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Preventive maintenance on highway-railway combined bridges

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ABSTRACT: Seto-Ohashi Bridge is a series of long-span bridges that locates at the center of three Honshu-Shikoku Expressways. The 9.4 km-long bridges are road-railway combined bridges and accommodates 4-lane expressway on the upper deck and 2-railway track on the lower deck. The bridges are surrounded by marine conditions and being exposed to severe weather. To ensure long service life and reduce a life cycle cost, a systematic maintenance that emphasize on preventive maintenance is conducted for the bridges. This paper describes current maintenance measures and the technologies for the preventive maintenance of Seto-Ohashi Bridges.

1 INTORODUCTIONS

1.1 *Honshu-Shikoku Bridges*

Japan consists of four major islands, i.e., Honshu, Hokkaido, Shikoku and Kyushu. The major island Honshu is connected with other islands by bridges or tunnels. Honshu and Shikoku are linked by Honshu-Shikoku Bridges (HSB) along three Expressways, consisting 17 long-span bridges, as shown in Figure 2. The Kobe-Awaji-Naruto Expressway including Akashi Kaikyo Bridge and Ohnaruto Bridge was constructed in two stages and finally completed in 1998. The Seto-Chuo Expressway including six double-deck long-span bridges for expressway and railway was opened in 1988 as the first route connected Honshu with Shikoku. The Nishi-Seto Expressway including the Tatara Bridge and Kurushima Kaikyo Bridges was constructed step by step basis and finally completed in 1999. Totally, 173 km long of the expressway are in service.

Figure 1. Location of Honshu-Shikoku Bridges in Japan

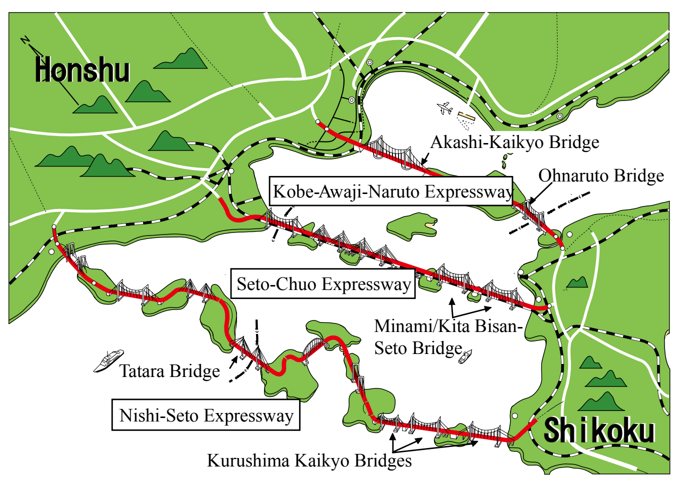


Figure 2. Outline of Honshu-Shikoku Bridges

In 2005, Honshu-Shikoku Bridge Expressway Company Limited (HSBE) was founded under the initiative of the government in order to take over Honshu-Shikoku Bridge Authority's business and to manage and operate the Honshu-Shikoku Expressways. The HSBE's object is to maintain the Honshu-Shikoku expressways healthy, to operate the traffic/transportation and thus to contribute to the economical development in the related regions.

1.2 *Seto-Ohashi Bridges*

Seto-Ohashi Bridges” is a nickname of a series of long-span bridges in the Seto-Chuo Expressway. The 9.4 km-long bridges are road-railway combined bridges and composed of six major bridges including three suspension bridges, two cable-stayed bridges and one truss bridge. All bridges accommodate 4-lane expressway on the upper deck and 2-railway track on the lower deck. The expressway is connected to the nationwide expressway network at both ends. The Seto-Ohashi railway line operated by JR-SHIKOKU is also connected to the existing railway network at both ends. The bridges are capable of loading additional two Shinkansen railway tracks.

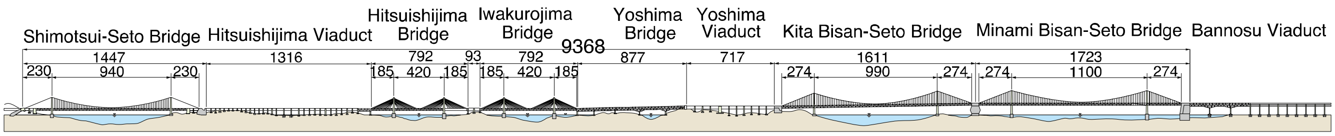
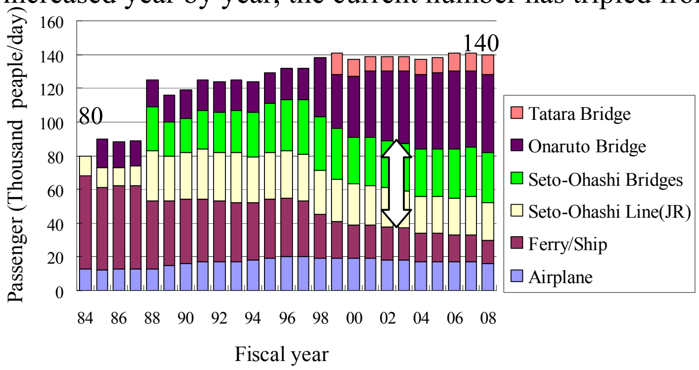


Figure 3. Side views of Seto-Ohashi Bridges

1.3 *Role of Seto-Ohashi Bridges in economy and life of the region*

The bridge has been playing an important role in national economy making transportation between two main islands, Honshu and Shikoku, smooth since it was opened. The current number of passengers crossing Seto Inland Sea has become 1.8 times more than that of 1984. As for Seto-Ohashi Bridges, it is the busiest route of the HSB in terms of number of passenger crossing Seto Inland Sea. Figure 5 shows number of vehicles and trains crossing Seto-Ohashi Bridges, the number of the vehicles has been increasing; even though there was temporary decreasing when other bridge was opened. In addition, as the number of the trains per day has been increased year by year, the current number has tripled from 1988.



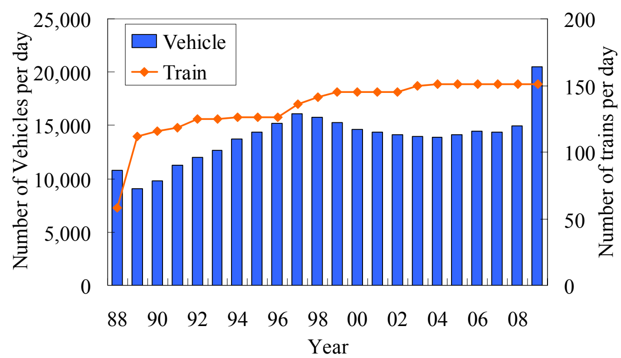


Figure 4. Number of passengers crossing Seto Inland Sea

Figure 5. Number of vehicles and trains across Seto-Ohashi Bridges

In addition to the transport function, the Seto-Ohashi bridges has a function of providing utility services by accommodating power supply cable, communication lines (optical fiber cable) and water supply pipe (for islander). HSBE has been keeping close contact with every utility operator about inspection or maintenance plan so that fixed inspection vehicles can be shard and no congestion in maintenance work may happen.

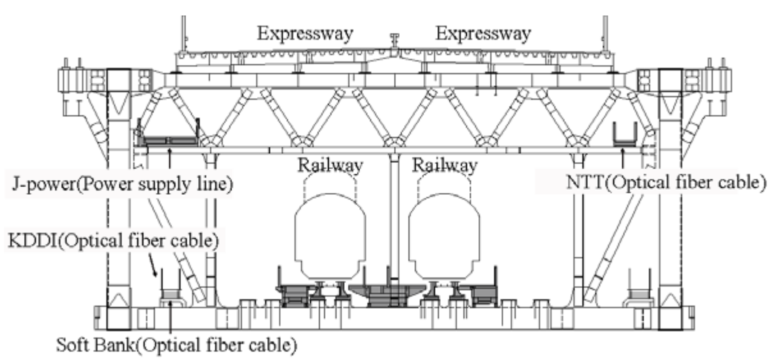


Figure 6. Functions and services on Seto-Ohashi Bridges

2 MAINTENANCE POLICY

2.1 *Preventive maintenance*

Adopting preventive maintenance is a key policy to ensure a 200 years of expected life span and minimize LCC since the bridges are situated in saline environment and exposed to harsh weather condition throughout the year and long term closure of any bridge would not be allowed due to absence of diversion.

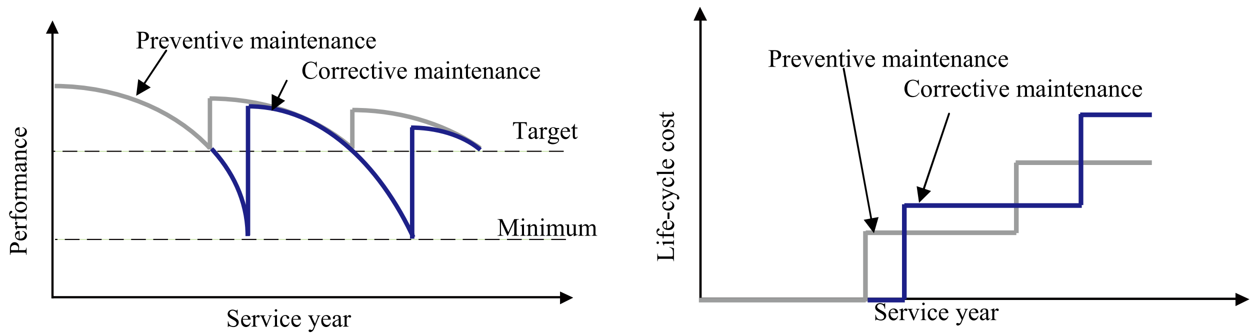


Figure 7. Conceptual drawing of preventive maintenance and life-cycle cost

2.2 *Inspection for long span bridges*

In conducting preventive maintenance, grasping degree of deterioration of a bridge as quantitative as possible is required. Therefore, inspections or investigations are key tasks in maintenance activities. In the course of preventive maintenance, making a decision on when and how to repair the identified damage is important. As Figure 7 shows, performance of a bridge must be recovered by taking appropriate repair measures before the deteriorating performance reaches the target level. Thus, the life span of the bridge can be ensured with less LCC than the case of adapting corrective maintenance.

On the HSB, the inspections for the long span bridges are classified as follows; 1) Patrol inspection, 2) Regular inspection, 3) Detail inspection, 4) Extraordinary inspection, 5) Special inspection. Patrol inspection is visual check to prevent falling incidents on daily basis. Regular inspection is visual check or touch check for structural members at intervals of one to two years. Detail inspection is conducted by measurement devices for bridge alignments and displacements at every five years. Extraordinary inspection is carried out immediate after natural disaster, such as typhoon, earthquake, heavy rainfall, etc.

2.3 *Patrol inspection*

Deteriorated highway structures have been occurred incidents of falling fragment frequently and have been drawing public attention. Securing safety of surroundings of the HSB as well as passengers on the HSB is the top priority for HSBE as the administrator of the bridges.

Therefore HSBE has been implementing "Patrol inspection" focused on preventing falling fragment incident. Above all, since as many as 151 trains per day are passing lower deck of Seto-Ohashi Bridges, HSBE has been emphasizing on reducing the risk that may be hidden in the upper deck or surrounding members by implementing patrol inspection daily basis.

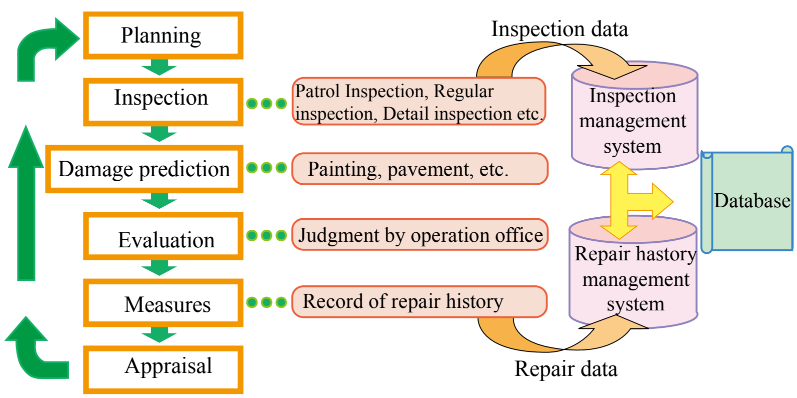


Figure 8. Cycle of "Preventive Maintenance"

2.4 *Inspection management system*

A specially developed data base for HSB comprising “Inspection Management System” and “Repair History System” helps HSBE to predict development of the damages and evaluate necessity of countermeasure as shown Figure 8. The data base has functions of accumulating inspection data and recording repair history.

2.5 *Maintenance vehicles for long-span bridges*

A large number of maintenance vehicles are in use for Seto-Ohashi Bridges to facilitate inspector or repair staff to approach bridge members. Structure of the vehicle differs depending on bridge type and position where the vehicle is set. U-shaped outside girder maintenance vehicle on steel truss girder covers three faces of the girder. The vehicle moves to the longitudinal direction, and an expansible stage moves in the transverse direction as well as in the vertical direction.

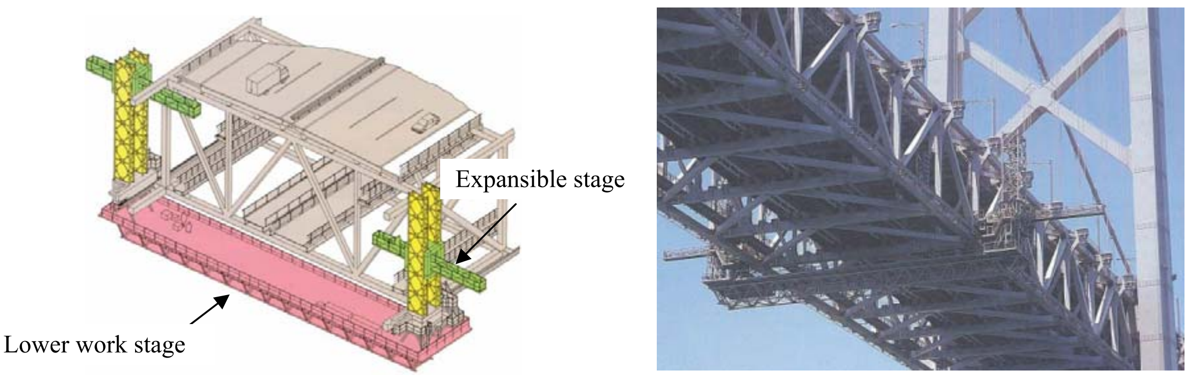


Figure 9. Outside girder maintenance vehicle for steel truss girder of suspension bridge and cable-stayed bridge

3 REPAINTING OF SUPER STRUCTURE

The painting area of external surface of the Seto-Ohashi Bridges is approximately 1,800,000m^2 and repainting work occupies a large portion of the maintenance cost. HSBE has been making an effort of reducing repainting cost by optimizing repainting schedule and using appropriate painting materials.

A heavy-duty coating system was adopted for the original coating of Seto-Ohashi Bridges intended to reduce repainting cost. Inorganic zinc-rich paint was used for the first layer of the coating system, epoxy resin paint was used for the third and forth layer, and polyurethane resin paint was used for the top coat.

Table 1. Composition of original coating for external surface of Seto-Ohashi Bridges.

Layer	Coating Material	Dry Thickness (μ m)
1st	Inorganic zinc-rich paint	75
2nd	Mist coat	--
3rd	Epoxy resin under coat	60
4th	Epoxy resin under coat	60
5th	Epoxy resin intermediate coat	30
6th	Polyurethane resin top coat	30
Total	----------	255

Inorganic zinc-rich paint used for the first layer and it contains high concentration of metallic zinc, which has a high rustproof property while the paint requires severe cleaning work of removing mill scale or others on the surface by blasting.

Therefore, repainting is implemented based on the following policy; 1) the inorganic zinc-rich paint and the epoxy resin under coats which protects the inorganic zinc-rich paint should be kept in a sound condition, 2) the top coat and the middle coat should be repainted before the epoxy resin under coat appears, 3) fluorine resin paint, which replaced the polyurethane resin paint for its high durability, is used for the top coat.

Table 2. Repainting composition for external surface of Seto-Ohashi Bridges.

Layer	Coating Material	Dry Thickness (μ m)
	Surface treatment	-
1st	Epoxy resin intermediate coat	30
2nd	Fluorine resin top coat	25
Total		55

3.1 *Periodic coat inspection*

Condition of the coating of HSB has been monitored at fixed points set on represemtative bridges at regular interbals to know when to starte repainting. Items to be cheacked at the inspection are as follows: thickness, grade of luster, adhesion. Coat thickness is a vital item in determining timing of repainting and measured with photograph of tiny paint samples taken by optical/scanning electron microscope.

Based on these results, exhaustion speed of the top coat and middle coat can be estimated and deterioration curve can be drawn. The deterioration curve shows beginning time of exhaustion of the under coat, which should be completion timing of repainting. So repainting works has to be started considered the timing and duration of repainting. Figure 11 shows repainting schedule for Seto-Ohashi Bridges. Thus repainting work started in 2006 and is scheduled to finish in 16 year.

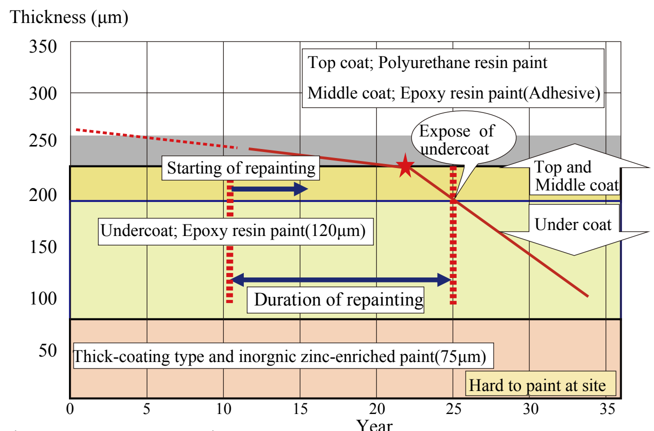


Figure 10. Coat aging curve

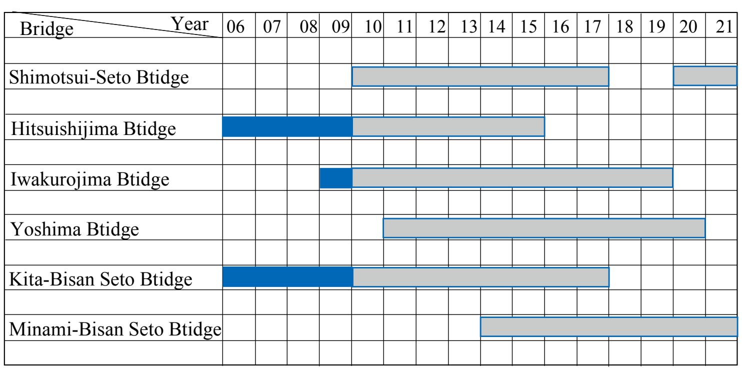


Figure 11. Repainting schedule of Seto-Ohashi Bridges

4 CONCRETE STRUCTURE

4.1 *Diagnostic test*

Diagnostic tests for the particular concrete structures have been added to the regular inspection items since 2001 to know condition of the concrete structures more quantitatively. Measurement items are: covering depth, chloride ion content, carbonation depth and electric potential of reinforcing bar. Development of chloride ion penetration and carbonation depth over 100 years of service life can be predicted based on this measurement and countermeasure can be determined.

Figure 12 shows distribution of chloride ion content by depth at 7A anchorage in Minami Bisan-Seto Bridge twenty-four years after completion and its prediction result in 100 years after completion. The prediction result indicates that chloride ion content would reach the corrosion limit (1.2 kg/m^3) at design covering depth (100 mm) in sixty two years after completion if no countermeasure is implemented.

Figure 13 shows prediction of chloride ion content by height at the south side of the 7A anchorage in one hundred years after completion at depth of 100mm from surface. The result indicates that countermeasure is required in the range of 5m to 35m above sea level.

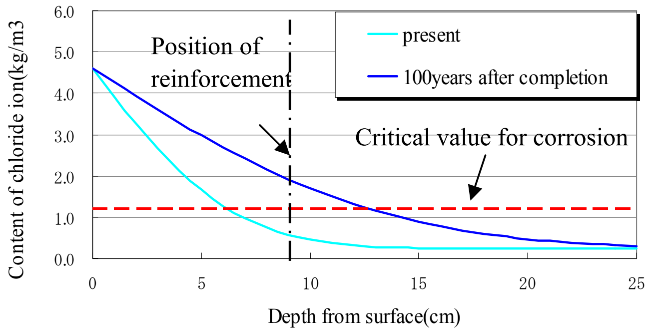


Figure 12. Prediction of chloride ion content by depth

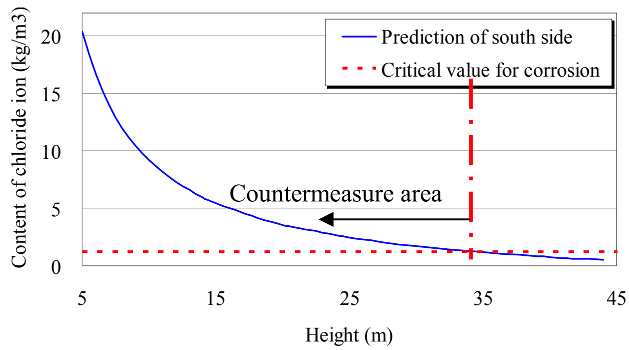


Figure 13. Prediction of chloride ion content by height

4.2 *Coating on mass concrete*

Based on the prediction result, coating works are in progress at selected area on mass concrete structure of Seto-Ohashi Bridges to prevent chloride damage and carbonation. As for the material of coating, acrylic urethane paint is adopted. After opening of Seto-Ohashi Bridges, the study on coating system for mass concrete started, aiming at finding the most suitable material. Several materials were used for trial basis. Finally acrylic urethane was selected as it showed the best performance in following movement of concrete crack. This coating was on experiment basis at the 7A anchorage of Minami Bisan-Seto Bridge.

After 20 years of the monitoring of the experimented coating, evaluation was curried out. The material that satisfied requirements was only urethane paint. Now, the acrylic urethane paint is used not only for mass concrete structure but also for waterproofing of pier of the concrete viaducts. The composition of the acrylic urethane paint is shown in Table 3.

Table 3. Coating composition for mass concrete.

Layer	Coating Material	Dry Thickness (μm)
1st	Epoxy resin type primer	--
2nd	Acrylic rubber type intermediate coat	
3rd	Acrylic rubber type intermediate coat	1,000
4th	Acrylic rubber type intermediate coat	
5th	Acrylic urethane type top coat	100
6th	Acrylic urethane type top coat	
Total		1,100

Photo 1. Anchorage of the Minami Bsan-Seto Bridge

5 INSPECTION ON FATIGUE OF STEEL STRUCTURE

Fatigue damage on steel member of HSB was an issue in the design and fabrication stage of the bridges, because millions of number of axle loading of the train was expected during the service life of the bridge and the bridges employ high-strength steel, which is sensitive to fatigue, to primary members.

After conducting a series of large-scale fatigue test, HSBE developed a welding methodology as well as a welding inspection system called "AUT: Automated Ultrasonic Testing system". As the AUT was effective in detecting welding defect in the factories, HSBE made several improvements on the system before HSBE started on-site AUT inspection in 1990 so that the system can be available to existing welding lines. There was no sign of crack progress as a result of 2 times inspection conducted by 2000. It was attributed to the fact that actual load of train is smaller than the design assumption.

Photo 2. Automated Ultrasonic Testing system

6 PROTECTION OF STEEL SHELL OF UNDERWATER FOUNDATION

6.1 *Electric deposit method for deep zone*

Underwater foundations of Seto-Ohasi Bridges were constructed by using “Laying-Down Caisson Method”, in which prefabricated large scale steel caissons were laid down on the seabed and pre-packed concrete was cast into the caisson afterward. No corrosion protection was made on the shell of the caisson because HSBE assumed that function of the caisson was a shuttering for underwater concrete and corrosion of the caisson would be no threat to integrity of the concrete because speed of corrosion would be slow compared with thickness of shell. However, a underwater survey to check condition of shell of a caisson conducted in 1990 revealed that remarkable pitting corrosion was developing at an alarming rate.

After conducting researches, HSBE decided to protect shell of caisson by using “Electric Deposit Method”. The method is an environment-friendly method in which natural substances in the sea are adhered to the shell and form a protection film. This method has advantages of free from underwater work and independent from tidal current.

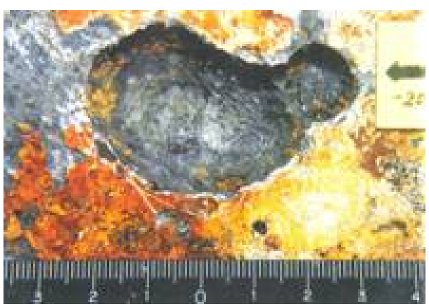


Photo 3. Pitting corrosion on steel shell

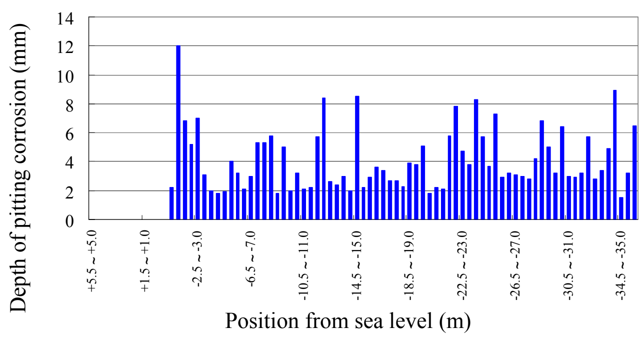


Figure 14. Maximum depth of pitting corrosions

In this method, faint electrical current of about 1A/m^2 between the anode placed in the sea and the cathode on the shell induces movement of substances and eventually form a deposit layer mainly composed of calcium carbonate and magnesium hydroxide as Figure 15 illustrates. This method was common as protection method for small structure in the sea. However, there was no application of this method to large scale structure, deep structure and structure in strong stream current.

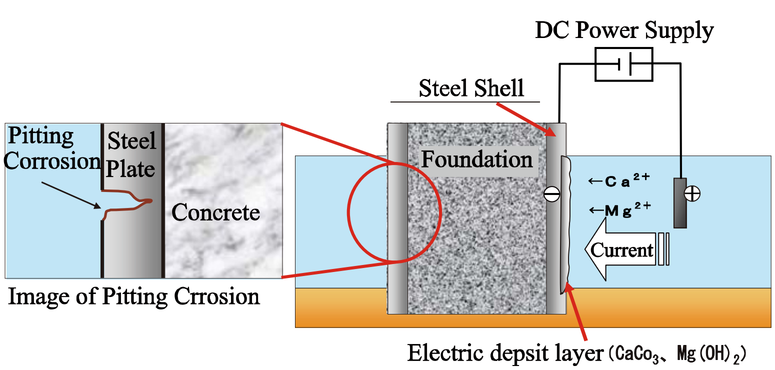


Figure 15. Image of “Electric Deposit Method”

Accordingly, several years were required before following subjects were cleared to put the method into practical use: 1) optimum arrangement of anode and cathode, 2) electric current intensity to obtain the electro-deposit with high waterproof, 3) necessary power supply time to obtain sufficient thickness of the layer, 4) effect of tidal current on forming the deposit. Protection work started in 1994. At present, deposit layers have been formed on the shell of three foundations. Power supply work is underway at a foundation.

Polarization resistance test is being used to evaluate corrosion protection performance of electric deposit method. This test result represents how much corrosion velocity of the shell is restrained by electric deposit. Polarization resistance was measured from both steel shells with electric deposit and without one.

Table 4 shows the result. The corrosion velocity of the without electric deposit is ranging from 0.1 to 0.3 mm/year, which is as almost same as the experienced value of underwater steel structure while the corrosion velocity of the shell with electric deposit is around 0.01 mm/year. As a result of this test the corrosion speed of the shell with electric deposit decreases to almost one-tenth, thus it is confirmed that electric deposit has a good corrosion protection performance sufficiently.

Table 4. Polarization resistance and estimated corrosion velocity

Case No.		Polarization Resistance ($\Omega \cdot m^2$)	Corrosion Velocity (mm/year)
With electric deposit	Test piece A	2.09	0.014
	Test piece B	2.28	0.013
	Test piece C	4.18	0.007
Without electric deposit	BB3P	0.30	0.10
	IB2P 1	0.12	0.25
	IB2P 2	0.25	0.12

*1 Test piece : taken from actual shell
*2 BB: Bisan Seto Bridge, IB: Iwakurojima Bridge

6.2 *Protection work on splash and tidal zone*

Splash and tidal zone is the most corrosive area of the steel shell. Photo 4 shows current situation of the splash zone at the 4A anchorage of Minami Bisan-Seto Bridge. The thickness of the shell at splash zone has decreased by 5mm (in average of particular area) from original thickness of 12mm. The protection work started in 2009, at the underwater foundations where the Electric Deposit Method had been completed. The coating area of slash and tidal zone is in the ranges from one meter below the sea level, which is top of the electric deposit, to the top of the steel shell.

Photo 4. The current situation of the splash zone of the steel caisson

A water hardening type epoxy resin putty was a candidate for the protection work while two difficulties must be before it was adopted to actual site; 1) the quality of coating relies on diver's skill, 2) sand blasting necessary for the coating affects the environment in the sea. In order to cope with this, HSBE has developed a new method and equipment called "Dry Box", which enables target coating area free from splash and tidal current.

Figure 16 shows the image of this system, and operation flow of this system is; 1) setting the Dry-Box at splash and tidal zone, 2) dry up (pump sea water up) inside Dry-Box, 3) blasting the shell, 4) coating the shell, 5) pour the sea water into Dry-Box, 6) remove the Dry-Box.

Coating works of the steel shell requires strict humidity control; humidity at steel surface after pumping of the sea water becomes almost 100%. Under this circumstance, wet type epoxy resin paint is suitable to secure quality of the coating and shorten work time. Compassion of this paint on splash and tidal zone is shown in Table 5, and composition of upper area of splash and tidal zone is shown in Table 6.

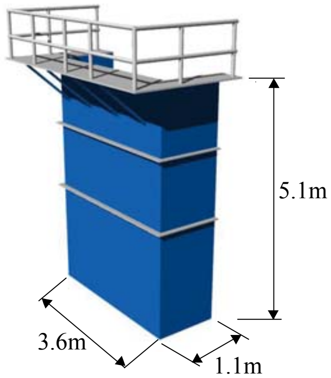


Figure 16. Image of "Dry Box"

Photo 5. Protection work by "Dry Box"

Table 5. Coating composition for the steel shell on splash and tidal zone

Layer	Coating Material	Dry Thickness (μ m)
1st	Wet type epoxy resin under coat	300
2nd	Wet type epoxy resin top coat	250
Total	----------	550

Table 6. Coating composition for the steel shell on upper area of splash and tidal zone

Layer	Coating Material	Dry Thickness (μ m)
1st	Wet type epoxy resin under coat	300
2nd	Wet type epoxy resin under coat	250
3rd	Epoxy resin intermediate coat	30
4th	Fluorocarbon resin finish coat	25
Total	----------	605

7 TRAFFIC MANEGEMENT

7.1 *Traffic control*

Traffic control is an essential activity in the operation of an important road. Generally, no diversion road can be operated for a long span bridge when a road is closed in case of severe weather, natural disaster like earthquake, or serious traffic accident. In this regard, traffic control utilizing monitoring equipments and deploying patrol teams are essential.

Photo 6. Graphic panel at traffic control center

Photo 7. Meteorological observation equipment

In the case of the Seto-Ohashi Bridge, HSBE equipped an efficient system to collect date on traffic conditions: traffic volume, speed of traffic flow etc., and weather conditions: intensity of rainfall, wind speed & direction, range of visibility, temperature of road surface. These data are quickly analyzed and appropriate measures are taken, by offering information to road users though the roadside LED information panels and highway broadcasting, etc.

In the case of emergency such as traffic accident or fire, HSBE cooperatively works with the highway police and fire departments.

7.2 *Security measures for cross wind*

Cross wind is one of the risk factors of traffic accident of Seto-Ohashi Bridges as the bridges structure high above sea level. Typhoon or depression induced strong cross wind sometimes overturns vehicle. In addition, a wind observation revealed that there were particular locations where cross wind is likely to be intensified in the approach viaduct. This wind was an impediment to the drivers.

According to that, windbreak fence was placed on the west side of the viaduct against seasonal dominant wind direction. The fence is made of polycarbonate board with 30-40% infilling ratio and 3m high. The board is transparent for a comfortable drive.

Photo 8. Windbreak fence on approach viaduct

8 CONCLUSION

Conclusions are as follows.

1) Preventive maintenance is the key policy in maintenance for Honshu-Shikoku Bridges to ensure 200 years of expected life span and minimize LCC. To ensure these maintenances, the HSBE do many measures such as, inspection procedure, use of various maintenance vehicles, together with efficient traffic control.

2) Repainting is a primary maintenance work and started before existing epoxy resin under coat appears. Periodic coat inspection provides an appropriate time to start repainting.

3) Diagnostic tests have shown necessity of coating for concrete structure, in terms of preventing chloride damage. Coating work using acrylic urethane paint is underway.

4) There is no sign of progress of fatigue damage of steel structure as the result of on-site AUT inspection.

5) The corrosion speed of the steel shell of the underwater foundations part has decreased to a one-tenth by operating the Electric Deposit Method.

6) In case of the coating works of foundation at splash and tidal zone, coating quality and shorting of work time were secured by using Dry Box.

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