Electrochemical corrosion control is a method designed to prevent deterioration in the performance of structures by preventing steel from corroding. Therefore, the verification focuses on steel corrosion. Steel corrosion is verified by confirming that the intended corrosion prevention effect can be achieved throughout the design corrosion prevention period, provided that the previously formulated implementation plan and the maintenance plan are followed. However, since the characteristics of materials and actions required for verification change with the environment and time, the method or combination of methods and indices used to confirm the intended corrosion prevention effects may differ depending on when the verification is performed.

In principle, response values are calculated using the established maintenance criteria for corrosion prevention, based on analytical results using an appropriate analytical model, or empirical rules based on extensive past experience and results, or experimental evidence, according to the applicable corrosion control method, the condition of structures or members, and the assumed deterioration mechanism.

Direct indices of these design values are: characteristic values such as the corrosion rate in the cathodic protection method, the chloride ion concentration around the steel in the desalination method, the pH around the steel in the re-alkalization method, and the resistance to the permeation of the material of the member after the application of the electrodeposition method. In the durability verification, these characteristic values will be determined based on the materials, equipment, and system components to be used in the corresponding corrosion control method, and on the characteristics of the materials and members. However, if it is difficult to make future predictions with the required accuracy, indicators can be adequately determined based on information accumulated from similar environments or structures, previous research and test results, and then the characteristic values obtained from the indicators can be used. Note that when it is necessary to ensure the continuity of the corrosion prevention effect on an entire system, as in a cathodic protection system, it may be effective to set an indirect index using the potential of the steel. For more details, refer to the relevant sections of the Method-Specific Standards part. When electrochemical corrosion control is used in combination with other measures to restore, maintain or improve mechanical or other performance, refer to the "Standard Specifications for Concrete Structures [Design] and [Maintenance]" and related guidelines.

(3) When maintenance criteria for corrosion prevention are used to confirm that the equation (3.8.1) is satisfied, in some cases the same maintenance criteria for corrosion prevention are used, while in other cases different values and levels are used for different stages such as steel corrosion verification at the time of design (verification assuming the conditions immediately after the application of electrochemical corrosion control method), quality control during implementation, confirmation of effect immediately after implementation (inspection), confirmation of corrosion prevention effect during maintenance inspections (evaluation). In both cases, it is necessary to establish appropriate maintenance criteria for corrosion prevention that can ensure that the intended corrosion prevention effect can be achieved over the design corrosion prevention period.

Chapter 4 Implementation

4.1 General

Implementation plans shall be adequately prepared, taking into account such factors as the characteristics of the materials and equipment to be used and the implementation conditions and constraints. Implementation shall be carried out in such a way as to ensure the quality assumed in the design.

[Commentary]

Electrochemical corrosion control may not be sufficiently effective as designed if it is not implemented under management and quality control appropriate to the characteristics of the materials and equipment to be used. Prior to implementation, it is necessary to prepare appropriate implementation plans in accordance with the standards and guidelines related to the materials and equipment. It is also very important to ensure the quality assumed in the design by assigning professional electrochemical corrosion control engineers on site to properly manage the implementation.

When electrochemical corrosion control is used to repair structures, time and space for implementation are often very limited, requiring detailed implementation plans. When electrochemical corrosion control is used to protect against chloride attack, it is not necessary to remove the sections of concrete where the chloride ion concentration exceeds the steel corrosion generation limit (in the cross section repair process, such sections must be removed); however, it is conceivable that if the degradation in the remaining sections is not properly treated, the intended corrosion prevention effect may not be achieved or deterioration may occur relatively early after the corrosion control is applied. Therefore, it is important to properly pretreat the damaged sections and repair the concrete as described in the Method-Specific Standards, and to record details such as the process and areas of pretreatment and repair.

4.2 Implementation Plan

(1) The implementation contractor shall draw up an implementation plan for the electrochemical corrosion control method specified in the design documents, taking into account the structural and environmental conditions and implementation requirements.

(2) The implementation plan shall specify the implementation method and procedures appropriate to the characteristics of the materials and equipment to be used, and the quality control items and procedures.

[Commentary]

(1) and (2) In formulating an implementation plan, the entire process, implementation method, materials and equipment used, quality control plan, safety and health management, environmental protection measures should be examined. The implementation plan should be consistent with the designer’s plan, as well as with requirements and constraints such as work period, environmental conditions, safety of work, and economical efficiency. Inspection plans agreed with the

contractee must be reflected in the implementation plan. The implementation contractor must fully understand the current condition of the structure and the implementation constraints, and should conduct additional investigations of the structure beforehand if the results of the Investigation for design and implementation are not sufficient. Work on structures in service often presents a different working environment from that of new construction, such as limited time and space, requiring careful consideration to ensure quality and safety.

The implementation plan covers all aspects from the actual work to quality control and implementation management. Since the characteristics of the materials used and the effects of the equipment used may be affected by environmental conditions such as temperature and humidity during implementation, it is necessary to examine appropriate implementation methods and procedures so that the corrosion prevention effects assumed in the design can be achieved. Quality control and implementation management procedures should also be prepared for each stage of implementation. The engineer in charge of each work should have access to the implementation plan.

4.3 Implementation

(1) Implementation shall be carried out according to the implementation plan.

(2) Implementation shall be carried out under the supervision of professional engineers specializing in the electrochemical corrosion control method to be used.

(3) Materials and equipment to be used shall be manufactured, processed, transported, and stored in accordance with their characteristics.

(4) The contractor shall perform quality control at each stage of the implementation according to the quality control plan.

[Commentary]

(1) and (2) Implementation should be executed efficiently and safely according to the implementation plan. In general, the quality of the work depends greatly on the ability of the engineers performing the work, so it is important to appoint professional engineers specializing in the electrochemical corrosion control method to be applied and have them supervise the work. It is also necessary to clarify the scope of responsibility and authority of each engineer during the implementation.

(3) Materials and equipment to be used shall be handled as specified. For example, in the cathodic protection method, all anode materials installed in a corrosion prevention circuit must be electrically conductive, so the anode materials and the distributor should be properly connected by spot welding or other method. The anode covering materials, which are generally made of cement mortar, should be protected from weathering by avoiding storage in rain or high humidity environments. The DC power supply equipment using an external power supply system, must be installed and grounded (Class D grounding) in accordance with the "Technical Standards for Electrical Facilities".

In the desalination method and the re-alkalization method, careful consideration must be given to worker safety and leakage prevention in the supply and storage of high pH electrolyte solution. Temporary DC power supplies should be grounded and preferably energized at 40 V or less.

When the electrodeposition method is used and anode materials are installed in the sea, they must be anchored to prevent damage from external forces such as waves and tidal currents. Electrolyte holding materials, if used, should be installed in such a way that the electrolyte solution does not leak.

(4) The contractor implements quality control based on the quality control plan to ensure the quality assumed in the design. In general, it is important for reasonable quality control to conduct frequent quality control at the beginning of implementation and to flexibly reviewing the quality control plan as the quality stabilizes. If quality control indicates that planned control limits are being exceeded, it is necessary to investigate the cause, take action, and review the quality control plan. If an abnormality occurs, the operator shall immediately report it to the contractor's supervising engineer. The supervising engineer shall stop work, identify out-of-specification areas, and immediately report to the supervising engineer for appropriate action.

4.4 Inspection

(1) The contractee shall provide the contractor with an inspection plan at the time of order placement and shall be responsible for conducting the inspections.

(2) If the inspection result is deemed unacceptable, corrective action shall be taken.

[Commentary]

(1) Corrosion prevention can be considered effective as intended if properly conducted inspections at each implementation phase confirm that electrochemical corrosion control has been implemented as specified in the design documents. The contractee shall make an appropriate inspection plan after having sufficiently examined the materials proposed by the contractor and the aspects such as reliability of the implementation process to be used. The inspection plan should include specific descriptions of inspection items, procedures, frequency, and pass/fail criteria. The contractor shall receive the inspection plan prior to implementation and confirm its contents. The contents must be agreed upon by the contractee and the contractor. The contractee shall be responsible for performing the inspections in accordance with the inspection plan.

Inspection items for the construction of the cathodic protection method include the following: continuity check between steels, reference electrode operation check, continuity check between anodes, insulation check between anode and steel, circuit operation check, and initial energization amount adjustment (polarization quantity test, depolarization quantity test). In the desalination method, there are inspections such as continuity check between steels, and desalination quantity check after completion of energization. In the re-alkalization method, there are inspections such as continuity check between steels and carbonation depth check after completion of energization. In the electrodeposition method, there are inspections such as continuity check between steels, confirmation of crack closure and coating condition after the completion of energization.

The inspection procedures and criteria differ depending on the type of structure, the materials used, and the electrochemical corrosion control method to be applied, and must be determined to enable efficient, reliable, and objective inspections. It is common practice in Japan to use the procedures and evaluation criteria specified in the Japanese Industrial Standards (JIS), the Japan Society of Civil Engineers standards, and the standards specified by the contractee.

(2) If an inspection reveals unacceptable workmanship or quality, corrective action such as rework or material change shall be taken. After taking corrective action, verify quality by re-inspection. The maintenance plan formulated in the design phase may need to be reviewed.

The purpose of inspections is to ensure the quality assumed in the design. The Implementation section of the Method-Specific Standards describes ways to confirm the corrosion prevention effect (cathodic protection method) and evaluate the achievement of the objective, but it should be noted that inadequate design may have been the cause of the failure to achieve the objective assumed in the design.

Chapter 5 Maintenance

5.1 General

(1) The method-specific maintenance plan shall be reviewed as necessary based on the inspection results, and changes to the plan shall be reflected in the maintenance plan of the structure.

(2) Based on the maintenance plan of the structure, the structure to which the electrochemical corrosion control method is applied shall be appropriately maintained.

[Commentary]

(1) and (2) The principle of maintenance is to formulate and implement a management plan to maintain the performance of a new or existing structure at or above the required level throughout the design service life of the structure. On the other hand, the electrochemical corrosion control is only one of many methods to prevent steel corrosion in concrete structures, and simply achieving the desired effect during the design corrosion prevention period does not necessarily guarantee the performance of the structure for the remainder of its service life. Therefore, after applying an electrochemical corrosion control method, it is necessary to review the maintenance plan for the method based on the results of method-specific inspections and update the maintenance plan of the structure accordingly.

For the cathodic protection method, the maintenance of the cathodic protection system shall be appropriately carried out together with the maintenance of the structure based on the updated maintenance plan of the structure.

For the desalination, re-alkalization, and electrodeposition methods, the maintenance of the structure shall be appropriately carried out based on the updated maintenance plan of the structure.

Chapter 6 Records

6.1 General

(1) The contractor shall record the details of the work performed.

(2) For maintenance purposes, the contractee shall maintain and retain records related to the design, maintenance plan, implementation, quality control, and inspection of the structure during its service period.

[Commentary]

(1) The records shall contain the implementation plan and the results of the work conducted in accordance with the plan, and should be retained to contribute to the quality assurance of the structure or its members to which the electrochemical corrosion control method is applied and to improve the quality and workability of structures in future projects.

(2) These records contain the information necessary to maintain the structure and can be used as a baseline for maintenance after the electrochemical corrosion control method has been applied. It is important that the records contain all the work information necessary for maintenance. In order to clarify the role and position of the engineers involved in the work, it is desirable that the documentation include the company, name, and other necessary information of the persons who performed each work. The records should be retained during the service life of the structure.