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Special Features:

30-year Offshore Exposure Tests for Steel Structures

Lifecycle Design for Port and Harbor Steel Structures

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Report on Research Attainments of 30-year Offshore Exposure Tests

Steel products are the main construction materials for port and harbor facilities, but they have one shortcoming—corrosion. The marine environment is a severe site for steel product applications, where steel products are likely to corrode. Accordingly, in order to maintain offshore steel structures in sound condition over a long period, it is necessary to provide them with appropriate corrosion-protection measures.

The Japan Iron and Steel Federation jointly with the Public Works Research Institute has carried out long-term offshore exposure tests starting in 1982 at the Marine Engineering Research Facility located in Suruga Bay, off the coast of Shizuoka Prefecture. The main aim of these tests is to discern how to improve the durability of offshore steel structures, or how to prevent the corrosion of steel products from occurring when applied offshore.

In addition, another set of long-term offshore exposure tests have been carried out from 1984 at the Hazaki Oceanographical Research Station located in the open sea of Kashima-nada, off the coast of Ibaraki Prefecture. These tests have jointly been promoted by the Port and Airport Research Institute, the Coastal Development Institute of Technology and the Japanese Technical Association for Steel Pipe Piles and Sheet Piles with the aim of developing corrosion-protection technologies for steel pipe piles applied offshore.

Taking the opportunity presented by these two sets of exposure tests having passed 30 years since their start, a joint report meeting on the research attainments obtained in the exposure tests was held on February 16, 2016 in Tokyo.

An outline of these two tests is introduced on pages 2 to 9. ■

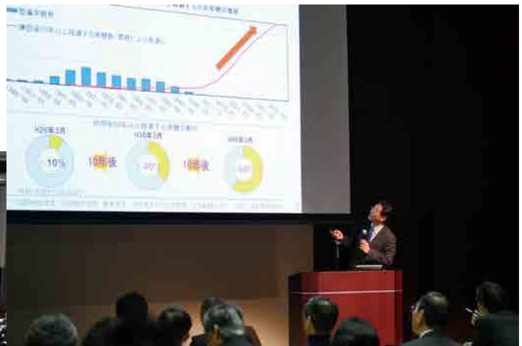

Joint report meeting on the research attainments obtained in the exposure tests

20th Symposium on Research on Civil Engineering Steel Structures

The Japan Iron and Steel Federation held its 20th Symposium on Research on Civil Engineering Steel Structures on February 26, 2016 in Tokyo. In 1995, JISF established a "subsidy system for steel-structure research and training" and since then has provided subsidies to researchers working in steel construction. The symposium has been held every year with the aim of publicizing the results of research, supported by the subsidy system, in the field of civil engineering steel structures while at the same time promoting the wider application of steel structures in the civil engineering field.

In the field of civil engineering structures, concerns are growing about deterioration in and the prolongation of the service life of existing and new port and harbor steel structures. To cope with this situation, a symposium titled "Initiatives for Establishing the Lifecycle Design of Port and Harbor Steel Structures" was organized and held, with the delivery of various lectures centered on the research attainments regarding long-term management technologies for port and harbor steel structures and their durability assessment. The symposium was successfully finished with the attendance of about 300 researchers and engineers.

The outlines of several of the lectures delivered at the symposium are introduced on pages 10 to 18. ■




20th Symposium on Research on Civil Engineering Steel Structures

Outline of Long-term Exposure Tests at Marine Engineering Research Facility in Suruga Bay

Iwao Sasaki: He has been studying application and durability of construction materials since fledgling researcher of PWRI Chemistry Division in 1989. B.Eng.: Tokyo University of Agriculture and Technology, Ms. International development studies: National Graduate Institute for Policy Studies, Dr.Eng.: Hokkaido University

by Iwao Sasaki
Public Works Research Institute

In Japan, diverse kinds of national land improvement plans have been worked out from the 1960s—such as straights-crossing highway projects and coastal preservation facilities. Most of these projects are located in severe corrosion environments in offshore and coastal areas, which requires the establishment of corrosion protection technologies in order to secure structural durability. The Public Works Research Institute (PWRI) has promoted from the 1960s atmospheric exposure tests for improving coating technologies for long-span bridges, and research on the corrosion characteristics of steel structures in splash, tidal, submerged and mud zones. Corrosion-protection methods for these structures were tested at a site within Tokyo Bay and at the Ajigaura and other sites in marine environments facing the Pacific Ocean.

Given this situation, comprehensive exposure tests for construction materials in Suruga Bay was planned. In 1983, "research on the effective utilization of offshore space employing offshore structures" was started and supported by Special Coordination Funds for Promoting Science and Technology of the Science and Technology Agency. Of the related research projects, the Chemistry Division of the Ministry of Construction (currently the Materials and Resources Research Group of PWRI) undertook "research on durability improvement technology for offshore structures by means of corrosion protection." The current exposure tests originated from this research project. PWRI has installed the Marine Engineering Research Facility (MERF) as an exposure test facility on the coast of Suruga Bay of Shizuoka Prefecture.

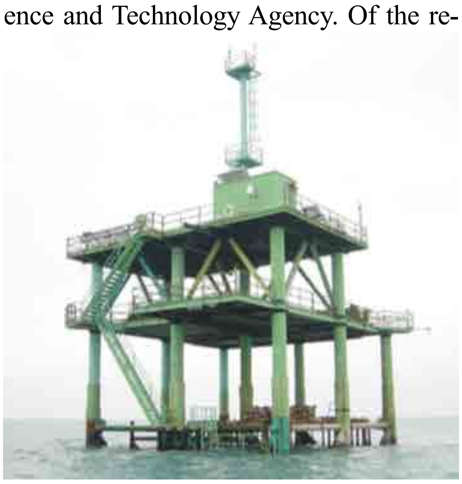
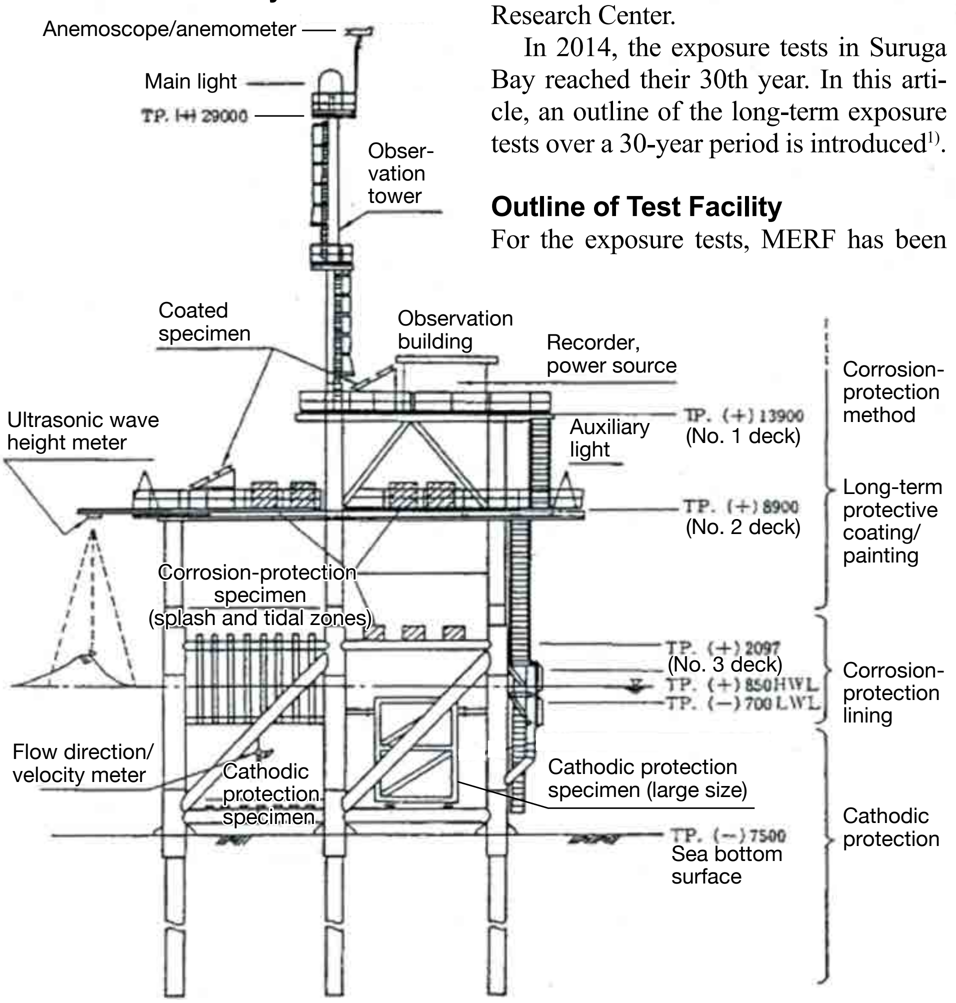


Photo 1 Full view of Marine Engineering Research Facility

Fig. 1 Outline of Marine Engineering Research Facility



Exposure tests employing MERF have been promoted as a cooperative project between PWRI and private organizations. The exposure tests for corrosion-protection technologies for steel structures installed in the splash, tidal and submerged zones have been promoted jointly with the Kozai Club (currently the Japan Iron and Steel Federation); that for concrete structures in the splash and tidal zones with the Japan Prestressed Concrete Contractors Association; and that for long-term protective coatings in an offshore atmospheric zone and cathodic protection design technology with the Public Works Research Center.

In 2014, the exposure tests in Suruga Bay reached their 30th year. In this article, an outline of the long-term exposure tests over a 30-year period is introduced[1].

Outline of Test Facility

For the exposure tests, MERF has been

adopted that is located in Suruga Bay facing the open sea of the Pacific Ocean. The testing site was selected as a representative coastal zone in Japan.

At MERF, exposure tests for corrosion-protective materials were conducted. Further, research relating to the prevention of coastal erosion was simultaneously conducted—offshore wind, wave and other marine conditions, phenomenon regarding the supply of sand to the coast, clarification of coastal deformation and drift sand phenomenon, and development of other coastal erosion preventive measures.

The location of the exposure test facility is 250 m off the Suruga coast in Suruga Bay with its commanding view of Mt. Fuji. Photo 1 shows an entire appearance of MERF. The facility is located outside the detached breakwater and is subjected directly to the waves of the open sea. It is installed in a high-wave area, including the surf zone, where the seabed sand undergoes great movement.

The MERF is built as shown in Fig. 1, with a steel-structure jacket installed on steel pipe piles supported by a sandy seabottom. The entire facility is targeted for corrosion-protection testing. The structure above the sea surface is composed of three decks, where large- to small-size test specimens are arranged. In its submerged area, steel pipe and sheet piles and cathodic protection test specimens can be installed. Its depth to the sea bottom is about 7.5 m, and its height to the top about 30 m. At the facility, material tests can be applied in wide corrosive environments ranging from the offshore atmospheric zone through splash and tidal zones to the submerged zone.

Corrosive Environments in Exposure Tests

Because MERF has been installed with the primary aim of conducting durability tests on construction materials, a corrosive environment has been selected that faces the open sea and is exposed to a large amount of airborne salts.

In ISO/TC156/WG4, internationally cooperative exposure tests were conducted in 49 areas of 13 countries over a span of 5 years starting in 1986. The main aim of the tests was to prepare a database that substantiates the standards. In Japan, a specialized research/survey committee was established to conduct the exposure tests at four locations in Suruga, Choshi, Okinawa and Tokyo.

In the surveys at MERF in Suruga Bay, various affecting factors were measured employing various measuring devices (ISO Wet Candle Method, JIS Gauze Method, PWRI-type Tank Method, etc.)—temperature, humidity, wetness duration (estimated from temperature and humidity), sulfur dioxide and airborne salt[2]. The environment surveys and survey results on the corrosion loss of steel products have made clear the relation between the corrosion factors and the distance from the sea surface and the weather conditions.

These survey results indicate that the current exposure test facility is designated as category C (High) in terms of environmental corrosivity in ISO's corrosion environment classification standard (ISO12944-2). Accordingly, it is accepted that the MERF can be utilized as a standard exposure site that is positioned as a corrosive environment from a global perspective.

Fig. 2 shows the survey results in FY1986~1989 and Fig. 3 shows those in FY2013~2015, both of which were obtained by means of the PWRI-type airborne salt collector (tank method). The amount of airborne salt falls in the range of 0.1 to several mg/dm²/d, excluding abnormal numerical values, which shows values consistent with the range of results in surveys in the Tokai area (covering Suruga Bay) among the nationwide surveys made by the Public

Fig. 2 Secular Change of Airborne Salt Amount by Means of PWRI-type Tank Method (Secular Changes of Past Survey Results: East and West Sides of No. 1 Deck)

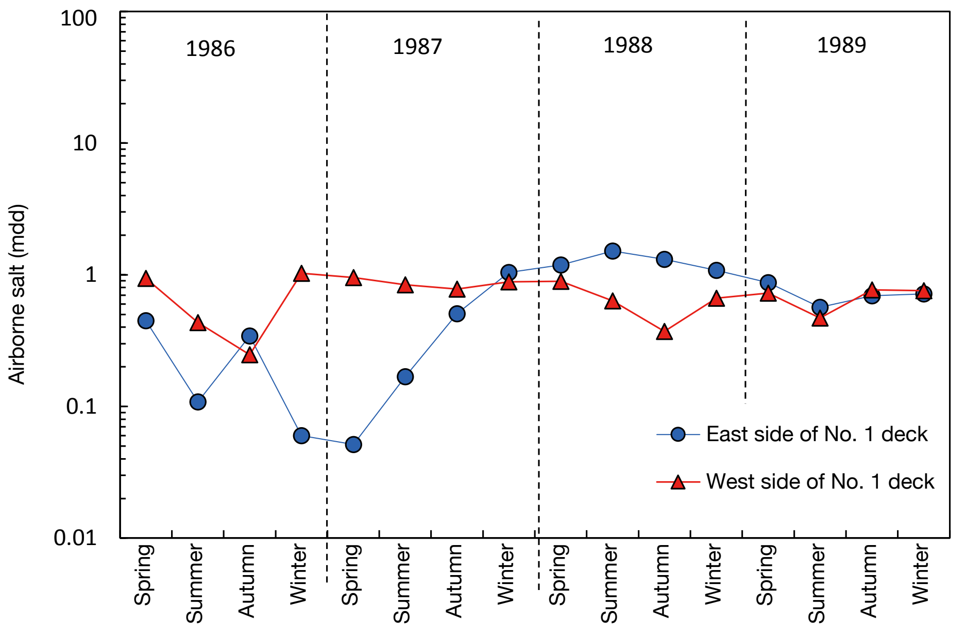
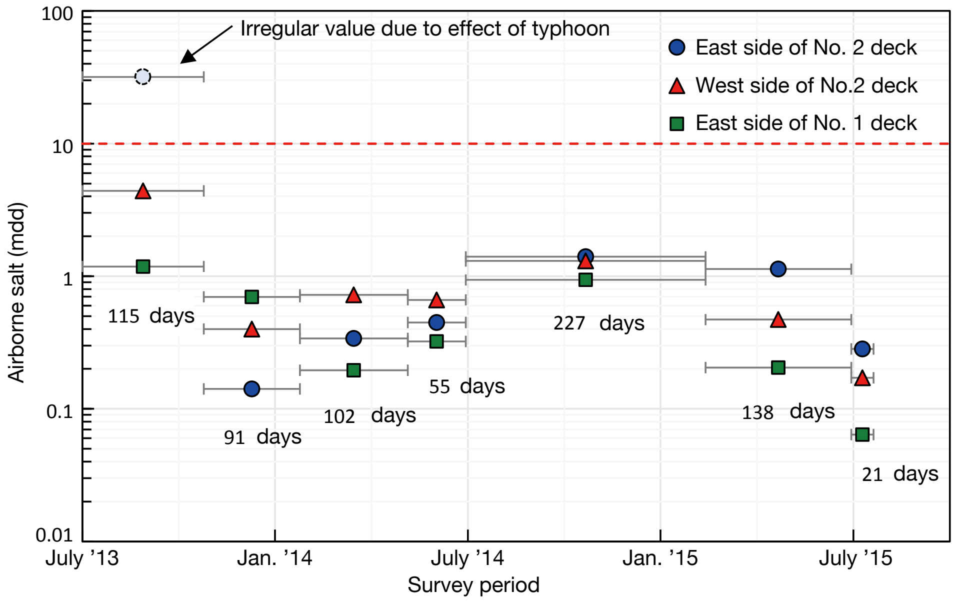


Fig. 3 Secular Change of Airborne Salt Amount by Means of PWRI-type Tank Method



Works Research Institute in the past[3].

In marine environments, the corrosive environment greatly differs depending on the vertical height from the sea surface. In past surveys made at MERF, it has been observed that the progress of deterioration differs depending on the deck used for the survey. The MERF has multiple decks in the vertical direction and thus comparative surveys of airborne salt environments are available.

Fig. 4 shows the effect of deck height from the sea surface on salt penetration obtained by means of the mortar thin plate method[4]. The level of salt penetration was highest in the No. 3 deck located about 2 m from the sea surface, fell as the deck height increases, and then showed a trend toward converging to nearly an identical level.

Research Fields and Main Test Materials

In the current research, exposure tests were applied mainly to steel and concrete structures, and various corrosion-protection methods for these structures were tested that employ highly corrosion-resistant metals, coating/painting and cathodic protection. Research fields and specific themes were settled by the corrosion-protection method, and the exposure tests and surveys were promoted as cooperative research projects among related organizations. (See Table 1)

Knowledge Obtained in the Exposure Tests and Future Prospects

In the long-term exposure tests thus conducted in Suruga Bay over 30 years, a rich store of knowledge has been obtained about corrosion-induced deterioration mechanisms and rates pertaining to not only conventional materials but also new materials.

In exposure tests for steel products with no corrosion-protection measures, it has been clarified that the corrosion rate differs depending on the exposure position and how the macro cell is formed, and at the same time it has been confirmed that the corrosion rate gradually reaches a constant level with the lapse of exposure time. As regards high corrosion-resistant metal protection, the effect of scratch damage in the tidal zone was clarified, and the combined application of corrosion-resistant metal and cathodic protection was indicated. In the corrosion protection by means of coatings, it has been confirmed that the improvement of the durability employing the zinc-rich paint-type primer coating was significant.

Continued exposure tests in the future will allow longer-term assessment of the durability of offshore structures, and the attainments obtained in the tests can be used for reference in assessing the expected durable years. Similar tests have been carried out in Okinotorishima and other sites where corrosion environments differ. It is considered that durability at diverse sites including those in the Asian block can be forecasted by comprehensively examining the exposure test results not only in Suruga Bay but at the other sites mentioned above.

We intend to promote continued examination aimed at the establishment of performance assessment approaches required for corrosion-protection methods for offshore steel and concrete structures and the performance forecasting approaches for the future. ■

Fig. 4 Effect of Height from Sea Surface on Airborne Salt Amount by Means of Mortar Thin Plate Method

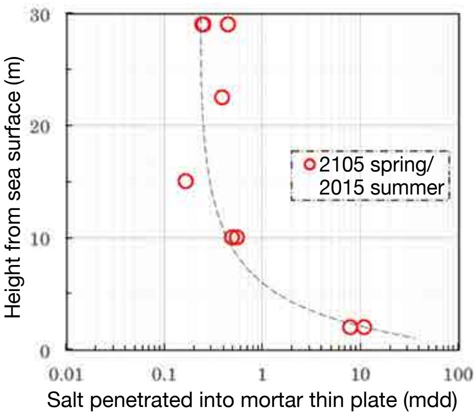


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Table 1 Research Fields and Themes, and Research Allotment

Research field	Specific research theme	Research allotment		
		1st WG	2nd WG	3rd WG
Research on corrosion-protection technology for steel structures in splash and tidal zones	1) Application test for corrosion-protection coating/painting materials (MERF structure) 2) Durability test for corrosion-protection coating/painting materials (test specimen)	A B B		
Research on corrosion-protection technology for concrete structures in splash zone	1) Corrosion-protection technology for steel product used in concrete 2) Development of design technology for seawater-resistant concrete member		A C A C	
Research on cathodic protection design technology in submerged zone	1) Development of cathodic protection design method according to structure shape 2) Development of combined coating-cathodic protection design technology			A D A D
Research on long-term protective coatings in marine atmospheric zone	1) Application test for long-term protective coating system 2) Durability test for long-term protective coating system			A D A D
Arrangement of research attainments		A B C D		

Research allotment:
A: Public Works Research Institute
B: The Japan Iron and Steel Federation
C: Japan Prestressed Concrete Contractors Association
D: Public Works Research Center

Long-term Exposure Tests for Steel Structures and Corrosion-protection Methods in Suruga Bay

by Kenichiro Imafuku
Steel Research Laboratories
Nippon Steel & Sumitomo Metal Corporation

Kenichiro Imafuku: After graduating from Department of Civil Engineering of Tohoku University in 1993, he entered Nippon Steel Corporation (currently Nippon Steel & Sumitomo Metal Corporation) and then was assigned to the company's Steel Research Laboratories. He assumed his current position as Senior Researcher, Materials Reliability Research Lab. Steel Research Laboratories in 2013.

In order to improve the durability of marine steel structures, the Japan Iron and Steel Federation and the Public Works Research Institute have jointly promoted long-term exposure tests for these structures. The main objective of the tests was to develop advanced corrosion-protection technologies for marine steel structures and to assess the long-term durability of these technologies. The tests were conducted employing Marine Engineering Research Facility located in Suruga Bay—250 m off the coast of Shizuoka Prefecture.

This article reports on the corrosion behavior of and the corrosion-protection technologies for marine steel structures, and the corrosion protection performance of these technologies and the care to be taken in their application, based on the results of long-term exposure tests over a maximum period of 30 years.

Kind of Exposure Test Specimens

In the current research, diverse kinds of steel product test specimens have been subjected to exposure tests in the marine environment extending from the splash zone to the submerged zone: steel products with no corrosion-protection measures, steel products covered with diverse kinds of highly corrosion-resistant metals, painted steel products, organic coated steel products and others.

Outline of Exposure Test Results

The exposure test conditions are shown in Photo 1, and the exposure test results are outlined in the following:

- **Steel Products with No Corrosion-protection Measures**

As a result of 19.5-year exposure tests for steel products with no corrosion-protection measures (140×140×18×3,800 mm), the following facts were confirmed:

—The corrosion rate becomes high in marine environment, particularly in the splash zone.

—The corrosion rate becomes somewhat low in the upper area of the tidal zone

Photo 1 Exposure test conditions

(main cause: in the tidal zone a large macro cell is formed in steel structures).

—The corrosion rate is low in the submerged zone (main cause: the supply of oxygen is less in the submerged zone than in the splash and tidal zones).

—The corrosion rate decreases with the passage of time, and gradually approaches a constant corrosion rate similar to that specified in the *Technical Standards and Commentaries for Port and Harbor Facilities in Japan*. (Refer to Figs. 1 and 2)

Fig. 1 Distribution of Depth-direction Corrosion (Ordinary Steel)

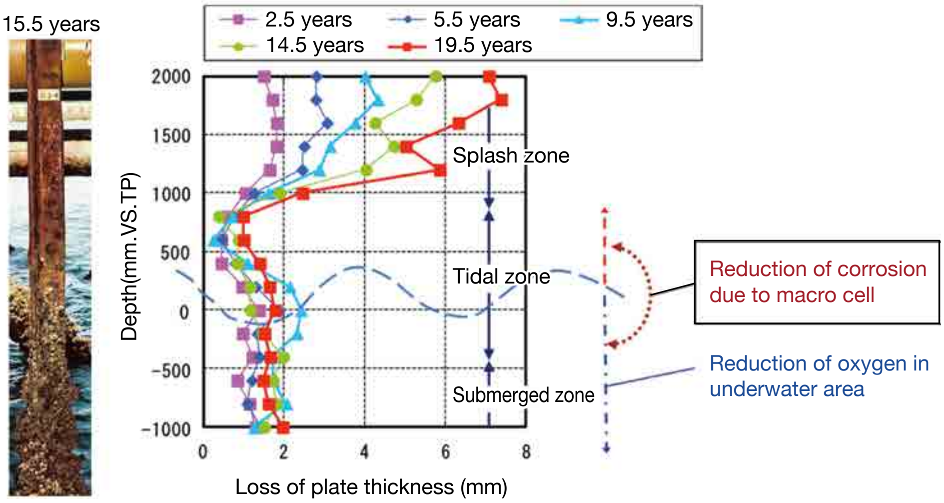
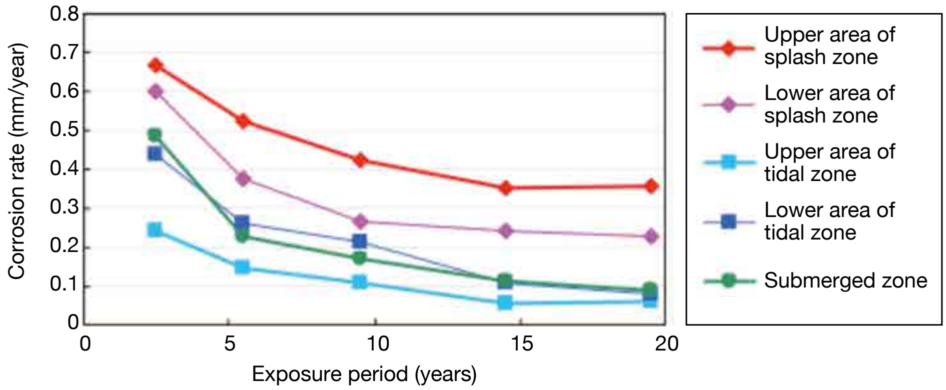


Fig. 2 Secular Change in Corrosion Rate by Marine Environment



- **Coated Steel Products (Common Painting, Thick-film Painting)**

In common painted steel products (inorganic zinc 25 μm+epoxy resin 600 μm), the corroded area increased in and after the 5th year in the tidal and submerged zones (Fig. 3). On the other hand, in the thick film-painted steel products (organic zinc-rich paint 15 μm+ultra-thick film-type epoxy resin 2,000 μm+fluorine 25 μm), it was confirmed that some corrosion occurred in damaged sections forecasted to be caused by driftwood, but painting film loss, cracking and other painting deteriorations were not observed, and the painting remained sound. (See Fig. 4)

- **Organic Coated Steel Products (Polyurethane, Polyethylene)**

No damage was observed in polyurethane coatings even after 23 years of exposure, and the coating remained in sound condition (Fig. 5). The normal part of polyethylene coatings also remained in sound condition even after 10 years of exposure, but in the scratch-damaged part (width: 1 mm, length 100 mm) that was artificially provided in advance, it was observed that corrosion occurred with a maximum plate thickness loss of 1.2 mm. As regards the section in which the damaged part was exposed for one year and then repaired by means of on-site deposition, sound conditions remained even after 9 years of exposure.

- **Highly Corrosion-resistant Stainless Steel Covering**

Observations were made of the corrosion conditions in highly corrosion-resistant stainless steel (Cr+3Mo+10N≥38 (mass%))-covered pipe to which cathodic protection was also applied. As a result, in the stainless steel-covered surfaces including the weld and weld-repaired sections, no corrosion was observed even after 10 years of exposure.

In the case where scratch-penetrated damage existed in the tidal zone, corrosion of the base metal of the steel pipe was not observed due to the effect of cathodic protection. On the other hand, in the case where scratch-penetrated damage existed in the splash zone, because the effect of cathodic protection did not extend to the splash zone, corrosion was observed in the base metal of the steel pipe (about 0.05 mm/y).

Further, when cathodic protection was not applied, corrosion (crevice corrosion) was observed in the gaps (specimen-fixed section) produced during installation of the specimen in the splash and submerged zones.

Based on the knowledge thus far obtained, a list was created of concerns regarding the marine environment when applying highly corrosion-resistant stainless steel covering protection, as shown in Table 1.

- **Titanium Covering**

In titanium-covered steel pipe after 29 years of exposure, while discoloration was observed in the splash zone, corrosion was not observed (Fig. 6). Even in the section below adhered organisms and gaps artificially produced by piling a titanium sheet on another titanium sheet, corrosion was not observed.

- **Other Corrosion-protection Methods**

In addition to the above corrosion-protection methods, the cupronickel, corrosion-protection cover method and the combined method by use of stainless steel, titanium or other materials were subjected to exposure testing, and it was confirmed that they offer long-term durability.

Exposure Tests Will Continue

Diverse kinds of corrosion-protection methods were subjected to long-term exposure tests, which led to the confirmation of their application effectiveness in a practical marine environment. Plans call for continued exposure tests for highly corrosion-resistant metal-type protection methods that are expected to offer long-term durability. ■

Fig. 3 Appearance of Common Painted Steel Products after Rust Removal (top: 5-year exposure; bottom: 19.5-year exposure)

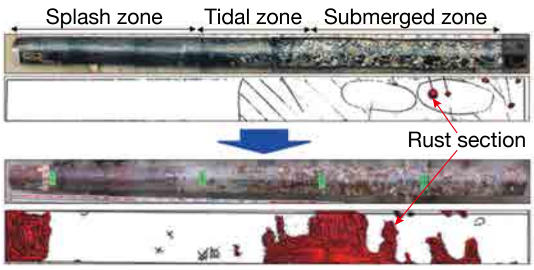


Fig. 4 Appearance of Thick Film-type Painted Steel Products (19.5-year Exposure)

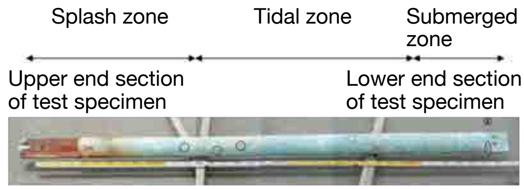


Fig. 5 Appearance of Polyurethane Coating after Rust Removal (23-year Exposure)

Table 1 Cares in Application of Highly Corrosion-resistant Stainless Steel Covering Protection Method

Corrosion-protection method	Highly corrosion-resistant stainless steel cover (Cr+3Mo+10N≥38 (mass%))		
	Combined use of cathodic protection (about −770~−1000 mV (vs. SCE))		
Section / Environment	Weld	Damage-penetrated section	Gap section
Splash zone	Weld-repaired section		
Tidal zone	Selection of appropriate welding material and implementation of appropriate welding	Repair is necessary	No production of gap in specimen installation
Submerged zone		Cathodic protection is effective	Cathodic protection is effective

Fig. 6 Appearance of Titanium-covered Steel Pipe after Shell Removal (29-year Exposure)

Long-term Offshore Exposure Tests for Corrosion-protection Methods for Steel Pipe Piles at HORS

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by Toru Yamaji, Materials Group
Port and Airport Research Institute

Steel products are an important construction material used in improving infrastructure facilities, and are extensively used for port/harbor facilities and offshore structures. Meanwhile, when steel products are left without corrosion-protection measures for long periods, cases arise in which the durability of these steel-structure facilities is impaired due to corrosion of the steel, which causes a deterioration of their safety and function. Accordingly, in order to maintain soundness over long periods in steel structures, particularly those in an offshore environment, it is necessary to take appropriate corrosion-protection measures.

Given such conditions, the Port and Airport Research Institute, the Coastal Development Institute of Technology and the Japanese Technical Association for Steel Pipe Piles and Sheet Piles jointly started in 1984 field tests in which various corrosion-protection methods have been applied to the steel pipe piles of a practical steel structure located offshore. The main aim of this test is to examine corrosion-protection methods that can be expected to offer long-term corrosion-protection performance. In 2014, the field test reached its 30th year.

This article introduces an outline of the results of this 30-year, long-term offshore exposure testing[1)].

Photo 1 Full view of Hazaki Oceanographical Research Station

Outline of the Exposure Test Site

For these field tests, the Hazaki Oceanographical Research Station (HORS), which is located in the open sea at Kashima-nada in Ibaraki Prefecture, has been used (Photo 1). The Kashima-nada open sea area is a high-wave area, including the surf zone, where the seabed sand undergoes great movement. Because high waves and rapid tidal currents work directly on the pier of HORS, the site is exposed to an extremely severe environment and serves as an excellent test field for corrosion-protection methods.

In HORS, a concrete superstructure sits upon steel pipe piles that are 600~800 mm in diameter and upon which prestressed concrete girders are placed (Fig. 1). The total length of the pier is 427 m and 47 steel pipe piles have been driven. The field tests have been conducted by applying various corrosion-protection methods to these pipe piles.

Corrosion-protection Methods Applied in the Field Tests

The corrosion-protection methods applied for the field tests are roughly classified into the following five types: organic coatings, inorganic coatings, petrolatum coating, painting and cathodic protection. The main features of each method are as follows.

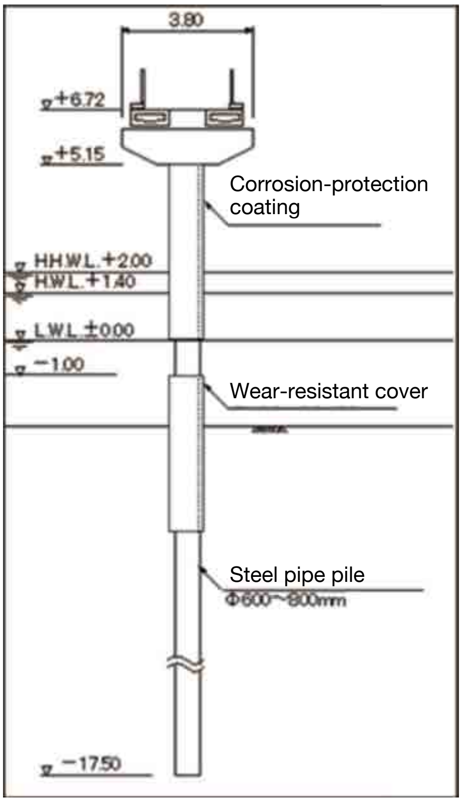
• Organic Coating Method

The organic coating method is a corrosion-protection method in which the surfaces of steel products are coated with polyethylene, an underwater cured-type material or other organic materials. The common coating thickness is 2~10 mm, which is heavier than the thickness applied in painting.

The polyethylene coating method has excellent durability, seawater corrosion resistance and atmospheric corrosion resistance. It is applied for newly-installed structures. (See Photo 2)

In underwater cured-type coatings, an underwater cured-type paint is applied to the surface of steel products to form a

Fig. 1 Example of Sections of Hazaki Oceanographical Research Station



thick coating. This application is effective even as a repair method. (See Photo 3)

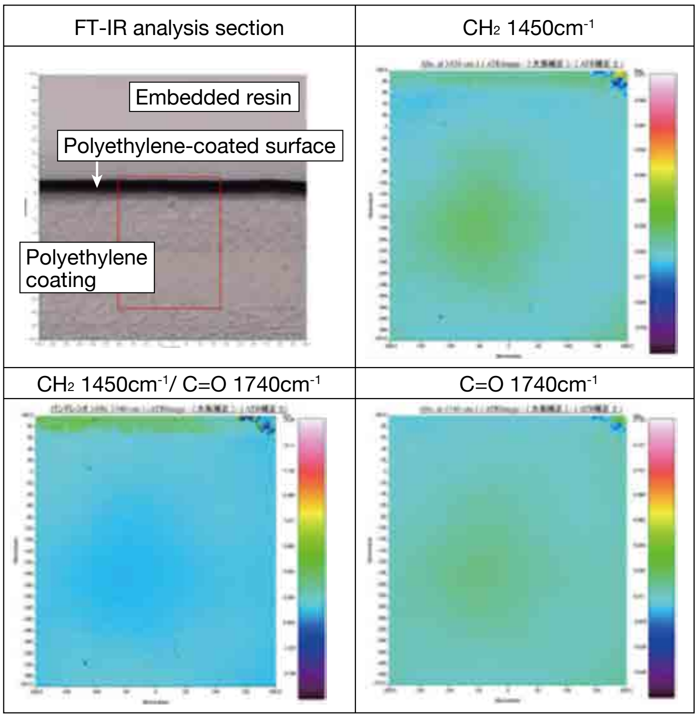
• Inorganic Coating Method

The inorganic coating method is a corrosion-protection method in which the surfaces of steel products are coated with cement mortar, reinforced concrete or other inorganic materials, including metals. The steel product surfaces are protected from corrosion by the dense, passive film formed on the steel surfaces due to the alkalinity possessed by the cement mortar or concrete.

Photo 2 Polyethylene coating (black section: polyethylene)

Photo 3 Underwater cured-type coating (coating of putty-state coat)

Fig. 2 FT-IR Analysis Results of Polyethylene-coated Surface



• Petrolatum Coating Method

The petrolatum coating method is a corrosion-protection method that combines the use of a corrosion-protection material that is composed of petrolatum (a kind of petroleum-based wax) and the cover that protects the corrosion-protection material. It is a highly reliable corrosion-protection method having a rich application record.

• Painting Method

The painting method is a corrosion-protection method in which the steel surface substrate is coated first with a zinc-rich primer (zinc powder-containing paint) and then with a liquid or semi-liquid paint. It has an extensive application record.

Among the paints adopted in typical painting methods in the field tests are extra heavy, thick film-type epoxy resin paint, glass flake epoxy resin paint and tar-epoxy resin paint.

• Cathodic Protection Method

The cathodic protection systems are roughly classified into galvanic anode system and impressed current system. The mainstream method currently adopted for port and harbor steel structures is the galvanic anode system.

In the galvanic anode system, a metal that is less noble than the steel product is electrically connected to the steel product, and a corrosion-protection current is supplied to the steel product by means of cell action that utilizes the electrical potential difference between the metal and the steel product. In terms of practical application, cathodic protection becomes feasible when the electric potential of a steel product surface is lower than −780 mV with the reference to silver-silver chloride-seawater electrode.

Survey Results after 30-year Exposure Tests

• Organic Coating Methods

—Polyethylene coating

It was confirmed that the polyethylene coating method has been effective over 30 years of the corrosion-protection testing. In the FT-IR (Fourier transform infrared spectrometer) test, nearly no ultraviolet ray-induced deterioration was observed (Fig. 2). Further, the insulation resistance shows no problems pertaining to the corrosion-protection performance, and it is assumed that the polyethylene coating will provide durability over the long term well into the future.

It was also confirmed that volume resistivity (calculated from the insulation resistance) is useful as an indicator in assessing the corrosion-protection performance of polyethylene coating.

—Underwater cured-type coating

When 20 years had passed since the start of the test, the underwater cured-type coating showed favorable corrosion-protection performance. However, after 30 years, some degradation was becoming outwardly apparent in the coating. Further, it was confirmed that the coating performance had clearly fallen in terms of insulation performance and the penetration depth of chloride ions.

It was confirmed that the insulation resistance and the penetration depth of chloride ions are useful as an indicator in assessing the performance of underwater-cured type coatings.

• Inorganic Coating Method

It was confirmed that after 30 years the concrete coating method not only showed no degradation in its outward appearance but maintained favorable corrosion-protection performance (Photo 4). Mean-

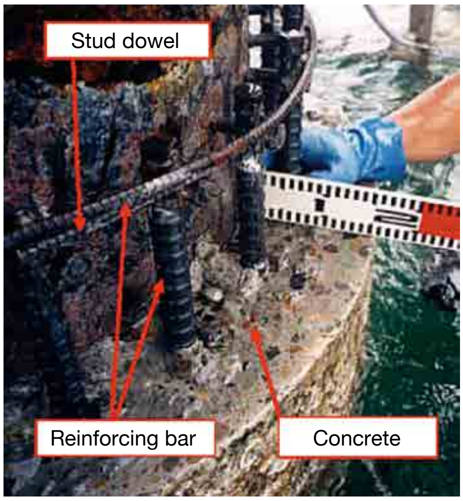


Photo 4 Internal structure of concrete coating

while, in the concrete coating exposed in the submerged and tidal zones, there was no remarkable corrosion even when chloride ions accumulated in high densities at the surface of the steel product or, further, when penetration of chloride ions from the interface of steel products was found. These two survey results suggest that it is difficult to forecast when corrosion of steel products due to the penetration of chloride ions will occur.

As far as an approach to forecasting the deterioration of concrete coatings is concerned, it will be necessary to conduct further examinations in the future.

• Petrolatum Coating Method

The corrosion-protection condition of the petrolatum coating method after a lapse of 30 years showed that, while the protective cover was in a nearly sound state, deterioration was confirmed of the bolts and other accessary members used to affix the protective cover (Photo 5).

The oil residual ratio is commonly applied as an indicator in assessing the performance of the petrolatum coating method. However, the accuracy of measurements employing the oil residual ratio is not so high, and it was reconfirmed that there are deterioration factors other than those found by use of the oil residual ratio, and many tasks remain pertaining to the appropriate performance assessment of the petrolatum coating method. In the future, it will be necessary to conduct further examinations of the deterioration mechanism of the petrolatum coating method to establish an appropriate approach to assess the performance of the method.

Photo 5 Appearance of protective cover of petrolatum coating method

• Painting Method

Examinations were made mainly on extra heavy, thick film-type epoxy resin paints. While the outward appearance of the painting method was sound after a lapse of 30 years, it was confirmed that salt gradually penetrated into the paint film to cause a gradual lowering of the film's corrosion-protection performance.

It was confirmed that impedance is useful as an indicator in assessing the performance of various painting methods (Photo 6).

• Cathodic Protection Method

In surveying the common galvanic anode system of the cathodic protection method, it was shown that the period of anode consumption can more quickly be forecasted by subdividing the deterioration judgement criteria from the current 2 levels to more levels. However, as regards the threshold value, it is necessary to cautiously settle it.

Further, examinations were made on the method to affix galvanic anodes to steel products employing magnets, and this showed that no anodes had fallen off after a lapse of 5 years since affixing them and that a favorable corrosion-protection condition was kept (Photo 7). However, because there are cases in which the electric potential fluctuates due to the effect of waves, it will be necessary to implement longer-term observation of the progress condition.

Photo 6 Impedance measurement for painting method

Photo 7 Magnet at anode-affixed section in cathodic protection method

Useful Results from Long-term Exposure Tests

Our survey of long-term offshore exposure tests for steel pipe piles shows that there exist many corrosion-protection methods that have demonstrated sure corrosion-protection performance over a 30-year period. It will become possible by continuing the exposure tests in the future to assess the longer-term durability of corrosion-protection methods applied offshore. At the same time, the attainments thus obtained will serve as reference points in assessing the expected durability of corrosion-protection methods.

The approach to assessing the performance of the different corrosion-protection methods are classified into two: approaches by which parameters could be extracted that can serve as indicators of performance assessment; and other approaches where there currently remain many tasks. Towards the establishment of approaches to assess the performance required for coating corrosion-protection methods and the establishment of methods to forecast the future corrosion-protection performance of the different methods, we will promote continuing examinations in the future. ■

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Port and Harbor Administration in Japan: Maintenance and Management of Port and Harbor Facilities

by Isao Sakai, Ports and Harbors Bureau
Ministry of Land, Infrastructure, Transport and Tourism

Isao Sakai: After finishing the master's course of School of Engineering, The University of Tokyo, he entered the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) in 1992. In 2010, he served as Director, Port and Airport Research Institute. He assumed his current position as Director, Engineering Administration Office, Engineering Planning Division, Ports and Harbors Bureau, MLIT in 2016.

For Japan, a country surrounded on all sides by the sea and where the population and properties are accumulated in coastal areas, it is the ports and harbors that support the distribution of goods and the flow of people as nodal points for both marine and land transport. Also, ports and harbors provide the international infrastructure that are indispensable in handling the export and import of most of the goods and materials that are required for the daily life of the people and are demanded by the manufacturing industry, the basis of the Japanese economy.

For these ports and harbors, new demands are arising. One is to structure efficient and stable transport networks, in the global market, that are connected to foreign ports and harbors in order to secure the competitiveness of enterprises operating in Japan. Another is to strengthen the competitiveness of all industries operating in Japan by enhancing their international logistics efficiency in order to create new jobs and incomes.

In such situations, there is a rapidly increasing number of port and harbor facilities in Japan that have seen 50 years pass since their construction, and thus it is important now to put into effect appropriate facility maintenance and management that take into account the entire port/harbor stock management in Japan.

In the following, diverse measures are introduced that are being promoted for the maintenance and management of port/harbor facilities in Japan.

Management Entities for Ports and Harbors and Their Facilities in Japan

• Role and Kind of Ports

The ports and harbors of Japan are classified into the following four kinds: "International Container Hub Port" that places priority importance on the strengthening of international competitiveness as the hub of international marine container transport; "International Hub Port" that serves as the hub of international marine cargo transport networks; "Major Port" that serves as the hub of marine transport networks and that have important relations with national interests; and local ports other than those mentioned above. The number of these ports and harbors in Japan totals 933. (See Table 1)

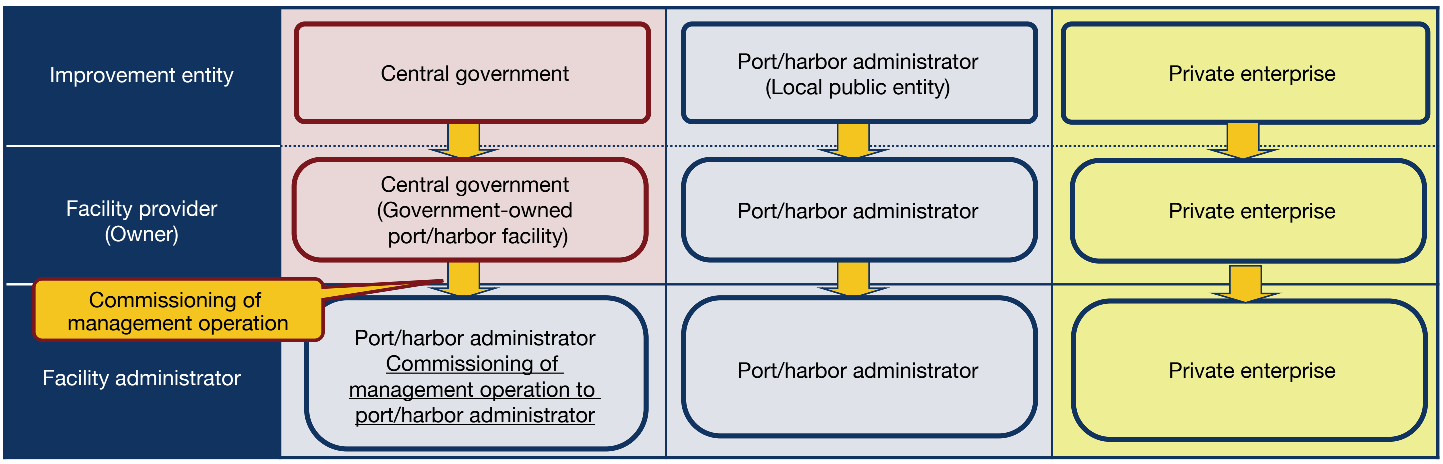
Table 1 Kind and Number of Ports in Japan

Kind	Number
International Container Hub Port	5
International Hub Port	18
Major Port	102
Local ports	808
Total	933

• Improvement and Management Entities for Port and Harbor Facilities

The core facilities of ports and harbors are classified into two types: public facilities that are improved and managed for public use by the central government and port/harbor administrators (local public entities); and private facilities that are improved and managed for the exclusive use of private enterprises. In basic practice, the management of port and harbor facilities to be improved by the central government is commissioned to the port and harbor administrator, who manages the public facilities in a bulk system. (Refer to Fig. 1)

Fig. 1 Improvement and Management Entities of Ports and Harbor Facilities



Superannuating Port and Harbor Facilities and Their Preventive Maintenance

• Increase of Superannuating Facilities

Port and harbor facilities in Japan were improved along with the growth of the Japanese economy. Most of these facilities were constructed during the period from the 1970s to the 1980s, and have played an important role as basic infrastructure for economic growth and physical distribution in Japan.

On the other hand, these facilities are becoming superannuated. To illustrate using wharfs that play a basic role in port and harbor facilities: of about 5,000 public wharfs nationwide with water depths of 4.5 m or less, those that have seen 50 years or more pass since their construction will rapidly increase from about 10% of the total in March 2014 to about 60% in March 2034, as shown in Fig. 2.

• Preventive Maintenance

For these rapidly superannuating port and harbor facilities, it will be necessary in planning appropriate maintenance to attempt to reduce the lifecycle costs while simultaneously securing stable facility functions. To attain this goal, it will be necessary to further promote preventive maintenance and renewal that will account for the prolongation of service life and the reduction of lifecycle costs, rather than corrective maintenance in which response measures are not taken until the renewal period. (Refer to Fig. 3)

Mechanism of Maintenance of Port and Harbor Facilities

• Maintenance Cycle for Port and Harbor Facilities

The objective of maintaining port and harbor facilities is that the required performances be satisfied over a specific in-service period. For that purpose, it is necessary to systematically conduct inspections, diagnoses and repairs, while at the same time closely monitoring the in-service period.

Specifically, port and harbor facility maintenance is carried out in the maintenance cycle shown in Fig. 4. In order to appropriately proceed with this maintenance cycle, related laws have been prepared and various guidelines have also been prepared that are useful in working

Fig. 2 Ratio of Public Wharfs with Water Depth of 4.5 m or Deeper and Pass of 50 Years since Start of Service to Total Wharfs

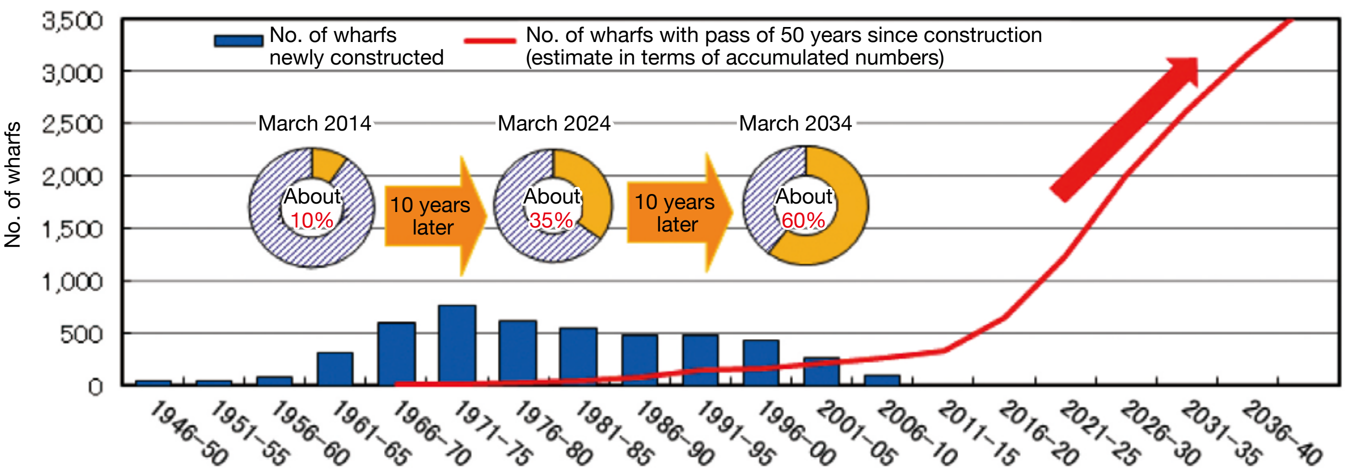
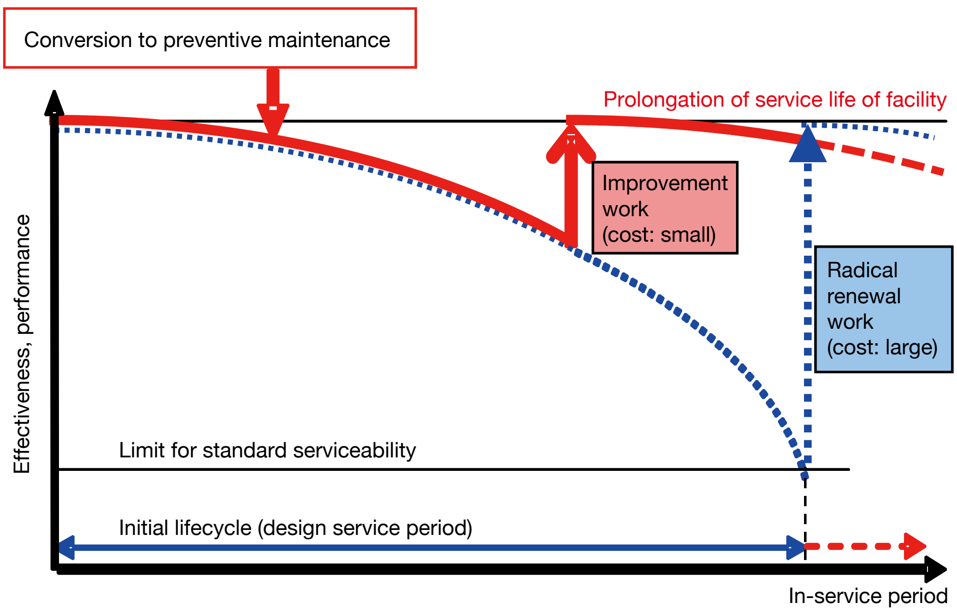


Fig. 3 Image of Preventive Maintenance



out maintenance/management plans and conducting inspections and diagnoses.

- **Maintenance Plans by Facility and Stock Management by Port and Harbor**

The maintenance of port and harbor facilities consists of two wheels: maintenance plans required to appropriately conduct maintenance by facility, and preventive maintenance plans required to strategically manage the facility stock by port and harbor (Fig. 5).

In preventive maintenance plans worked out by port and harbor, the priorities in the maintenance and renewal of each facility are determined based on the maintenance plans worked out by facility, and the expense required for the maintenance of each facility is leveled. Another role of preventive maintenance plans is to strategically promote stock management by port and harbor, such as facility integration, application changes and qualitative improvements, in conformity with emerging changes in social and economic situations. ■

Fig. 4 Maintenance Cycle for Port/harbor Facilities

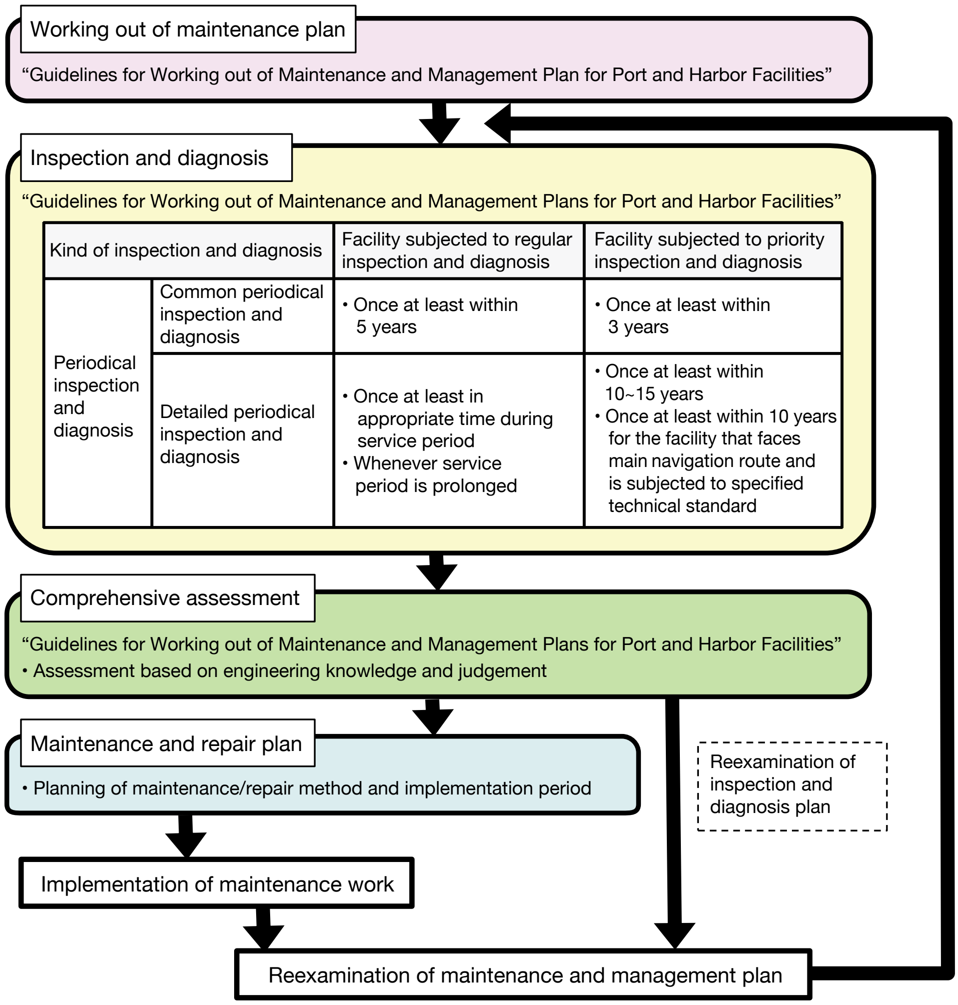
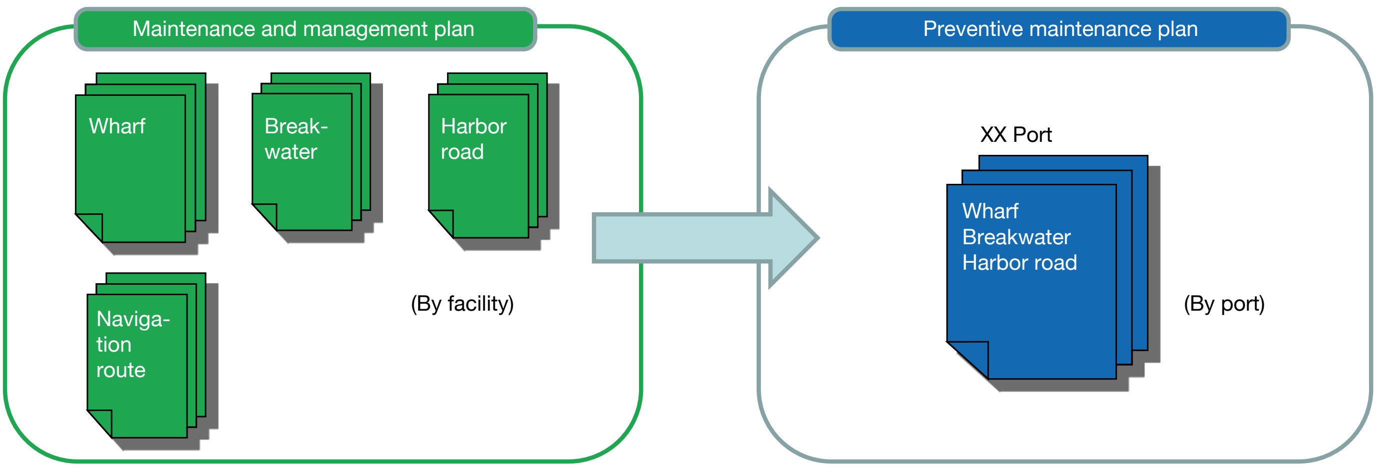


Fig. 5 Maintenance/Management Plan and Preventive Maintenance Plan



Plan	Maintenance and management plan	Preventive maintenance plan
Plan unit	By each facility	By each port and harbor
Objective	To contribute towards promotion of appropriate maintenance and management (inspection, maintenance, etc.) by each facility	To contribute towards planned implementation of countermeasure against superannuation by each port and harbor
Plan content	Working out of basic concept for facility maintenance and management, planned and appropriate inspection and diagnosis of relevant facility and their implementation period, maintenance content and its implementation period	Working out of countermeasure against superannuation and prioritizing of implementation of countermeasure depending on importance level of facility by taking superannuation and application condition for respective facility into consideration

Structure Design System under the Concept of Life-Cycle Management

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Introduction

A structure has been adequately planned and designed to keep its structural performance over respective requirements throughout its life-cycle. However, serious deterioration of structural members may be caused due to various reasons. To meet these facts, it is extremely important to pursue coordination between design and maintenance. The life-cycle management is an organized system to support engineering-based decision making for ensuring sufficient structural performance and long life of a structure at the design, maintenance, and all related work during its life-cycle[1]. This article deals with structural design system under the concept of life-cycle management.

Life-Cycle Management

The service life of a structure is made up of all the activities, which includes planning, basic (conceptual) and detailed designs, execution, maintenance and repair, and decommissioning. The life-cycle management is an integrated concept to assist in activities managing the total life-cycle of structures based on managements of each stage to ensure structural functions and performance and to realize sustainability as shown in Fig. 1. In other words, the life-cycle management can provide an overall strategy to be used in ensuring that a structure meets the associated performance requirements defined at the time of design or as may be subsequently modified. Figure 2[2] shows the PDCA cycle that is a key procedure of the life-cycle management. The PDCA cycle is implemented based on the data collected at the maintenance stage. For maintenance procedure, it is important to identify the mismatch or difference of design assumption and real situation (Check), which may be applied for improvements on future maintenance, design and/or execution methods (Action). During that process, the output from the system can be fed back to planning, design, and/or execution stage(s) if necessary. Therefore, it can be said that mainte-nance data should be of very importance.

Service Life Design

The fundamental concept on how the structural performance should be ensured must be well considered based on conditions, design service life, structural characteristics, material properties, difficulties in assessment and remedial action, social and economic importance, etc. During the initial design stage, the service life (durability) design will be applied to predict the performance degradation. Specific methodologies on the service life design for structures are based on the concept of a fully probabilistic approach, a partial safety factor approach, a deemed-to-satisfy approach, and an avoidance deterioration approach.

For steel structures, corrosion of steel is a principal cause of performance degradation to be considered at the initial design. Accordingly, corrosion of steel itself and/or deterioration of a corrosion protection system should be fully taken into account. Prediction at the design stage is done based on theoretical models or specific values determined by investigating existing structures or experimental findings. When the fully probabilistic approach is taken, all the design parameters should be modelled with probability functions. An example showing changes in failure probability over time due to corrosion of steel has been provided in some references[1)3)]. Otherwise, corrosion protection has been generally applied as an avoidance of deterioration approach such as surface covering and cathodic protection. Under that approach, deterioration models for corrosion protection should be considered for the service life design.

Serious deterioration may be caused by insufficient durability design with optimistic assumptions against materials deterioration and by lack of proper maintenance after construction of the structure.

Fig. 1 Life-Cycle of Structure and Its Management

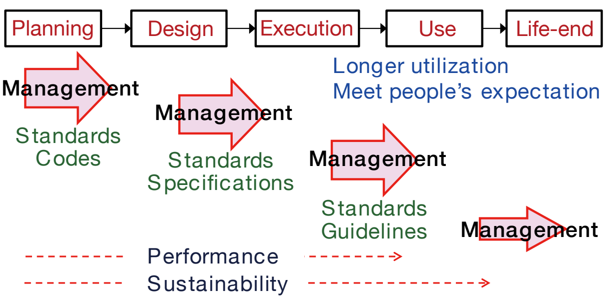
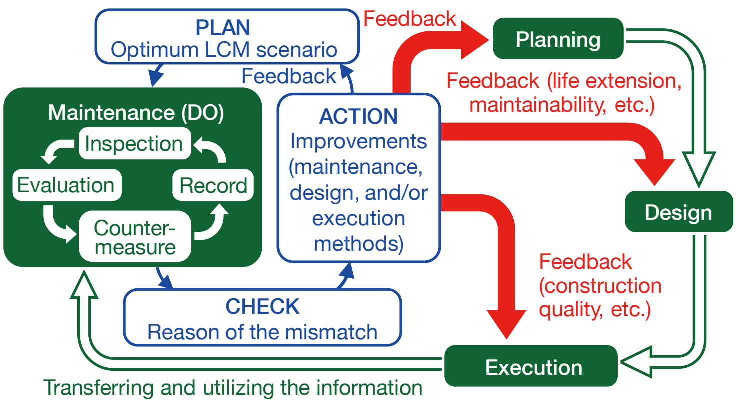


Fig. 2 P-D-C-A Cycle in LCM[2)]



Based on the performance-based design concept, it is necessary to provide the methods to ensure the structural performance requirements over the minimum limits during the design and maintenance stages.

Performance Assessment in Maintenance

Maintenance is the major strategy to counter the degradation, which is carried out to assess the present conditions of structure and to quantify the level of structural performance. In addition, it is necessary to predict the future progress of structural performance degradation. During the maintenance stage, maintenance engineers will initially follow the scenario (life-cycle management scenario; LCM scenario) that had been assumed at the design stage. The output of the design has to be verified with the maintenance work because progress of deterioration would not follow the design assumptions. The progress of corrosion differs widely by its location because of inhomogeneous characteristics of materials and diversity of environmental conditions. By using the real corrosion data, the LCM scenario has to be updated.

The level of inspection and investigation has an influence on the method of structural performance assessment. Assessment can be made by the condition-based concept and the performance-based concept[4]. Visual inspection is only able to provide the change in appearance of structural member, but structural performance has to be evaluated as precisely as possible. If the relationship between structural performance and the grade of deterioration could be found even tolerate margins of errors, the intervention could be discussed using the deterioration grade.

Feedback from Maintenance Results

As shown in Fig. 3, prediction at the design stage is generally done based on theoretical models, but that at the maintenance stage may be done with stochastic mathematical model such as survival analysis and Markov model. Some theoretical rules, simulation models, verification formulae, etc. are used for the prediction of deterioration progress. However, the trend that is observed through regular maintenance work, for example the measured corrosion rate, may have potentials for use in the future progress of deterioration and/or degradation during the maintenance stage. Based on the data and assessment results, the rule and process of deterioration and/or performance degradation have to be modified and the scenario be updated for further prediction.

If member failures might cause hazards to safety, possible failures should be categorized by their consequences. To reduce the risk of failure occurring within the design life when the consequences of failure are judged to be critical, it may be necessary to require particularly long design lives for specific members or to strengthen the requirements for inspection and maintenance.

Sustainability Indicators

The life-cycle management takes into account the sustainability indicators such as life-cycle cost, environmental impact, etc. as shown in Fig. 4. To determine the LCM scenario including one or more sustainability indicators will be of great use. To evaluate the LCM scenario, costs or life-cycle costs have been generally used as an indicator, where the scenario having the lowest cost/life-cycle cost should be selected as the most appropriate scenario. However, from the viewpoint of sustainability, not only indicators of economic aspects but also indicators of social and environmental aspects should be considered hopefully in the future. These indicators, as examples[5], should be determined in consideration of the following items:

- Use of energy and material resources;
- Emissions to air, water, and soil;
- Production and management of wastes;
- Species and ecosystem;
- Landscape;
- Community and territorial system; etc.

Concluding Remarks

The life-cycle management concept should be installed in the structural design of steel structure and performance assessment system should be established soon. This can lead to realize life-cycle design of structure. To highly develop the system, research is necessary on the following subjects:

- Performance verification at the design and maintenance stages which includes prediction on future performance degradation;
- Probability approach;
- Risk management; and
- Appropriate sustainability indicator(s)

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Fig. 3 Assessment and Prediction

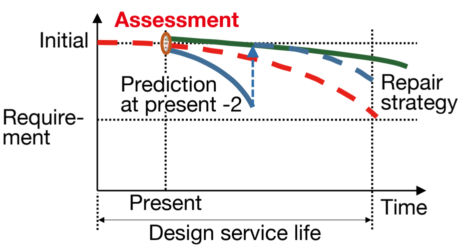
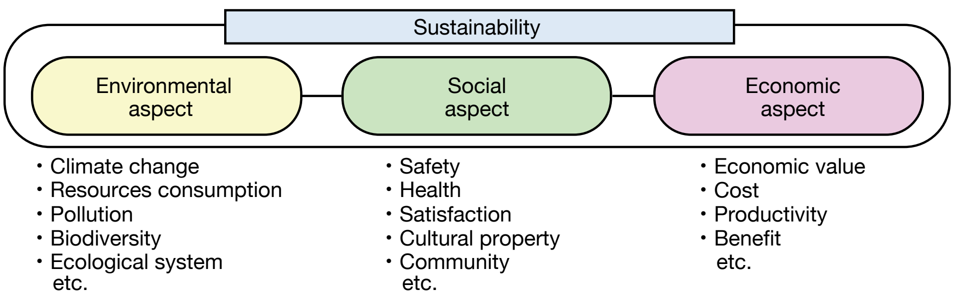


Fig. 4 Sustainability Indicators



Structural Integrity Assessment Method for Jacket-type Steel Pier with Corrosion Damages

Kunitomo Sugiura: After finishing the doctor's course at State University of New York at Buffalo, he became Assistant Professor at Kyoto University in 1988. He assumed his current position as Professor, Department of Civil and Earth Resources Engineering, Graduate School of Engineering, Kyoto University in 2006.

by Kunitomo Sugiura
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Toward Longer Service Life of Port and Harbor Facilities

After the Sasago Tunnel Ceiling Collapse on the Chuo Expressway in 2012[1], the Ministry of Infrastructure, Land, Transport and Tourism of Japan (MILT) has notified the regulation to periodically inspect all the infrastructures, e.g. for every 5~10 years in order to assess their health condition. Particularly, developments in the technology of damage detection and health condition assessment are urgent in order to implement "preventive maintenance" to prolong the service life of large stocks of such facilities[2].

Because of the applicability of steel sheet piles in rapid construction, these steel products have been extensively used for port and harbor facilities. However, steel port facilities are exposed to seawater and its severe corrosive environments, so that developments have been made in understanding corrosion mechanisms, diverse corrosion-protection methods, inspection methods and improving repair and strengthening methods[3]. Meanwhile, it is well known that corrosion reduces the steel plate thickness of structural members applied in steel structures and causes a deterioration in the load-carrying capacity. Then, various parameters have been assessed by means of analytical and experimental approaches to evaluate the load-carrying capacity of steel members with various cross sectional shapes subjected to combined sectional forces[4]. However, most of these experimental and analytical approaches were based on precise corrosion profiles of the structural members, and thus evaluations are not very frequently made in-situ condition and a performance assessment of an entire structure composing of steel pipe piles and RC slabs with corrosion damages was very limited[5].

Then, in the following, an assessment by means of vibration characteristics is conducted targeting a jacket-type pier composed of steel pipe piles and RC decks (the existing Shiomi No.3 Wharf of Sakai-Senboku Port referred to Photo 1). The frequency characteristics are summarized based on FE analysis as well as the loading test on this existing steel pier and its feasibility to assess structural integrity based on vibration characteristics is discussed.

FE Analysis of a Spatial Jacket-type Steel Pier with Pipe Piles and Its Assessment by Loading Test

A spatial frame structure (pile length: 26.0 m; pile intervals: 4.0 in the direction parallel to the shoreline and 4.5 m in its perpendicular direction (land-sea)), in which 20 pipe piles (outside diameter: 812.8 mm; wall thickness: 14 mm) are arranged regularly to lengthwise and crosswise at identical intervals, is adopted as a model of an entire jacket-type pier having steel pipe piles and RC deck in width of 20 m, in depth of 17.5 m and with thickness of 1.2 m referred to the structural details of Shiomi Wharf No.3 of Sakai-Senboku Port of Osaka Prefecture. Due to the corrosion damages in steel pipe piles as well as the deterioration of RC decks, this wharf is under reconstruction works. Therefore, the effect of a spatial frame with certain damages on the horizontal load-carrying capacity is assessed by the vibration test using shaker in conjunction with the frequency analysis by changing the corrosion deterioration patterns in steel pipe piles and varying other conditions. In the analysis, the finite element analysis code ABAQUS (Ver. 6.12)[6] is used. Fig. 1 shows the spatial frame model that is structured as a pier model by shell elements and beam elements in the FEM analysis.

Steel pipe piles are embedded in seabed with depth of 15, 15, 13, and 11 (m) in every row from the shoreline. The pipe piles are modeled by shell elements for the upper 6 m length and by pipe elements for the lower 20 m length. Meanwhile, the shell elements and the pipe elements are to be rigidly joined at the nodes. On the other hand, the RC deck is modeled by solid elements, and to be rigidly joined with the shelled area of the pipe pile tops. The base edges of the pipe piles are completely fixed on soil-pile springs in the vertical direction and the pipe piles embedded in the seabed are also connected to soil-pile spring in the horizontal direction. The ground spring constants used in the FE analysis are based on the ground profile investigated by Osaka Prefecture and calculated according to the specifications for highway bridges as given in

Fig. 1 Finite Element Model of Shiomi Wharf No.3

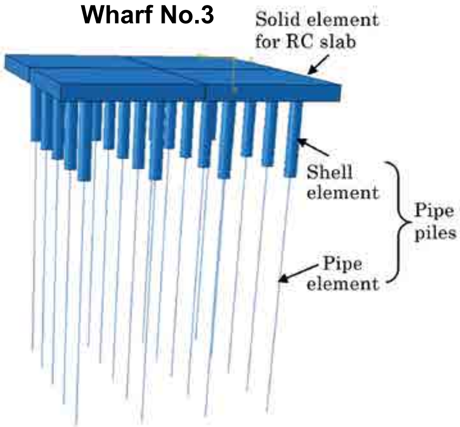

Photo 1 Overview of Shiomi Wharf No.3 of Sakai-Senboku Port (Osaka Prefecture, Port Authority)

http://www.pref.osaka.lg.jp/kowan/kankatsu/sakasen-all.html

Table 1[7]. As for the steel pipe piles, the density of 7.85 (ton/m^3), the elastic modulus of 210 (kN/mm^2), and Poisson's ratio of 0.3 are assumed. Furthermore, the density of 2.4 (ton/m^3), the elastic modulus of 23.1 (kN/mm^2), and Poisson's ratio of 0.2 for RC deck are also used. As for the eigen-frequency analysis, the consistent mass matrix is used and the Rayleigh Damping is employed, where the damping factor of 0.03 is assumed. The natural frequency is summarized in Table 2. It is understood that the natural frequency is influenced significantly by the subgrade reaction from the seabed. It is also reminded that the riprap at seabed surface could cause a change in the natural frequency. On the other hand, the stiffness of RC deck is found to be less influential. This is because the bending moment becomes large near the seabed as well as close to RC deck for the 1st horizontal vibration mode.

The shaker with loading capacity of 19.6 kN is set at the center of RC deck. In Fig. 2, the maximum acceleration response in the numerical simulation is plotted varying the frequency of excitation. It is obviously understood that the peak acceleration is obtained at the natural frequency of 0.7-1.5 Hz as obtained by eigen-frequency analysis, and that the peak is significantly affected by subgrade reaction from the seabed and riprap. Furthermore, the good agreement is also obtained in acceleration response as shown in Fig. 3.

According to Renewal Works of Shiomi No.3 Wharf, the pipe piles are inspected by measuring their thickness at the depth of 0.75 and 1.75 m below the L.W. level and it is reported that the average thickness loss ratio of 5.0% and 4.25% at each location made the Osaka Prefectural Government to decide the reuse of existing steel pipe piles in reconstruction. In the FE analysis of a pier with corrosion damages in steel pipe piles, according to thickness measurement, the fictitious thickness loss in pipe piles by 2, 12 and 39% is assumed and the dynamic response analysis is made subjected to sinusoidal excitation given at RC deck. Table 3 summarizes the reduction in the maximum acceleration response for all the cases. It is understood that the peak acceleration is reduced by 58% at most, and it is indicated that the structural integrity could be assessed by the changes in vibration characteristics.

Table 1 Ground Spring Constants Assumed in FE Analysis

Ground spring constants	Height from ground reference in seabed (m)		
	0-11	11-13	13-15
Vertical (kN/m)	49,247		
Horizontal (kN/m)	5,294	3,208	2,088
Rotation (kN·m/m)	29,136	20,863	15,647

Table 2 Natural Frequency Obtained by FE Model (1st order horizontal vibration mode)

Condition	Parallel to the shoreline	Perpendicular to the shoreline
Fixed at seabed (top surface)	1.037 (Hz)	1.091 (Hz)
Fixed at seabed (bottom surface)	0.393 (Hz)	0.389 (Hz)
Ground spring considered	0.688 (Hz)	0.718 (Hz)
Note: Torsional vibration mode with 0.843 Hz		

Concluding Remarks and Acknowledgements

As a result of a spatial frame analysis on a jacket-type steel pier with vertical steel pipe piles and RC deck, it was learned that the natural frequency of a steel pier is affected by mainly the stiffness of pipe piles, and that the less effect by the stiffness of RC slab is observed. Therefore, a corrosion-damaged steel pipe piles could be assessed by the change of vibration characteristics such as a first horizontal vibration mode because the stiffness of a section expected to have severe corrosion may contribute the natural frequency of lower vibration modes. It is also found that since the shaker with capacity of even several tons could be utilized to evaluate the natural frequency, the dynamic interaction of fully loaded trucks running over RC deck with steel pier could be practical use for the structural integrity assessment.

At the end, acknowledgements should be given to Port Authority of Osaka Prefectural Government for the loading test on the existing steel pier and providing the information of structural design and ground conditions. The author also would like to thank Toyo Construction Co. Ltd. for their technical assistance. ■

Fig. 2 Acceleration Response of RC Deck in the Horizontal Direction

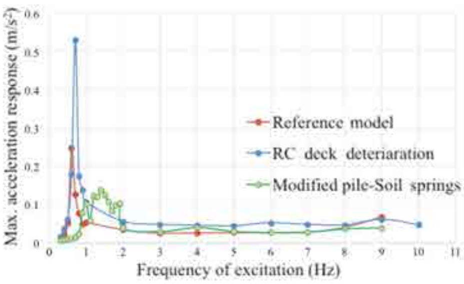

Fig. 3 Comparison of Acceleration Response

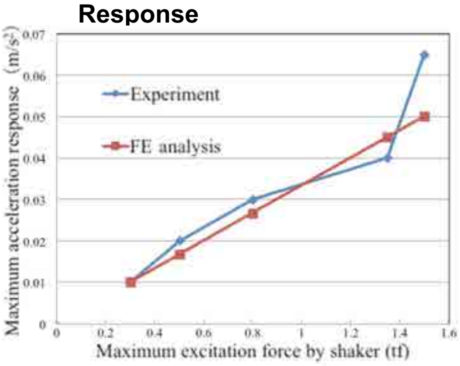

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Table 3 Reduction in Acceleration Response by Corrosion Damages

Reduction in cross sectional area (%)	Maximum acceleration response (m/s^2)	Reduction (%)
Intact	0.158	—
2	0.157	0.62
12	0.125	20.8
39	0.090	57.5

Inspection and Repair Technologies for Corrosion-Damaged Port Steel Structures

by Yoshito Itoh, President, National Institute of Technology, Gifu College; Yasuo Kitane, Associate Professor, Dept. of Civil Engineering, Nagoya University; Kazuo Furunishi, Senior Manager, Toyo-Giken Consulting Civil Engineers Inc.; and Mikihito Hirohata, Associate Professor, Dept. of Civil Engineering, Nagoya University

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Introduction

To keep port/harbor steel structures in a satisfactory condition with less maintenance cost, a maintenance cycle of inspection, condition evaluation, repair/strengthening, and record keeping should be repeated during the design service life of a structure. In this article, an efficient inspection method to measure thickness of steel members and a repair design for corrosion-damaged steel pile piles to recover seismic performance are discussed.

Inspection and Condition Evaluation

Corrosion reduces a cross-sectional area of steel members, leading to a decrease in load carrying capacity. Therefore, to evaluate a current condition of steel structure, a thickness measurement of steel members should be conducted during an inspection. The most popular thickness measurement method is the ultrasonic testing method (UT), which yields an accurate measurement, but requires a surface preparation to remove marine growth, coating and rust prior to measurement. Since the surface preparation needs time and resources, more efficient thickness measurement methods are desired.

One of such efficient thickness measurement methods is the pulsed eddy current testing method[1] (PEC), which does not require the surface preparation since PEC uses a pulsed magnetic field to produce eddy currents in the surface layer of steel plate. PEC has been used to detect corrosion in pipelines, risers, and insulated pipes. It is said to give an average thickness of a certain area called *footprint*, and therefore, it is usually used in a screening process of inspection. After detecting corrosion by PEC, a more accurate measurement is usually conducted by removing surface coating and rust.

PEC Thickness Measurement

To examine a feasibility of PEC thickness measurement for underwater inspection work of port steel structures, the field thickness measurement[2] of steel pipe piles by PEC was conducted at a quay in the Port of Nagoya, and the results were compared with values from UT. Fig. 1 shows the measured pipe piles. The quay was 41.5 years old at the time of measurement. Since the subsea zone of piles has been cathodically protected, and the atmospheric, splash, and tidal zones of piles have had coating protection, severe corrosion damage was not observed for these piles.

Measurement was done by PEC first. Then the surface of piles was cleaned to remove marine growth and rust, and

Fig. 1 Measured Pipe Piles

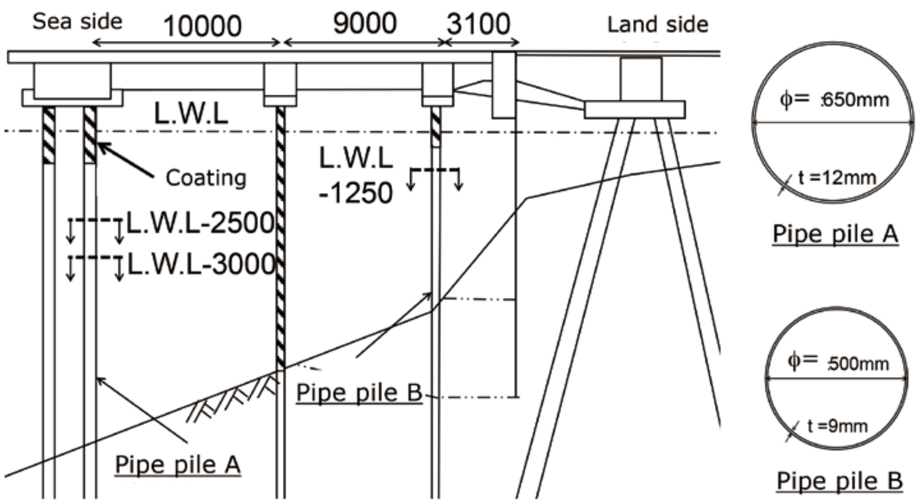
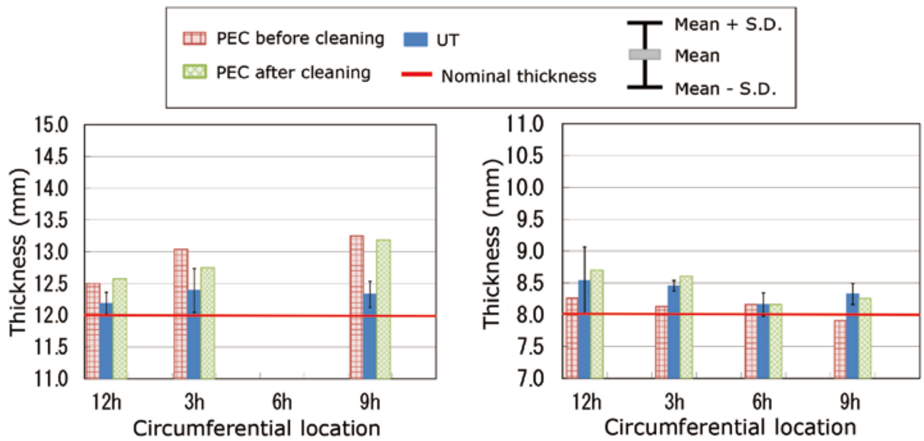


Fig. 2 Measured Thickness



thickness was measured by UT. Finally, PEC measurement was conducted again to examine the effect of surface preparation. Fig. 2 summarizes the measurement results at L.W.L−2.5 m of Pile A and at L.W.L.−1.25 m of Pile B. The horizontal axis of Fig. 2 shows circumferential locations in the cross-section of pile, and 12 h and 6 h correspond to the sea side and the land side, respectively.

The results show that the difference between PEC and UT measurements ranges from 1 to 8% of the thickness with an average of 5.5%, and that the effect of surface preparation on the PEC measurement is insignificant. Furthermore, the time required for the measurement was 15 to 20 min. per location for UT while it was only 15 to 30 sec. per location for PEC. These results indicate that thickness measurement by PEC has a potential to be used for the inspection of port steel structures.

Patch Plate Repair Design

One of the popular repair methods for corroded pipe piles is to weld a patch plate on the corrosion-damaged area, and in the typical design practice, a patch plate with a thickness equivalent to a thickness reduction is used. However, to recover seismic performance of the pipe pile to the initial level, a larger thickness may be required to recover the energy absorption capacity. In this study, finite element modeling for a steel pipe pile repaired by patch plates was developed, and pushover analyses of pipe piles with different structural parameters were carried out to examine the patch plate thickness required to provide the same energy absorption capacity based on the load-displacement curve as that of an intact pipe pile[3].

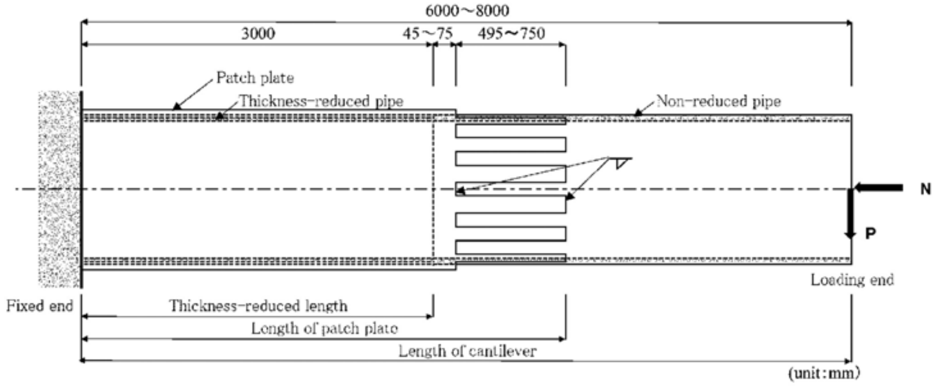
A pipe pile was modelled as a cantilever which is the top 60% of the whole pile. Fig. 3 shows the cantilever model extracted from the upper part of steel pipe pile. In the model, a thickness reduction was assumed to be uniform for the length of 3000 mm. The axial force, N, was applied first at the loading end, and the pushover analysis was carried out by gradually increasing horizontal displacement.

Pipe diameters used in the analysis are 600 mm, 700 mm, 800 mm, and 900 mm. Original thickness of steel pipe is either 12 mm or 16 mm. Thickness reductions are assumed to be 6 mm, 8 mm, and 10 mm. Cantilever lengths considered are 6000 mm, 7500 mm, and 8000 mm. Steel piles of both SKK490 and SKK400 are used. A ratio of the axial force to yielding axial force of an intact steel pipe, N/N_y, was considered in the analysis ranges from 0% to 20%. A total of 106 cases were analyzed.

Required thicknesses of patch plate from 106 cases are plotted in Fig. 4. In Fig. 4, the parameter of the horizontal axis was selected by referring to Ref. 4), where λ_p is a slenderness ratio parameter of thickness-reduced steel pipe pile, and R_{tp} is a radius thickness ratio parameter of the pile. The vertical axis is a parameter that represents a ratio of the patch plate thickness to the intact pipe thickness, where t_s, t_{p0}, σ_{ys}, σ_{y0} are patch plate thickness, intact pipe thickness, yield stress of patch plate, and yield stress of SKK490, respectively. A ratio of the required patch plate thickness to the thickness reduction was found to range from 1.0 to 1.4.

In Fig. 4, a trend curve of average values obtained by a nonlinear least square method is shown as a dashed line, and a solid line is an upper limit curve of the required patch plate thickness which is an average plus twice the standard deviation. The equation of the upper limit curve is also shown in Fig. 4. By using this empirical formula, a required patch plate thickness can be determined.

Fig. 3 A Cantilever Model of Thickness-reduced Pipe Repaired by Patch Plate



Summary

In order to achieve true life cycle management of port steel structures, the life cycle performance should be understood for the whole structure. Efficient inspection methods and effective repair methods discussed in this article will be able to contribute to better life cycle management techniques. ■

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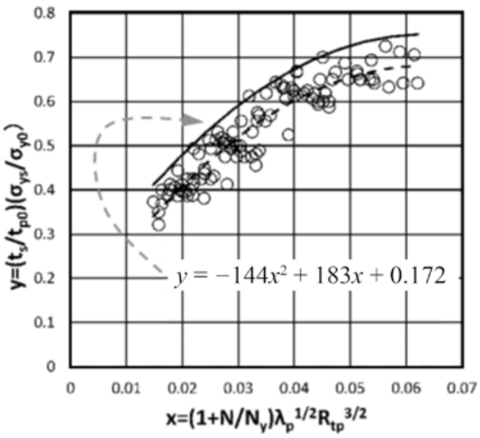
Fig. 4 Required Patch Plate Thicknesses from 106 Analytical Cases



Two Seminars for the Steel Industry Cooperation Program of Japan-Thailand EPA

The Japan Iron and Steel Federation (JISF) in collaboration with the Iron and Steel Institute of Thailand (ISIT) held two steel seminars in Japan. These two seminars were planned as part of government-initiated cooperative projects pursuant to the Japan-Thailand Economic Partnership Agreement.

• Steel Construction Seminar

A one-week Steel Construction Seminar was held in December 2015 in Tokyo, in which 18 Thai engineers participated. The seminar has been held every year since the start of the Japan-Thailand EPA, and the 2015 seminar marked its eighth year.

The seminar programs, selected for their interest to Thailand, covered a wide range of fields in steel construction—bridges, welding, concrete-filled steel tubular structures, seismic design and wind-resistant design. In parallel with the lectures, a tour of program-related construction sites and production plants was held. Further, the current state of concrete bridge construction in Thailand was introduced by Thai participants. In the seminar for an exchange of views, various measures being promoted for the wider application of steel bridges in Japan were presented.

• Newly Recruited and Young Engineer Training Program

As a new program of the Steel Industry Cooperation Program, two Training Programs were held, one in September 2015 and the other in March 2016 (each for one week), in Osaka. They were attended by a total of approximately 50 young engineers from the Thai government, steelmakers and trading companies. The training program in the first program covered basic metallurgy and flat steel products for automobiles, and those in the second program, steel for machinery and construction and civil engineering which were added by the request of Thai side. A tour of steelworks and other sites was also held.

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In the Japan-Thailand Economic Partnership Agreement: Steel Industry Cooperation Program, diverse kinds of programs in addition to those mentioned above were held both in Japan and Thailand.

Steel Structure Conference in Cambodia

The Japan Iron and Steel Federation held a conference titled "Recent Technologies for Steel Structures 2015" in Phnom-Penh, Cambodia on December 3, 2015. It was jointly held by the Ministry of Public Works and Transport of Cambodia and the Institute of Technology of Cambodia, and was supported by the Embassy of Japan in Cambodia, JICA Cambodia Office, JETRO PHNOM-PENH and the Japanese Business Association of Cambodia.

In the conference, five lectures covering such topics as ports and harbors, bridges and building construction were delivered by experts from both Cambodia and Japan, and about 120 engineers and university students from Cambodia attended. Key persons from both nations participated in the subsequent Small Group Session of the conference, where views were exchanged on the current situation of standardization and legislation in Cambodia and the future diffusion of steel structures in Cambodia.

This conference is the third in the series, following those held in 2012 and 2014. A fourth conference is planned to be held in Cambodia in 2016.

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