

LONG-TERM PLAN FOR STRUCTURAL REPLACEMENT AND REHABILITATION OF EXPRESSWAY BRIDGES IN JAPAN

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Expressways are important social infrastructures supporting the society and economic activities in Japan. More than 50 years have passed since the first expressway in Japan, the Meishin Expressway, connecting the cities of Kobe and Nagoya, opened to traffic. Since then, Japan's expressway network has expanded. So, as long as 50 years have passed for many other subsequent expressways in Japan. It is expected to remain serviceable for another 50 years. However, to ensure long-term serviceability, it is essential to continue with appropriate maintenance work, while rehabilitating or replacing structures when needed. In this paper, the major factors causing damage to expressway bridges are systematically investigated based on the results of structural soundness predictions and comprehensive inspections carried out by the managing companies in the east, central and west regions as of the end of 2011. At the same time, the prospect of long-term deterioration of the structures is then estimated. The purpose is to develop a long-term plan and issues for major replacement and rehabilitation that ensures continued serviceability of the expressway network for a longer period.

1 Introduction

Fifty-two years have passed since the first section of the Meishin Expressway between Ritto and Amagasaki Interchanges opened in 1963. As of March 31, 2015, the total length of expressways in the national network had expanded to 9,206km. The expressways in the network are operated by East Nippon Expressway Co., Ltd., West Nippon Expressway Co., Ltd., and Central Nippon Expressway Co., Ltd., (hereafter, NEXCO). The average number of vehicles using the expressway network in fiscal 2014 was some 7.2 million per day. As of the end of fiscal 2013, about 40 percent of these expressways have been in service for more than 30 years (Fig. 1). And by 2050, about 80 percent will have been in service for over 50 years, increasing the risks associated with long-term degradation.

An increasing number of overloaded vehicles on the expressways and greater use of anti-freeze agent are causing to new deteriorations (defined in this paper as "initial defect, damage and deterioration"), pointing to difficulties in maintaining the long-term health of expressway structures using conventional maintenance methods. To cope with this issue, NEXCO has set up Committee to Study Technology on Replacement and Long-term Maintenance of Expressway Assets

(the Long-term Maintenance Study Committee).

This paper reports the following areas of study by the committee: 1. necessity of structural replacement and rehabilitation; 2. actual structures needing rehabilitation or replacement; 3. rehabilitation measures; and 4. issues that need to be resolved for carrying out rehabilitation. What the committee did was to analyze the age and degree of deterioration of bridges, and clarify the relations between the cause of deterioration and the deterioration itself.

NEXCO had expected that by repairing and strengthening deteriorated members, the performance and function of a bridge would be restored to the same level as the time of completion of construction, but this assumption was proved to be wrong by this study. Deck slab replacement work⁶⁾ on the Aotsu Bridge is an example of this finding. The analysis showed that, depending on the structure of the bridge, functionality may continue to deteriorate even if partial repairs are repeated. Refer to Section (1), Paragraph 5 for the details of the repair.

The expressway network is a part of the country's social infrastructure. The maintenance of the function and performance necessary for expressways, which support everyday lives of the people as an important social infrastructure, is

inevitable even after expiry of the reimbursement period. For this reason, studies were carried out to confirm where major replacement and rehabilitation are needed, and to determine exactly what level of deterioration requires rehabilitation or

replacement and the methods to be used. Table 1 shows the definitions of the major rehabilitation and replacement applied in this paper compared with the ordinary repair.

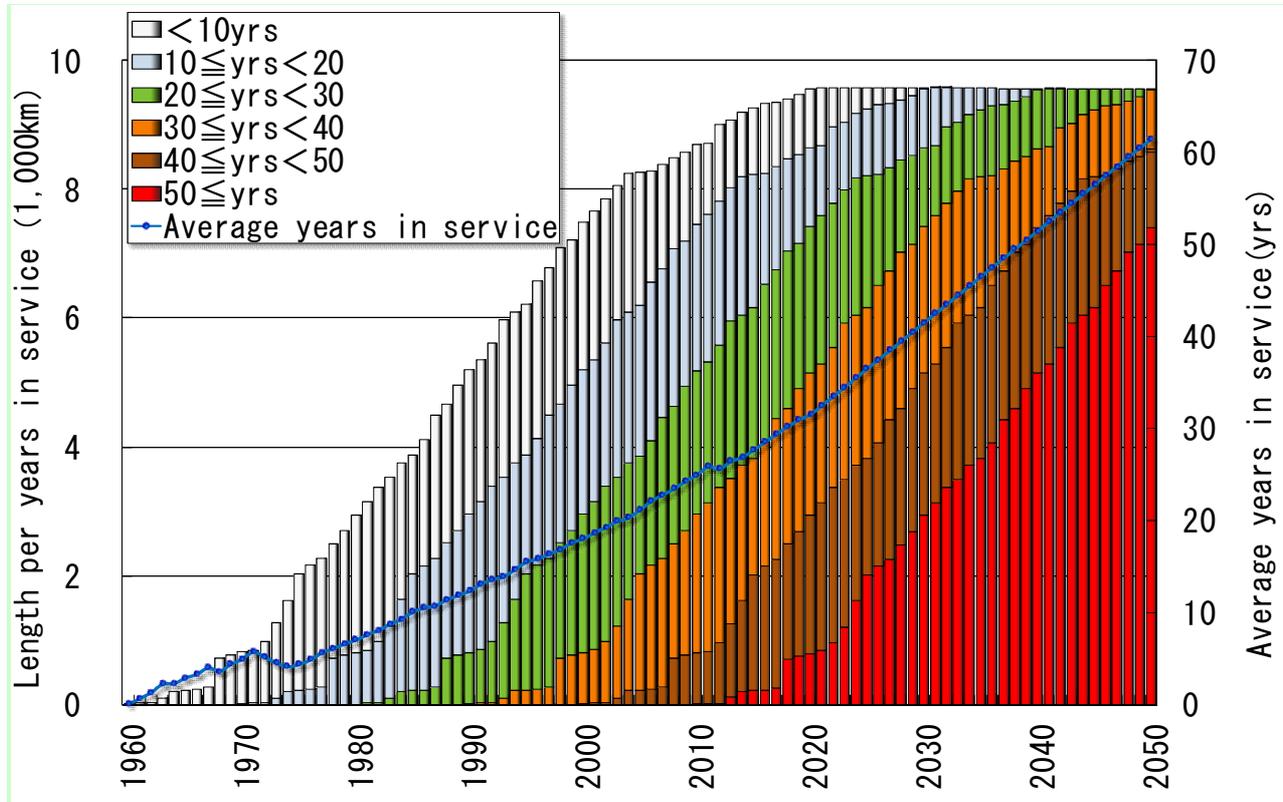


Fig. 1. Transition of Years in Service

Table 1. Definition of Major Replacement and Rehabilitation

Item	Definition	Purpose
Major replacement	To maintain and strengthen function by replacing a structure that will not recover its function in the long-term even if repairs are carried out.	To apply the latest technology to secure functions equal to new structures or better
Major rehabilitation	To recover function and performance through repair and strengthening and to prevent new deteriorations and prolong life for preventive maintenance	To apply the latest technology to secure performance equal to that of at the time of construction or better
Ordinary rehabilitation	To recover or maintain function and performance through repair and strengthening	the same level of performance as time of completion of the construction

2 Conventional countermeasures for deterioration

Changes in social conditions have prompted cutbacks in the long- to mid-term public investment budget, so in 2001, when an extensive revision of inspections manuals was scheduled, the Japan Highways Public Corporation (for-runner of NEXCO) began an effort to reduce road maintenance costs and work out effective measures against the aging of expressway structures. As part of this effort, NEXCO began developing its Bridge Management System (BMS) with reference to the bridge assessment management system used in Japan and many other countries around the world at the time. This system was designed to shift maintenance from the repair of deteriorated structures to planned preventive maintenance as a means to minimize life-cycle costs (LCC).

BMS draws up an optimal bridge maintenance and management plan as follows. First, deterioration is predicted for each bridge using data about the bridge and deterioration prediction

formula for each deterioration mechanism, such as carbonation, chloride attack, and fatigue. The formulas are provided by the Japan Society of Civil Engineers and other societies. Next, the difference between the health grading result obtained from the inspection of each structural member and the deterioration prediction is corrected. Based on the results, an optimal maintenance plan is made by selecting optimal repair and strengthening methods and timings to minimize LCC of each bridge. Health gradings are evaluated according to the deterioration grades shown in Table 2.

Although the system was ready for use when the Long-term Maintenance Study Committee came into being, the health grading of each structural member of some 20,000 bridges and entry of those grades into the BMS has been taking time. Therefore, all the necessary bridge soundness grading has been completed before being subject to the examination of the aforementioned Long-Term Maintenance Study Committee.

Table 2. Grades of Bridge Deterioration

Degree of deterioration and deterioration		Countermeasures		
Grade	description	Future		Now
		Continue observation	Preventive maintenance	Breakdown maintenance (Carry out promptly)
I	No problematic deterioration	↕		
II	Minor deterioration		↕	
III	Deterioration found			↕
IV	Major deterioration			↕
V	Serious deterioration			↕

3 Changes of environment surrounding expressway structures

(1) Aging of expressway structures

As of the end of fiscal 2012, about 43 percent of bridges on Japan's expressways were over 30 years old (Fig. 2).

(2) Changes in usage

(larger vehicles on expressways)

Along with the rising number of large vehicles using

expressways and due to the easing of vehicle weight restrictions in 1993, vehicle total weight is on the rise.

Estimates taken from vehicle weight (per axle) data of vehicles traveling on major expressways in 2005 showed that about 30 percent of large vehicles traveling on the Tomei and Meishin expressways are overloaded, violating Paragraph 2 of Article 47 of the Road Act, which stipulates the total weight of a vehicle on the road (Table 3).

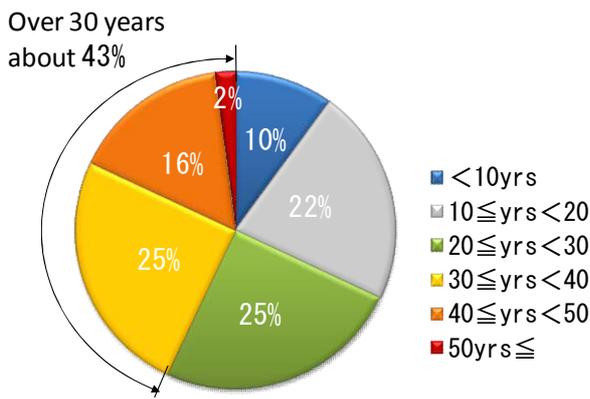


Fig. 2. Percentages of bridges per years in service

Table 3. Percentages of overloaded (total axle weight) vehicles estimated from 2005 per-axle-weight data

Expressway	Location	Over-loaded vehicles
Tomei	Nihon-daira	34.3%
Meishin	Mukou-machi	29.3%
Keiyo	Sono	20.2%
Keiyo	Kaijin	29.8%
Sanyo	Higashi-hiroshima	6.0%

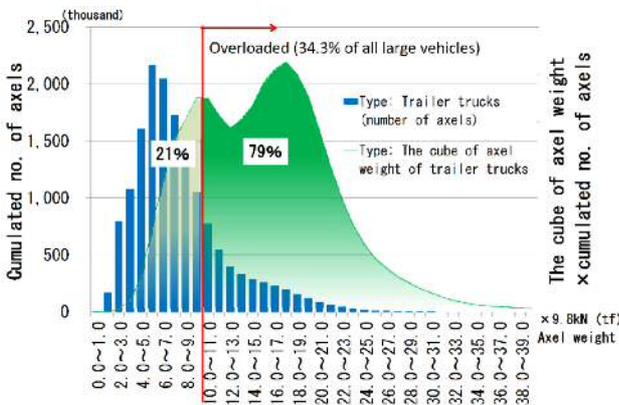


Fig. 3. Relation between cumulated number of axels taken at axle-load meter installed on the mainline and "the cube of axle weight × cumulated number of axels" (data from axle load meter on the Tomei, 2005)

Fig. 3 shows the analysis result based on the above-mentioned data regarding the effect of overloaded vehicles on expressway structures. The blue bar shows that the rate of vehicles of the total number of large vehicles which exceed accumulated axle number remain 34.3%. On the other hand,

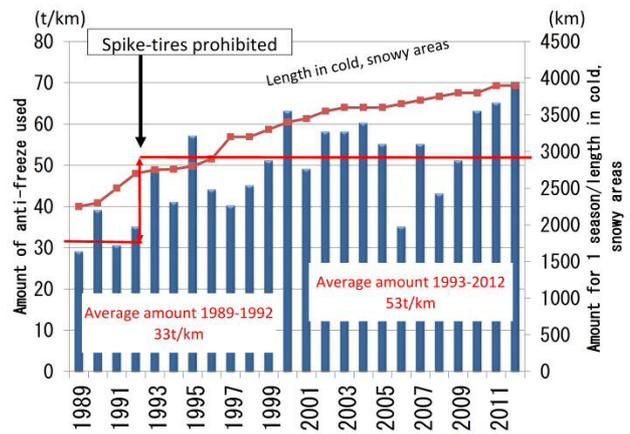


Fig. 4. Transition of amount of anti-freeze used

assuming that the damage to steel structural members by vehicle loads is proportional to the cube of axle weight, the green curved line in the diagram represents the total number of axles of large vehicles and trailers multiplied by the cube of the median of the axle weight group (e.g. 10.5 for axle weights between 10.0 and 11.0) in a frequency distribution. Fatigue damage occurs to the right of the red line in the diagram, which accounts for an area ratio of 79 percent, demonstrating that overloading is a major cause of steel member fatigue.

(3) Maintenance issues (increased in-service length in cold snowy regions)

The amount of anti-freeze agent (sodium chloride) applied per year in cold snowy regions was an average of 53tons/km between 1993 and 2012, which is an increase (Fig. 4) compared with the average of 33tons/km between 1989 and 1992. This resulted from the increase in the total length of expressways in service in cold snowy regions and the introduction of penalties, in 1993, for the use of spiked winter tires. More anti-freeze agent is used on bridges and viaducts, where road surfaces are prone to be frozen, which is the major cause of deterioration of structures.

(4) Deterioration risks related to design and construction issues

The known deterioration risks related to bridge design and construction methods are corrosion and breakage of PC tendons caused by water leakage and standing water at PC grout filling points or at

fixing points. Among the bridges managed by NEXCO, 148 pre-stressed concrete bridges (with inbound and outbound lanes counted separately) built between 1962 and 1996 have been inspected. It was found that, out of the 4,087 pre-stressing steel tendons inspected, grouting was inadequate in 26 percent. The percentage was higher, at 35 percent, in structural members using pre-stressing steel rods.

4 The state of deteriorated expressway bridges

As explained in Paragraph 2, the conventional approach to expressway maintenance was to carry out repairs after damage is discovered. Consequently, the structural deterioration was not adequately controlled. NEXCO, therefore, checked and collated the situation of major deterioration of structures managed by the companies as of the end of March 2012. The analysis results are shown in Table 4.

The relations between bridge age and deterioration, evaluated in terms of five grades (using the health gradings given in Table 2), are shown in Figs 5, 6, and 7 for three categories of bridges (reinforced concrete bridge (hereafter, RC), Pre-stressed concrete (hereafter, PC) bridge and steel bridge).

All bridges were analyzed except those that were under inspection and had not been graded and PPC bridges. The number of bridges per type and age is shown in Table 5. The relations between the NEXCO health grading and the health grading per structural member as given in the June 2014 Manual on Periodic Bridge Inspections, compiled by the Ministry of Land, Infrastructure, Transport and Tourism, are shown in Table 6 (hereafter, MLITT).

Table 4. Number of bridges analyzed per type of structure (as of the end of Mar. 2012)

Type	Number	Notes
Bridge	19,608	Counted per type of super-structure, such as steel bridge, PC bridge. In- and out-bound lanes counted separately

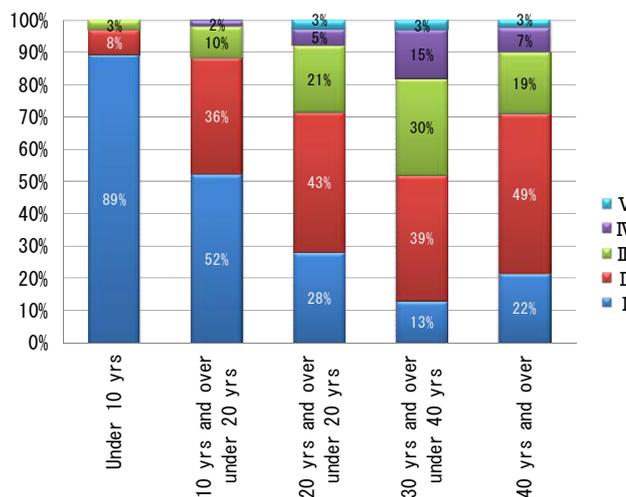


Fig. 5. Relation between age and health of RC bridges

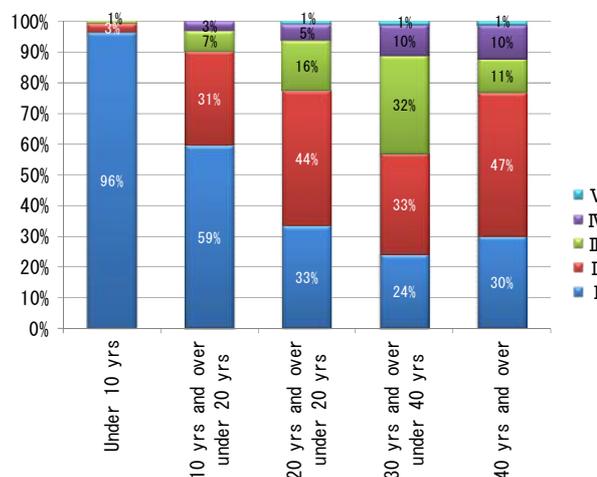


Fig. 6. Relation between age and health of PC bridges

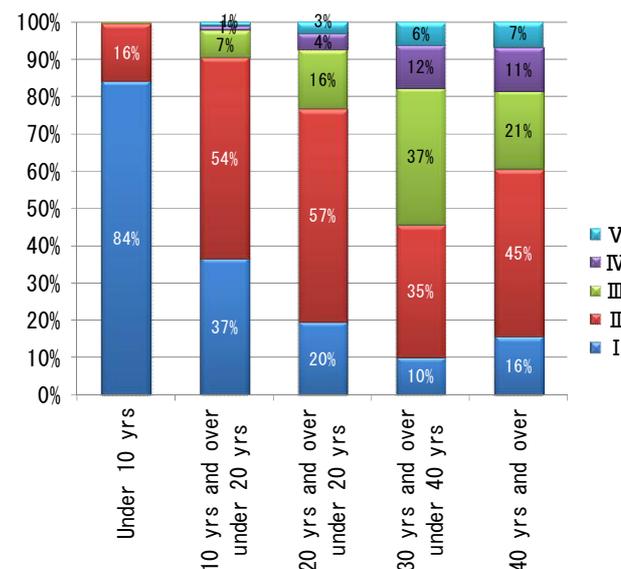


Fig. 7. Relation between age and health of steel bridges

Table 5. Number of bridges analyzed per type and age

	RC Bridges	PC Bridges	Steel Bridges
Under 10 yrs	66	406	783
10 yrs and over	818	1,628	1,280
Under 20 yrs			
20 yrs and over	1,720	1,879	1,484
Under 30 yrs			
30 yrs and over	1,621	1,489	1,430
Under 40 yrs			
Over 40 yrs	1,090	840	849
Total	5,315	6,242	5,826

For all bridge types, health tends to be deteriorated with aging. After 30 years, in particular, about half of all bridges develop deterioration that needs care (health grading higher than III). To the contrary, however, after 40 years, the health is relatively improved for reinforced concrete bridges and PC bridges. This is because, in many cases, when the health grading reaches grade IV, repair work is carried out, improving the bridge soundness from grade IV to grade II.

5 Necessity of Major Structural Replacement and Rehabilitation

(1) Health grades of the structure and its rehabilitation

As the schematic diagram in Fig. 8 shows, NEXCO assumed that the function of bridges will be recovered and secured permanently by repeating partial repairs to the same level as the initial level obtained at the completion of construction. However, the partial repairs did not work for the case of the Aotsu Bridge on the Chugoku Expressway, a steel three-span continuous non-composite plate girder bridge put into service in 1978. Chloride attack to the reinforced concrete deck slabs had progressed due to the anti-freeze agent used on a daily basis during winter to prevent freezing. The slab upper surface and waterproofing were repaired 15 years after the bridge opened, and, moreover, 22 years after the opening, the lower surface was repaired.

Table 6. NEXCO's bridge health grading and health grades in the Bridge Inspections Manual compiled by the MLITT

MLITT's health grades for each member		Bridge		
		NEXCO's health grades (main girder, slab)		
Grade	Description	Deformation grade	Degree	Definition
IV	Emergency measures needed Functions obstructed or highly possible of being obstructed. Emergency measures needed.	—※	—※	—※
III	Prompt measures needed High possibility of functions being obstructed. Measures should be taken quickly.	V	Serious obstruction of function	Safety problems caused by serious lowering of load bearing capacity. Travel performance has deteriorated posing problems in usability.
		IV	Serious deformation	Load bearing capacity is lowering and may cause safety problems. Travel performance is deteriorating and may affect usability.
II	Deal with preventive maintenance No obstruction of function, but preventive measures should be taken	III	Deformation found	Deterioration has progressed considerably and load bearing capacity and travel performance need to be watched carefully.
		II	Minor deformation	Deterioration has progressed but has not affected load bearing capacity or travel performance.
I	Healthy No obstruction of function	I	No problematic deformation	No deterioration

※ NEXCO's does not have grading equivalent to MLITT's Grade IV, as NEXCO take emergency measures immediately after a bridge is found to have deformation at the emergency level, and the measures taken are recorded in its computer system.

Curve calculated under the assumption that health of bridges at time of construction may be recovered and structure function maintained permanently by repeated partial repairs,

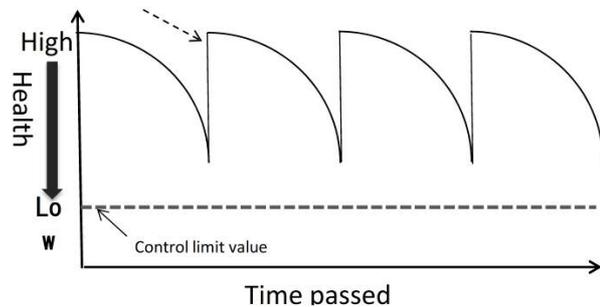


Fig. 8. Conceptual diagram of relation between health and repair/strengthening

But even after these repeated partial repairs, inspection records show that, as aging progressed, corrosion causing bubbling and flaking were found on the lower surface of the slab, indicating that corrosion was progressing in the same way similarly as before the repairs.

Further, the upper surface of the deck slab was breaking up into gravel and potholes occurred frequently, demonstrating that the upper surface was also deteriorating as before the repairs. The deterioration progressed further, spreading to the entire deck slab and seemed to be reaching the

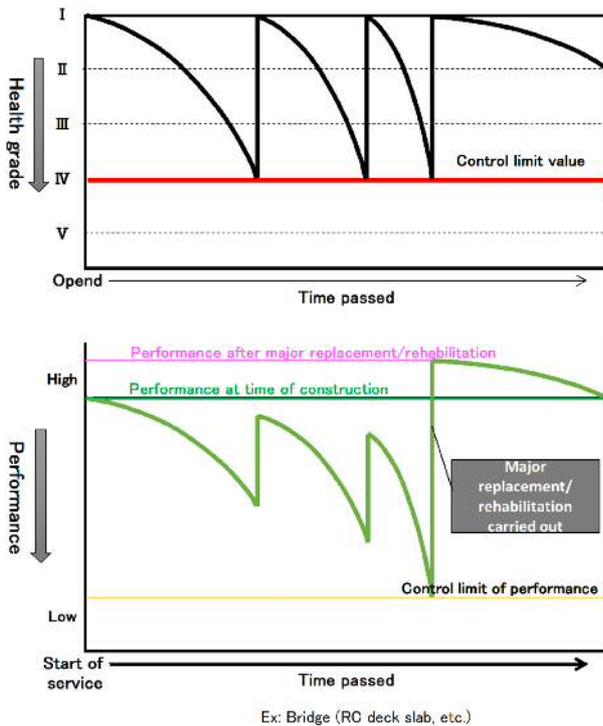


Fig. 9. New concept on bridge performance

control limit. Finally, 30 years after opening, the deck slab was replaced with highly durable PC slabs.

An increasing number of bridges like the Aotsu bridge need slab replacement because deterioration has progressed even with repeated partial repairs. Fig. 9 is a diagram illustrating a new concept that repeated partial repairs will not restore the original function of the bridge, and that, in the end, replacement or major rehabilitation is needed.

Based on inspection and repair histories of expressway bridges operated by NEXCO, the characteristics of deterioration (location, cause, degree) and the countermeasures taken in each case where rehabilitation was carried out are shown in Table 7.

(2) Deterioration analysis and predictions

Multiple regression analysis was used to analyze the various causes of deterioration, combinations of causes, and the relationship between bridge health and the various causes. Of the analyses of different structures carried out, the deterioration of a reinforced concrete slab is described below as an example. The number of axles (converted to 10t

Table 7. Characteristics of deformation on bridge structures and countermeasures

Member	Deformation characteristics			Countermeasures
	Location	Cause	Degree	
Deck slab	RC slab	Chloride attack, ASR, fatigue	Progressing	Replacement, Strengthening, preventive maintenance
	PC slab		Progressing gradually	
	Steel slab	Fatigue	Apparent on heavy traffic routes	Strengthening
Girder	RC girder	Chloride attack, ASR	Progressing	Replacement, Strengthening, preventive maintenance
	PC girder		Progressing gradually	
	Steel girder	Fatigue	Apparent on heavy traffic routes	Strengthening
		Cavities in PC grout	Confirmed in some	Double safety measures, monitoring

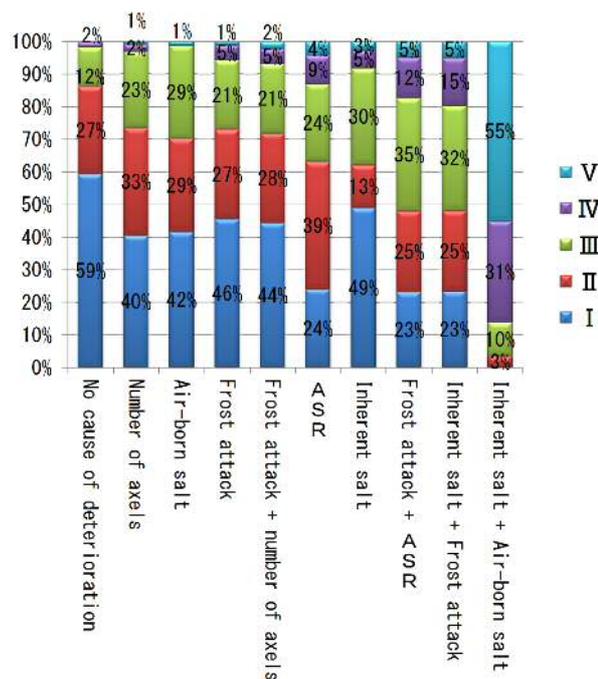


Fig. 10. Health of RC deck slab per cause of deformation

axels, total of over 30 million axels); airborne salt (less than 1km from the sea); inherent salt (from the sea sand used); ASR (effects of alkaline-silica reaction depending on aggregate used); frost attack (amount of anti-freeze used, more than 1,000t/km) are assumed to be the main causes of deterioration, and the relationships between deck slab health and the causes of deterioration for each combination of

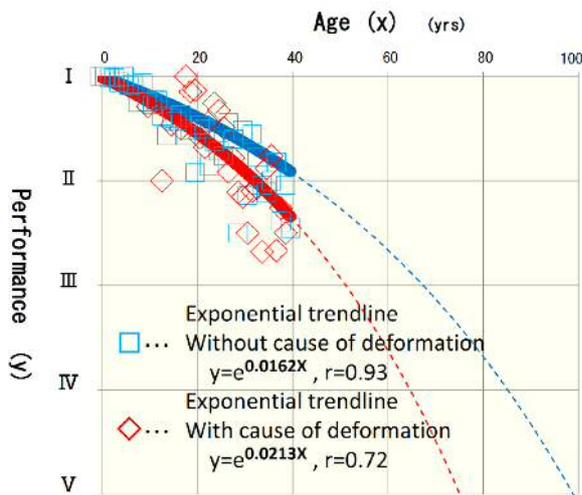


Fig. 11. Transition and prediction of health of RC deck slab with age

these causes, and other factors, are shown in Fig. 10.

As can be seen above, when there is even one cause of deterioration, health tends to deteriorate as compared with when there is no cause of deterioration affecting the structure. With inherent and airborne salt, especially, the total percentage of slabs with current health gradings of III, IV, and V is over 95 percent, indicating that the health of the slabs has deteriorated considerably.

An exponential function offers a close fit to a plot of changes in health grading with years of service, based on health data for 7,422 bridges that have not been repaired. The fitted curve is then extrapolated to provide a deterioration prediction (Fig. 11). With so many data points, all of them are not shown individually in the plot. Instead, the mean value of health grading for each year of service is shown, marked “◇” where affected by the causes of deterioration and “□” where unaffected by such causes. The extrapolated exponential trend line for those bridges that were affected by deterioration causes, shown in red, shows that their health tended to degrade earlier over time as compared with bridges exposed to no deterioration causes, shown in the blue line. Further, even for bridges shown in blue (without deterioration causes), health tended to degrade at a faster rate as the bridges aged. It can be concluded that, even if measures such as described in Fig. 9 are taken, repeated partial repairs will not prevent deterioration (as in the case of the Aotsu Bridge), and the upper surface of the slab will break down into gravel, causing

potholes and prompting frequent lane closures for repairs. Such traffic disruptions will gradually have more and more effect on society and, one day, the bridge will be unable to provide its expected function and large-scale replacement work will be needed.

(3) Structures that will need replacement or major rehabilitation work

Structures expected to require replacement or major rehabilitation, as of January 2014, were selected based on whether deterioration causes are present and the deterioration prediction method outlined in previous paragraphs, as well as in consideration of their repair and replacement history. Bridges are classified into slab and girder types, and, further, they are subdivided into reinforced concrete, PC concrete, and steel. Structures requiring replacement or major rehabilitation for concrete structures are determined based on the presence or absence of deterioration factor such as chloride attack and the degree of deterioration, and those for steel structures are determined based on the degree of deterioration by fatigue. Structures requiring major repairs or replacement are shown in Table 8.

6 The long-term plan for replacement and rehabilitation

Table 9 shows the scale of works for those structures requiring major rehabilitation or replacement. Deterioration that was not clearly identified and that results from unknown mechanisms is not included in this analysis.

7 Conclusions

In the Paragraph 1 through 3, the changes of maintenance in expressway bridges were overviewed. In addition, the expansion of the total length of expressways, its increase of years in service, changes of social and environmental surroundings were organized, therefore the cause of bridge deterioration were described.

In the Paragraph 4, the states of deteriorated expressway bridges were analyzed using all health grade data.

In the Paragraph 5, we analyzed the various causes of deterioration, furthermore, it was

predicted that the structure performance fall below the control limit of required one in step with the health degrade. To use the expressway in the long term, necessity of structures replacement work was demonstrated. Besides, the major rehabilitation

was needed with the object of preventive maintenance as soon as possible. In addition, these necessities were organized by deterioration.

In Paragraph 6, the scale of works for bridges described above was presented.

Table 8. Structures needing major replacement/rehabilitation

Detail		Structures for major replacement / rehabilitation
Member	Type	
Deck slab	RC	Major replacement: Slabs of health grade III, IV, V that are affected by inherent and air-born salt, and other deformation causes (chloride attack, heavy traffic, etc.). Major rehabilitation: Slabs with health grade of I, II that are affected by deformation causes (chloride attack, traffic, etc.) and those not affected by the causes but without high-durability waterproofing at time of construction.
	PC	Major rehabilitation: Slabs without high-performance slab waterproofing at time of construction.
	Steel	Major rehabilitation: Slabs affected by large-vehicle traffic (10t vehicles converted to total of over 30m axels)
Girder	RC	Major renewal: girders affected by inherent salt, chloride attack, etc., excluding those that fall under the conditions in the above mentioned major rehabilitation.
	PC	Major rehabilitation: girders affected by chloride attack (including those structures that have a high risk of deformation of PC steel)
	Steel	Major rehabilitation: girders affected by large-vehicle traffic (10t vehicles converted to total of over 30m axels)

Table 9. Breakdown of project numbers (length: km)

Item	Member	Main measures	Number needing measures [km]	Approx. project cost [yen]
Major replacement	Deck	Replace	About 230	1.65tn yen
	Girder	Replace	About 10	100bn yen
Major rehabilitation	Deck slab	Repair and carry out high-durability waterproofing	About 360	160bn yen
	Girder	Strengthening by adding cross-frame, etc.	About 150	260bn yen