MAINTENANCE MANAGEMENT AND PRESENT CONDITION OF CONCRETE STRUCTURES OF HONSHU-SHIKOKU BRIDGE EXPRESSWAY

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Abstract

The Honshu-Shikoku Bridge Expressway (HSBE) has a total of 276 bridges. The bridges have served for 12 to 32 years. Of the 276 bridges, Non-destructive testing (NDT) of the concrete structures has been conducted for 181 bridges. This paper presents maintenance strategy for concrete structures in the HSBE and the outline of the test results.

Introduction

For the maintenance of concrete structures in the HSBE, maintenance activities based on preventive maintenance strategies have been conducted in order to prolong their service lives. Since 1999, as part of this activity, NDT surveys have been conducted to obtain their current conditions. In this paper, maintenance strategy for concrete structures in HSBE and the outline of the test results is presented.

Outline of the HSBE

The country of Japan consists of four main islands: namely, Hokkaido, Honshu, Shikoku, and Kyushu. The HSBE connects Honshu, the largest island, and Shikoku, the smallest, by three straits crossings, Kobe-Awaji-Naruto Route, Seto-Chuo Route, and Nishi-Seto Route (Figure 1). The Expressway has 10 suspension bridges, which include the Akashi-Kaikyo Bridge which is the world's longest suspension bridge , 5 cable-stayed bridges, 2 truss bridges, 1 arch bridge and many viaducts. In total, it has 276 bridges.

Maintenance Strategy for Concrete Structures

The bridges located in the straits are exposed to very harsh sea salt environments. Therefore, for the concrete structures located in this area, a maintenance strategy to prolong their service lives aiming longer than 200 years by preventive maintenance and reduce life-cycle cost (LCC) is taken. Also, in order to secure the function of the HSBE as a whole, other viaducts are maintained with NDT and deterioration predictions as well.

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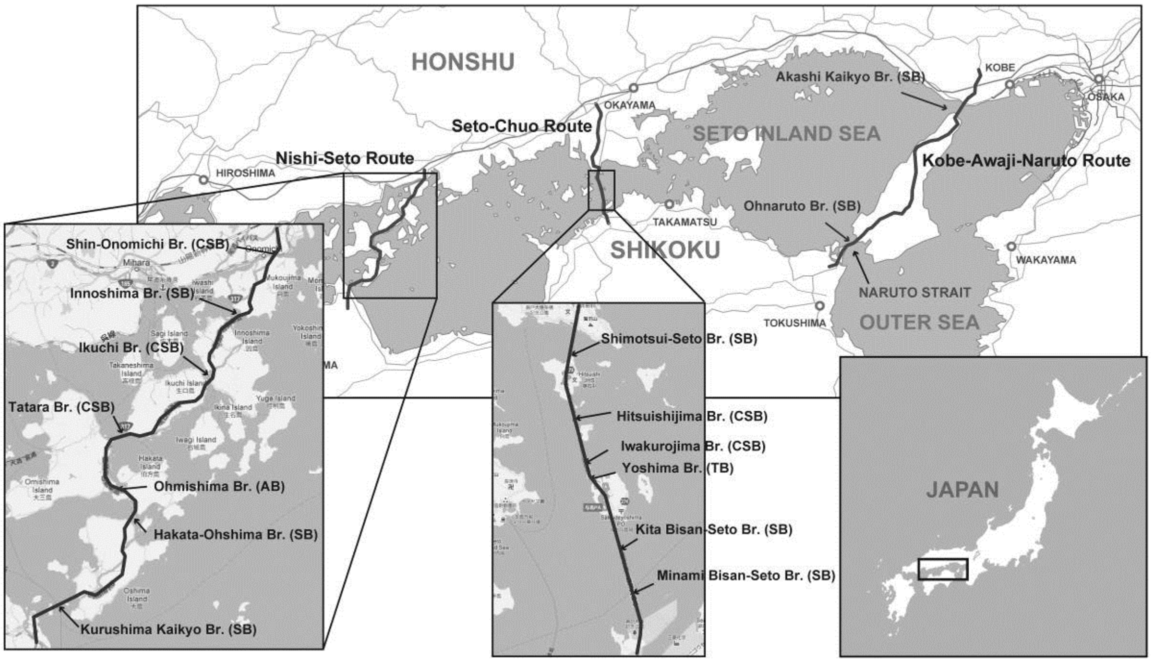


Figure 1 Outline of Honshu-Shikoku Bridge Expressway
(SB: suspension bridge, CSB: cable-stayed bridge, TB: truss bridge, AB: arch bridge)

To obtain the conditions of concrete structures, NDT survey started in 1999. These surveys are conducted in accordance with the “Manual for Non-Destructive Testing of Concrete Structures in Periodical Inspection (draft)” (HSBE, 2001). Maintenance flow of concrete structures is shown in Figure 2.

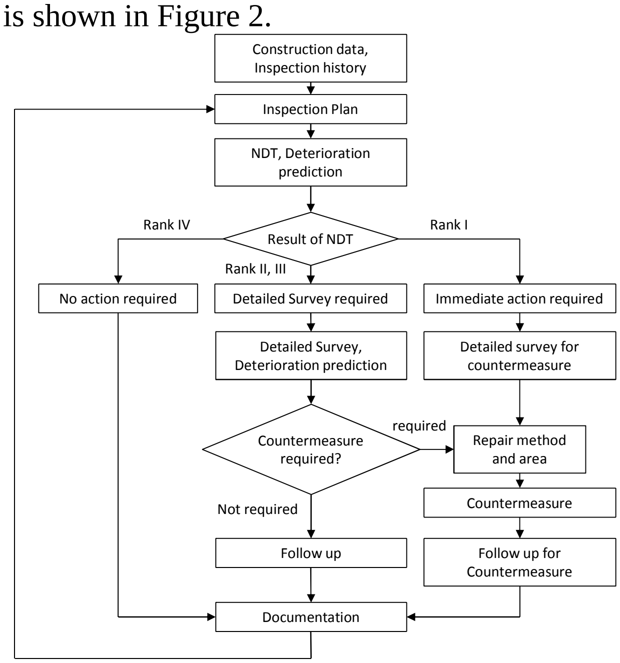


Figure 2 Maintenance flow of concrete structures

The interval of surveys are set according to the environment and repair history as in Table 1. Items of surveys are listed in Table 2. From the survey results, current conditionsare judged for each NDT item based on Table3. Current conditions of the concrete structure are judged by using the worst Ranked. Also, predictions of chloride penetration and progress of carbonation are calculated as reference.

Table 1 Interval of NDT survey

Repair history	No			Once or more		
Area	A	B	C	A	B	C
Interval (years)	5-10	10	10-20	5	10	10

Area	Prescription
A	Over sea or within 100m from coast line
B	100-500m from coast line
C	Other than A or B

Table 2 Items Covered in NDT Surveys

Item	Description
Cover thickness	Measure cover thickness in survey area by RC radar
Chloride ion	Measure chloride ion density with concrete dust obtained by drilling from 2 sampling points. In each point, data shall be obtained every 20 mm.
Carbonation depth	Measure carbonation depth by phenolphthalein using holes drilled for chloride ion measurement
Rebar corrosion	Measure self-potential. Exposed rebar, to which one electrode is attached, shall be visually inspected. Structures in area A and B are subjected to this survey. Structures constructed before the “regulation of chloride contents” are subjected to even in area C.

Table 3 Criteria of condition

Rank	Chloride ion density Cl (kg/m^3)	Carbonation depth X_c (kg/m^3)	Self-potential E (mV vs CSE)	Assumed condition
I	Cl >= 2.5	X_C >= cd	-350 >= E	Steel members are assumed to be corroded. Detailed survey shall be planned immediately.
II	2.5 > Cl >= 1.2	cd > X_C >= 0.5cd (cd < 40mm)	-250 >= E > -350	Steel members have high probability of corrosion. Detailed survey is highly expected.
III	1.2 > Cl >= 0.3	cd > X_C >= 0.5cd (cd >= 40mm)	-150 >= E > -250	Steel members have probably begun corroding. Detailed survey is expected considering importance of structure and maintenance level.
IV	0.3 > Cl	0.5cd > X_C	E > -150	Steel members are considered not to be corroded. Continue periodical inspection.

*cd: cover depth

Based on Table 1, all the bridges are categorized by their locations (Table 4). Basically, all the bridges are subjected to NDT survey. For the bridges located in the strait locations, ramps are excluded. Also, for the three consecutive suspension bridges (the Kurushima Kaikyo Bridges), one bridge is surveyed as a representative of the trio. For the bridges in area C and bridges constructed after the "regulation on chloride content"* was issued, 2-5 bridges are grouped by surrounding natural environments and one bridge is selected from each group as a representative.

*"Regulation on chloride content" was issued in 1986 by the Ministry of Construction in the context of increasing concrete structures damaged by chloride induced deterioration. It regulates the allowable chloride content for newly constructed structures.

Table 4 Bridges subjected to NDT survey

	Area	All bridges	Selected for survey	Surveyed	To be surveyed
Strait	-	48	34	34	0
Other	A	2	2	2	0
	B	43	43	43	0
	C	183 (55)*	107 (55)*	102 (50)*	5 (5)*
Total		276	186	181	5

*the number in parenthesis shows bridges constructed before adoption of the "regulation on chloride content."

Survey Result

Table 5 shows the survey results and progress of countermeasures. By NDT survey, 50 bridges (18% of all bridges) were judged as Rank I or II. By detailed survey, 14 bridges (5% of all bridges) were judged as "countermeasure required."

For the bridges located in the straits, 7 bridges are judged as "countermeasure required" in 34 surveyed bridges (20%). For 5 bridges, countermeasures have already been taken. The remaining 2 bridges, countermeasures are in the process.

For the bridges located in other than strait locations, 7 bridges are judged as "countermeasure required" in 147 surveyed bridges (5%). For 2 bridges, countermeasures were taken. For 2 bridges, countermeasure is being taken or under monitoring. The other 3 bridges will be examined this year.

Table 5 NDT survey result and countermeasures

Category	All bridges	Surveyed	To be surveyed	Rank I or II	Countermeasure required	Countermeasure taken
Strait	48	34	0	7	7	7
Other	228	147	5	43	7	4
Total	276	181	5	50	14	11

(1) “Regulation on chloride content”

Figure 3 shows chloride ion density at rebar comparing the before and after the “regulation on chloride content.” As shown in the figure, chloride ion density of structures after the “regulation” is lower than that of before.

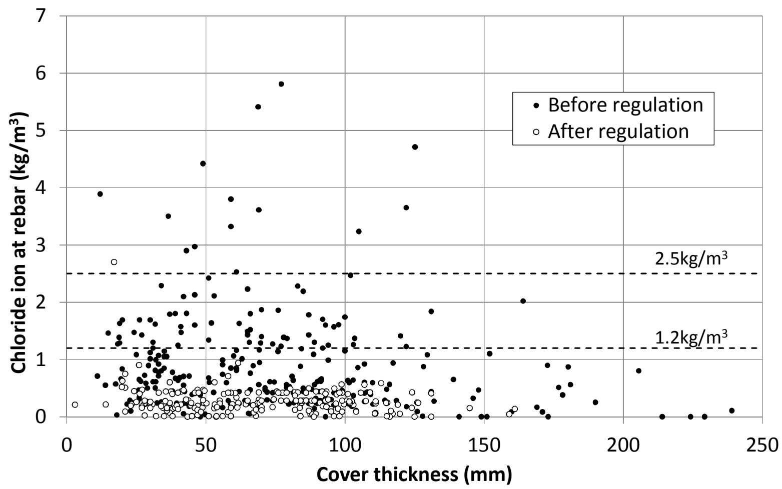


Figure 3 Chloride ion density at rebar before and after the “regulation”

Many bridges that have chloride ion density larger than 2.5kg/m^3 at rebar are near the Naruto Strait. This strait is only exposed to the outer sea while the other locations are inside of inland sea (Figure 1) and therefore considered to be the most harsh sea salt environment. Also, many bridges in this area were constructed before the “regulation” and some have thin concrete cover.

The other bridges with high chloride ion are the older bridges such as Ohmishima Bridge and the viaducts near Innoshima Bridge.

A bridge constructed in 1988 shows high chloride ion density although it was constructed after the “regulation” and located in area C. This is because that the cover thickness of the measured point is very thin and deicing salt might intrude from the end of the road surface.

(2) Distance from coast line

Figure 4 shows the relation between surface chloride ion density (C_0) and the distance from the coast line. C_0 is calculated by fitting measured data to Fick’s 2nd law of diffusion. In the figure, C_0 specified in “Standard Specifications for Concrete Structures - 2007, Maintenance” (JSCE, 2007) is also shown.

C_0 is highly correlated with distance from coast line and bridges located within 50m have large C_0. The bridges exhibit C_0 higher than 15 kg/m^3 are the ones near the Naruto Strait, ones in the strait location of the Seto-Chuo Route, and Ohmishima Bridge.

In some data, chloride ion density near concrete surface is small by the effect of carbonation and such data were omitted when fitting Fick’s equation. By this manipulation, obtained C_0 might be different from actual C_0.

On the other hand, C_0s for inland viaducts give good agreement with JSCE's value.

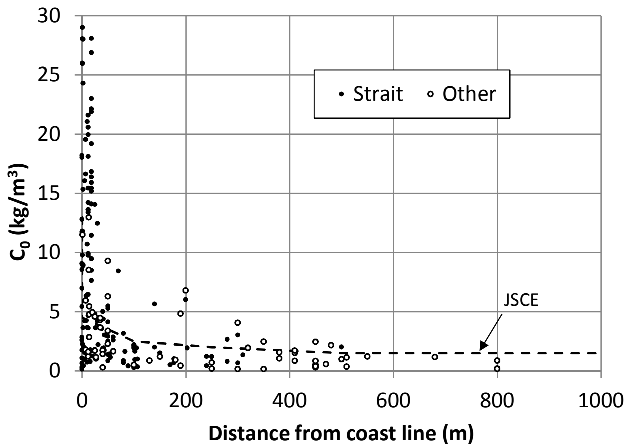
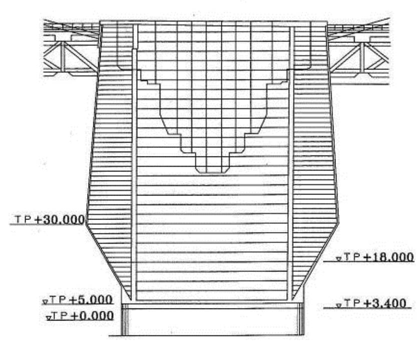


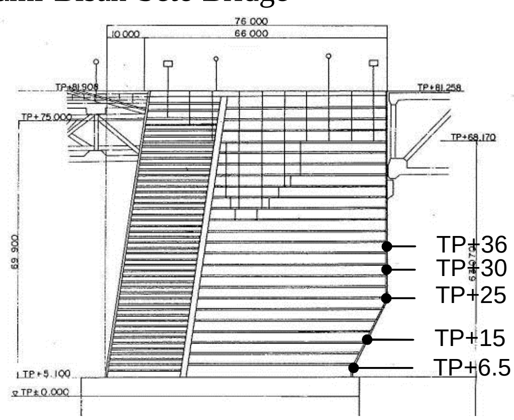
Figure 4 C_0 and distance from coast line

(3) Anchorage

At both anchorages of the Minami-Bisan-Seto Bridge, samples were taken height-wise and direction-wise. Figure 5 shows general view of the bridge and side views of both the anchorages. Figure 6, 7, and 8 show results.

(a) General view of Minami-Bisan-Seto Bridge





(b) 4A (c) 7A

Figure 5 4A and 7A anchorages of Minami-Bisan-Seto Bridge

*TP: Tokyo Pail (Tokyo Bay Mean Sea Level)

Chloride ion distribution profile becomes higher as altitude gets lower for both anchorages. From Figure 8, it is observed that only the south face shows a very high chloride ion distribution profile. As similar as north and south faces of 4A, south face of 7A has “overhung” in lower portion. In vertical or inclined surfaces, it is generally considered that rain water may flush away chloride ion adhered to the concrete surface. However, in overhung surfaces, this flush-away effect may be weaker. High chloride ion profiles may attribute to this.

As a countermeasure for chloride induced deterioration and combined deterioration*, overhung areas and lower portions were coated (Figure 9).

* At the lower segment of overhung, exposure of aggregates by disappearance of cement paste and “pop-out” of aggregates were observed. Causes of these combined deteriorations are considered as chemical erosion caused by sea water, ASR, and wet-dry cycle.

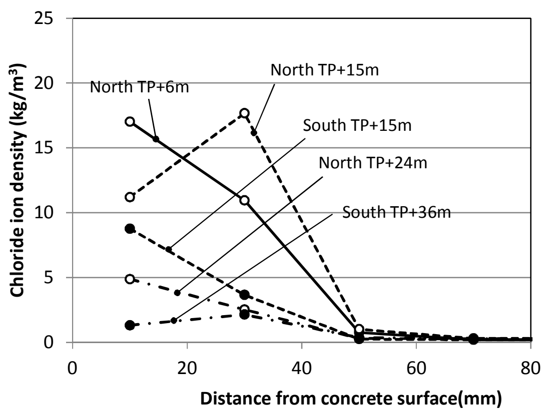


Figure 6 Chloride ion density distribution (4A, north and south faces)

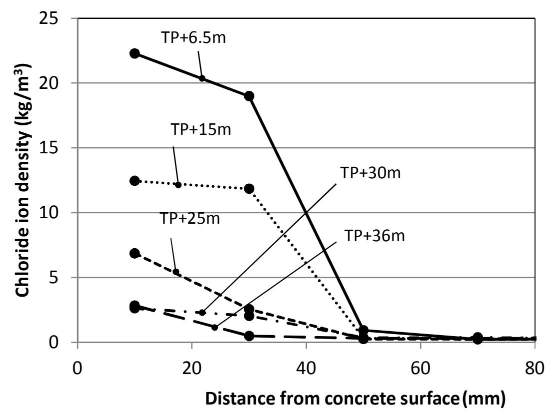


Figure 7 Chloride ion density distribution (7A, south face)

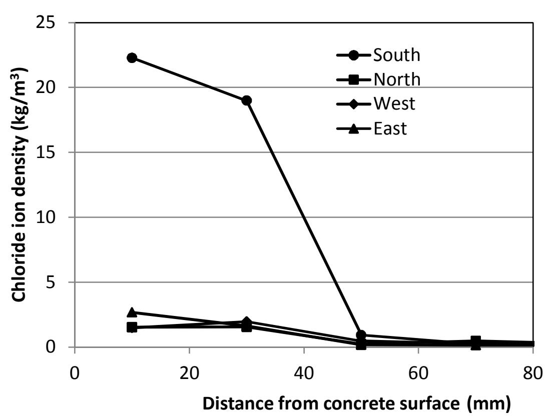
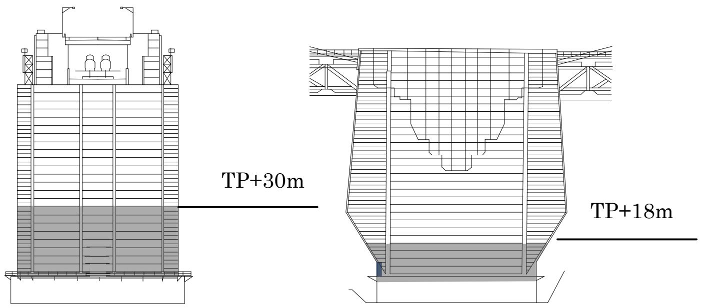
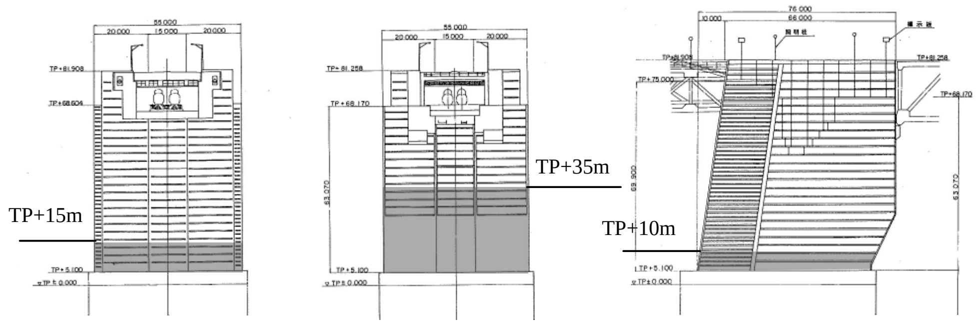


Figure 8 Chloride ion density distribution (7A, TP+6.5m)



(a) 4A



(b) 7A

Figure 9 Coated area (gray) of anchorages of Minami-Bisan-Seto Bridge

(4) Surrounding terrain

Tozaki Viaduct has a total span of 1,010m and connects to the Ohnaruto Bridge. It has a 3-span and a 4-span continuous steel box girders. Figure 10 shows the general view of Tozaki Viaduct. The viaduct is located at the southern foot of Tozaki, a peninsula with 60-100m wide, 40-80m high, and about 1km long (Figure 11).

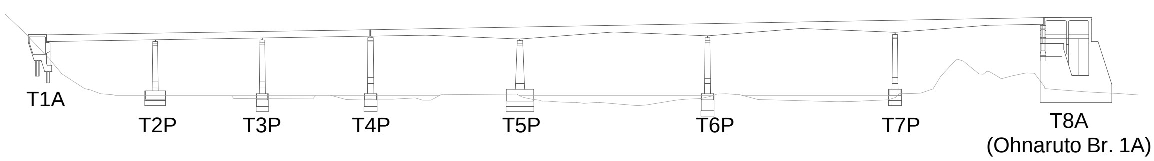


Figure 10 General view of Tozaki Viaduct

Figure 12 and 13 show chloride ion density distributions measured in T6P of the viaduct. Although profile does not vary with height very much, Tozaki's face shows a higher profile than the outer sea face. From the wind rose in Figure 11, it is observed that the wind from the outer sea direction (south-east) is dominant. Causes of the difference in chloride ion profile can be considered as follows. 1) Sea salt brought by the south-east wind may be blocked by Tozaki and dense chloride atmosphere is created between the viaduct and Tozaki, 2) rain water with south-east wind may have flushed away chloride ion adhered on to the outer sea surface of the pier.

Because of the high chloride ion density at rebar position, spalling of cover concrete, and exposure of rebars, repairs were started in 2007.

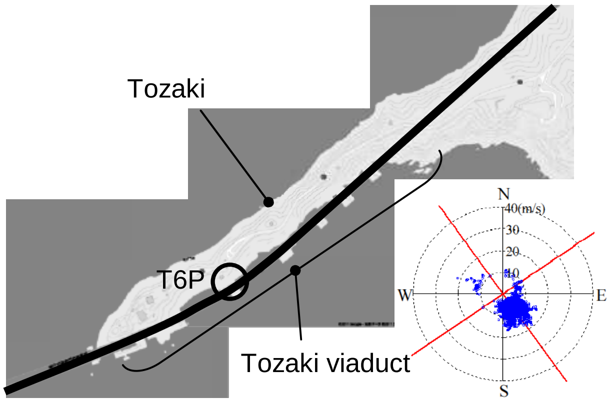


Figure 11 Tozaki viaduct and surrounding terrain and wind condition

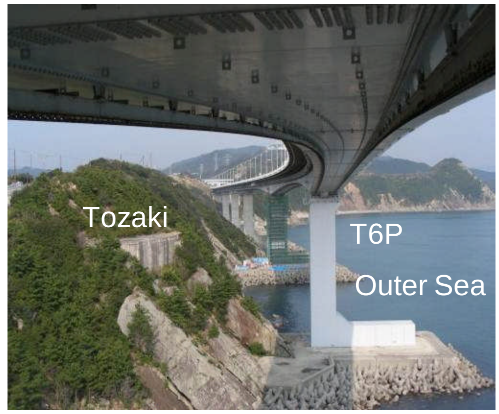


Photo 1 T6P (from T7P)

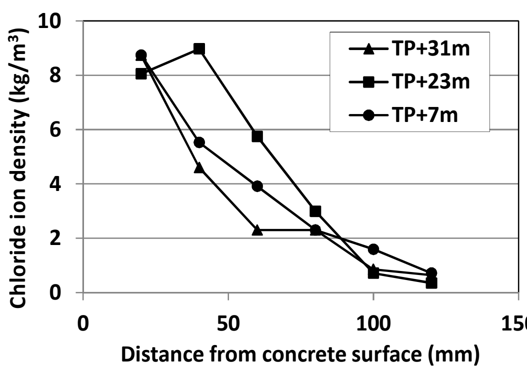


Figure 12 Chloride ion density distribution (Tozaki face)

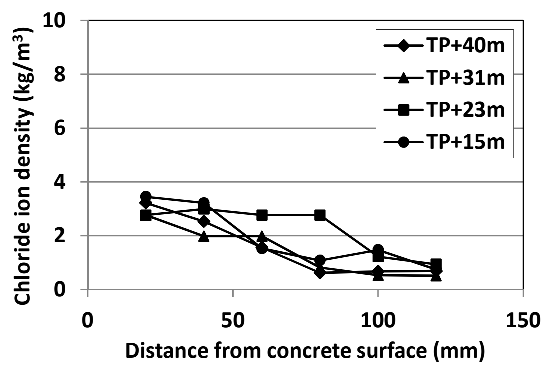


Figure 13 Chloride ion density distribution (Outer sea face)

(5) Evaluation of predictions

For the bridges located in the straits, the first rounds of surveys were completed and currently the second round is ongoing. Examples of the comparisons of the first and second round surveys are shown in Figure 14 (Kameura Viaduct, near Ohnaruto Bridge), 15 (Bannosu-Minami Viaduct, southern end of Seto-Chuo Route), and 16 (Ohshima Bridge).

Increase of chloride ion profile of Kameura Viaduct, which is located near Naruto Strait, is larger compared with the other locations.

In the figures, predicted distributions for the second round survey were calculated by using the first round data are shown. For the Kameura Viaduct and Bannosu-Minami Viaduct, measured values in the second round survey are higher than predicted. In order to improve the reliability of the predictions, continuous data acquisition is expected.

Because of the high chloride ion density at rebar position and concerns that consequent spalling of concrete cover may fall on to the fishing ports or roads beneath the viaduct, repairs of the Kameura Viaduct has started from 2011.

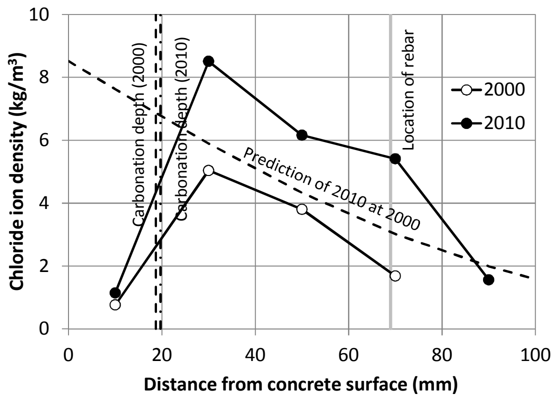


Figure 14 Chloride ion density distribution
(Kameura Viaduct 4P North, 2000 and 2010)

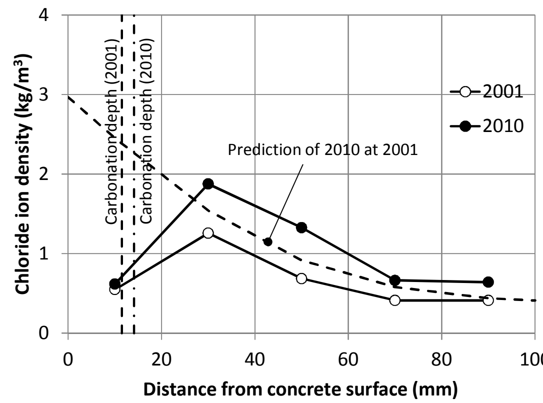


Figure 15 Chloride ion density distribution
(Bannosu-Minami Viaduct 12P West, 2001 and 2010, cover thickness = 103mm)

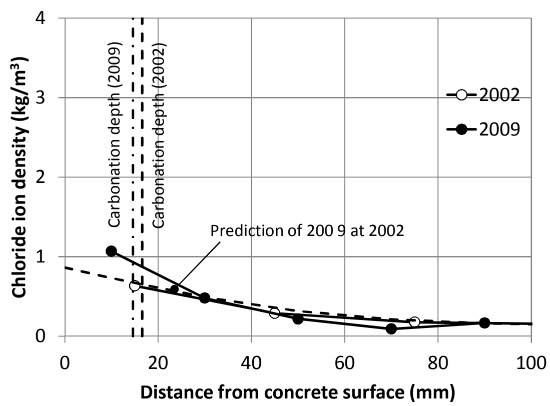


Figure 16 Chloride ion density distribution
(Ohshima Bridge 6P, 2002 and 2009, cover thickness = 169mm)

(6) Effectiveness of surface coating

In order to verify effectiveness of surface coating, data was sampled from the portion where surface coatings were applied.

Figure 17 shows the chloride ion distribution obtained from the pile cap of the 3P tower of the Ohnaruto Bridge in 2004. The pile cap was coated in 1988. 10 years after the coating, peel offs were found in some areas. Profiles of intact portions are much smaller than that of peeled portions.

In 7A anchorage of the Minami-Bisan-Seto Bridge, test coatings were applied in a small area in 1989. In 2008 and 2009, chloride ion distributions were measured from the coated areas and the areas that were not coated Sample points are shown in Figure 18 and Photo 2. The results are shown in Figure 19.

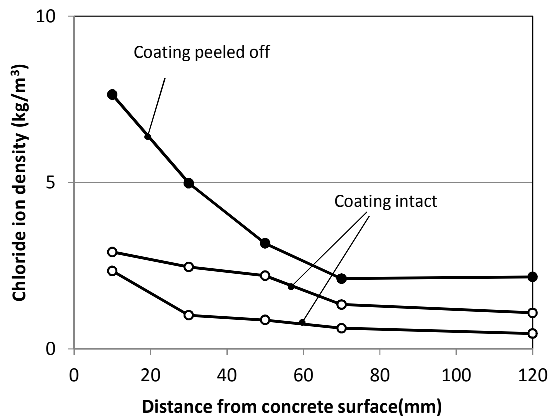


Figure 17 Chloride ion density distribution
(Ohnaruto Bridge 3P pile cap)

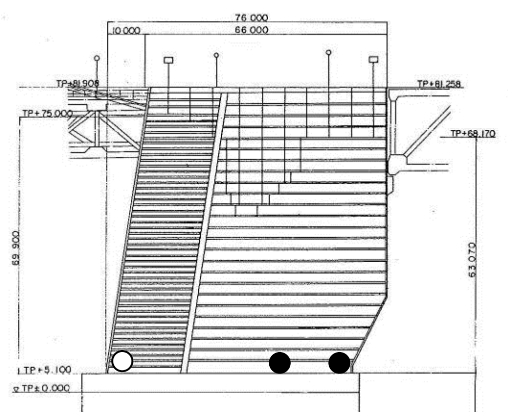


Figure 18 Sampled points in 7A of Minami-Bisan-Seto-Bridge
(○: coated, ●: not coated)

Photo 2 Sampled point (coated) in 7A of Minami-Bisan-Seto Bridge

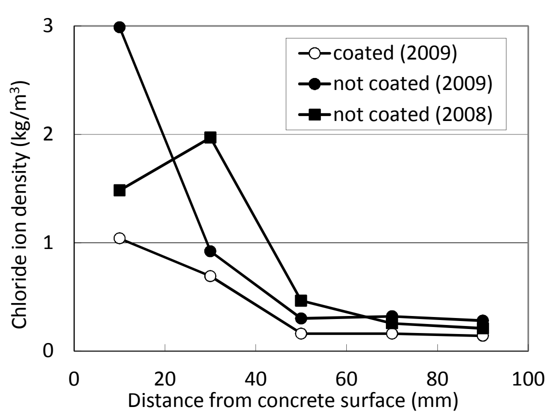


Figure 19 Chloride ion density distribution
(Minami-Bisan-Seto Bridge 7A)

Concluding Remarks

In the HSBE, there are 276 bridges and their ages range from 12 to 32 years. As a result of the NDT surveys of 181 bridges (34 in strait part and 147 in the other area), 50 bridges were assessed as “steel members are corroded or highly probably corroded.”

As a result of the detailed surveys, 14 bridges (7 in strait part and 7 in the other area. 5% of all the bridges) were judged as “countermeasure required.” 11 bridges are under repair or were repaired. The other 3 will be addressed from this year.

As a result of the chloride ion surveys, the followings were found:

1) Influence of “Regulation on chloride content” is large.
2) Influence of distance from coast line is large. Especially within 50m, chloride ion density becomes high.
3) As altitude gets high, chloride ion density becomes low.
4) In overhung portion, chloride ion density is high because of less flush-away effect by rain water.
5) Influence of surrounding terrain is high.

Comparing the results of the surveys of the first and second rounds, increase of chloride ion was much higher than the predicted value in the Naruto Strait area. In order to improve the reliability of predictions, continuous data acquisition is expected.

From the surveys of the Ohanaruto Bridge and Minami-Bisan-Seto Bridge, the effectiveness of surface coating was verified.

For the bridges located in strait locations, the NDT surveys will be continued because 1) they are located in very harsh sea salt environments, 2) improvement of prediction methods is required, and 3) evaluation of countermeasures is required.

For the bridges in areas other than straits, the survey frequency for bridges with Rank III and IV will be reduced.

For the members assessed as “countermeasure required” for chloride induced deterioration by the predictions, countermeasures shall be taken by surface coatings as a primary method. For ASR, the application of surface impregnation method shall be considered since the progress of deterioration is relatively slow. Also, the most recent repair materials shall be considered.

References

Japan Society of Civil Engineers, “Standard Specification for Concrete Structures – 2007, Maintenance”