Life Extension of Steel Structures by Corrosion Prevention Technology
—Especially Port and Harbor Steel Structures—

Dr. Hidenori HAMADA
Professor of Kyushu University

HIDENORI HAMADA *is a Professor of Kyushu University. He received Doctor of engineering degree from Kyushu University in 1998. He has been engaged in Concrete Technology and Corrosion Engineering for about 25 years.*

KYUSHU UNIVERSITY
744, Motooka, Nishi-ku, Fukuoka city, Japan.
Tel: 81-92-802-3390, or, 3387
Fax: 81-92-802-3387
E-mail: h-hamada@doc.kyushu-u.ac.jp

Abstract

This paper discusses corrosion-protection technologies applied to port and harbor steel structures. The history of corrosion-protection technologies in Japan extends back more than 50 years, and includes a diverse array of surveys and research. As a result, these technologies have developed to the remarkable level where protection against the corrosion of port and harbor steel structures is nearly complete.

The conditions affecting the application of corrosion-protection technologies will differ from country to country, so the methods used will differ accordingly. But, it is believed that the diversity of experience acquired in this field in Japan will also be of use in Vietnam and Indonesia. I believe that this paper will undoubtedly contribute to the development of appropriate corrosion-protection technologies for steel structures in Vietnam and Indonesia.

1. Port and Harbor Steel Structures in Japan

1.1 History

The first steel harbor structure built in Japan was a pier constructed using steel screw piles in the Port of Kobe in 1876. After that, piers using steel screw piles were successively constructed at the Ports of Yokohama, Nagoya, Osaka, and Tsuruga.

In the last part of the Taisho era (1912~1926), steel sheet piles were imported to restore damage caused by the Great Kanto Earthquake. Initially, because of concerns about corrosion, steel products were only applied in temporary construction. But steel products became increasingly common in the construction of more permanent structures due to the advantages they offered with regard to ease of construction and shorter construction period. The first steel sheet pile-type mooring quay was constructed in 1926 at the Port of Osaka.

Entering the Showa period (1926~1989), imports of steel sheet piles increased, initially totaling 25,000~35,000 tons annually. Then in 1929, trial manufacture of steel sheet piles started at the government-run Yawata Steel Works, and full production started in 1930. It was a harbor facility completed in 1931 at the Port of Miyako that domestically-produced steel sheet piles were first applied. Other major ports and harbors where steel sheet pile mooring quays were constructed in the early Showa period were those of Osaka, Nagoya, Fushiki, Hakodate, and Rumoi.

In the post-war period, steel pipe piles were extensively used for port and harbor facilities. The application of these piles in pier foundation structures was expanded following their use in the construction of Shiogama Port in 1954.

The first cell-type mooring quay using flat steel sheet piles was constructed at the Port of Shiogama (commencement: 1954; completion: 1959). This type of quay was then constructed at the Ports of Tobata, Nagoya, Naoetsu, Aomori, Yokohama, and elsewhere.

In the same period, the steel plate cell method was developed whereby steel plates, instead of flat steel sheet piles, are formed into circular shapes and the cells thus completed are installed at the work site. This cell method was first applied at the Port of Kobe in 1957.

Entering the 1960s, the pressing task was to improve port and harbor facilities so that they could handle the increasing amount of loading/unloading cargoes. To meet this need, steel pile pier methods were developed and were increasingly used to build large-capacity mooring quays in many ports and harbors. Typical were both the Yamashita pier at the Port of Yokohama and the Maya pier at the Port of Kobe. Owing to the successful application of this type of pier at both ports, steel structures were extensively used to build port and harbor facilities throughout the nation.

Recently, in order to meet the need for rapid construction and for construction on soft ground, jacket-type steel structures are increasingly being adopted for port and harbor facilities. Typical of these are the Ooi container berth and the new D-Runway being constructed at Tokyo International Airport.

As stated above, port and harbor steel structures in Japan have shown remarkable development, and these structures now account for nearly a half of the nation's total mooring quays constructed.

1.2 Features of Port and Harbor Steel Structures

Currently, nearly a half of the mooring quays in Japan are constructed using steel products. This is rare worldwide and a feature peculiar to Japan. In particular, while concrete piles are used for pier construction overseas, mostly steel pipe piles are used in Japan.

A couple of major reasons for the greater use of steel products in Japan are the development of the Japanese steel industry as a core element in the country's rapid economic development in the 1960s and the resulting supply of steel products in large quantities and at low cost. Another economic advantage that can be cited for the wider use of steel products is the rich array of shapes and dimensions that are available, which in turn makes it easy to select steel products conforming to any design conditions. Further enhancing their wider use are the high strength and uniform quality of steel products as structural members.

Meanwhile, the frequent presence of soft ground at port and harbor sites is cited as conducive to the wide use of steel products in Japan. While gravity-type structures require a rigid foundation, steel structures can mitigate the effect of soft upper ground strata by driving steel piles to an underlying support stratum. In addition, steel sheet pile structures can be built at sites with bad ground conditions and, in general, have shorter construction terms than concrete structures.

In particular, because Japan's rapid economic development beginning in the 1960s demanded that port and harbor facilities be quickly improved, the possibility of rapid construction was an additional reason for the enthusiastic adoption of steel structures. The total extent of mooring quays employing steel structures has reached 490 km.

At the Port of Tokyo, the ratio of steel structures to total port and harbor facilities (including breakwaters and wave-removal banks) has rapidly grown. Of the total extension of 200 km or more of port and harbor facilities, steel structure facilities have surpassed 150 km.

1.3 Typical Port and Harbor Steel Structures

Among the mooring quays that use steel products as structural members, two kinds have been adopted—steel sheet pile-type quays and pier-type quays.

(1) Steel Sheet Pile-type Quays

Steel sheet pile-type mooring quays are constructed by driving steel sheet piles into the ground to form an earth-retaining wall (see Fig. 1). The most common steel sheet pile-type mooring quay is formed using tie rods to connect the steel sheet pile wall to a strut structure (steel pipe, steel sheet pile, shape, etc.) installed behind the wall. Depending on the size of the load to be supported, two kinds of piles are used for the pile wall—commonly adopted U-type steel sheet piles and steel pipe piles having connection joints. In cases when a small load is applied, as in ports with shallow water depth, a self-supporting wall structure is adopted without the use of a strut structure and tie rods.

Even when using steel sheet piles or steel pipe piles, the front surface of the pile wall is subjected to harsh corrosive environments because these piles are directly exposed to seawater or to the marine environment. While there are cases in which the steel products used for back surface of the pile wall, the tie rods, and the strut structure are directly exposed to the external environment, the corrosive effect is not so severe.

When pits form on the steel pile wall due to corrosion, sand from behind the wall flows out through these pits, causing a very dangerous situation for the quay structure. Even when pits do not form, it is strongly believed that the structure will suffer a reduction in structural strength due to sectional defect.

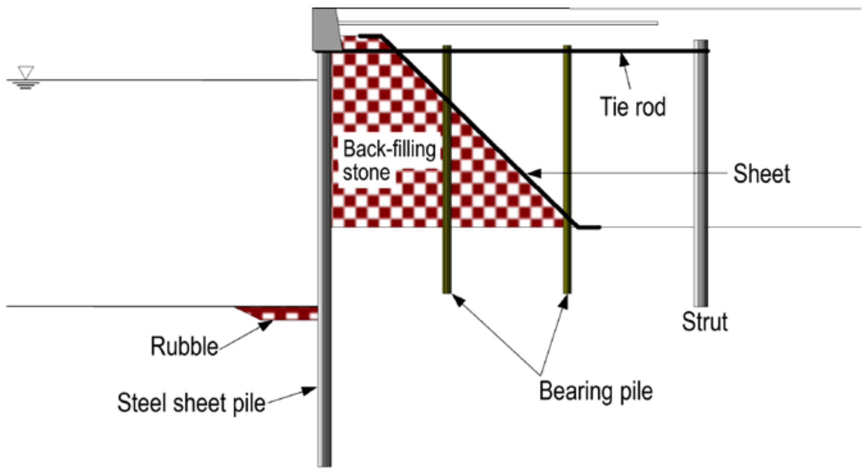

Fig. 1　Typical Structure of Steel Sheet Pile-type Mooring Quay

(2) Pier-type Mooring Quays

Pier-type mooring quays are structured by placing the upper structure on columnar structural members. There are two types of these quays—mooring quays in which vessels can moor on both sides and the mooring quays (shore bridge type) with mooring on one side only. In Japan, the shore bridge-type mooring quay is widely adopted. The pier-type quay, represented by the shore bridge quay, consists of a pier located at the front of the quay and an earth-retaining structure to the rear, with steel products widely used for the front pier. In Japan where earthquakes having large seismic force occur, steel pipe piles are used as the columnar structures of most piers. (See Fig. 2)

On the other hand, reinforced concrete or precast concrete beams and floor slabs are installed on the upper structure. The pier and the earth-retaining wall to the rear of the pier are structurally independent and are thus provided with a gangway footplate to facilitate smooth vehicular traffic between them. Accordingly, in most cases during an earthquake, the bending moment reaches maximum level at the joints where the pile heads connect to the upper structure.

When lower-structure performance is lost due to corrosion of the steel pipe piles, the feasibility of collapse exists for the quay structure not only during earthquakes but also in a state of constant vertical loading. Among port and harbor facilities, the concrete upper structure is the site where structural deterioration due to salt damage most frequently occurs.

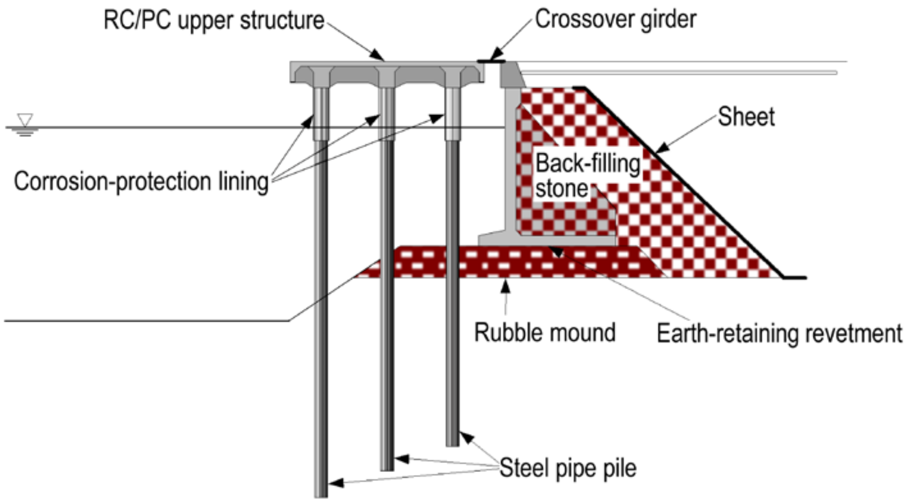

Fig. 2 Typical Structure of Steel Pipe Pile-type Mooring Quay

2. Features of Corrosion in Marine Environments

The environment where port and harbor steel structures are applied is roughly classified into five zones, starting at the top and going down: atmospheric zone, splash zone, tidal zone, submerged zone, and mud zone. In cases where long steel products such as steel sheet piles and steel pipe piles extend through multiple environments (tidal zone, submerged zone, and mud zone), macro-cell corrosion attributable to differences in these application environments occurs. The area where problems arise regarding the corrosion of steel structures used without corrosion-protection measures is the vicinity just beneath the splash zone and the mean low water level (hereinafter referred to as M.L.W.L.).

Corrosion tendencies by corrosive environment are introduced below (Fig. 3):

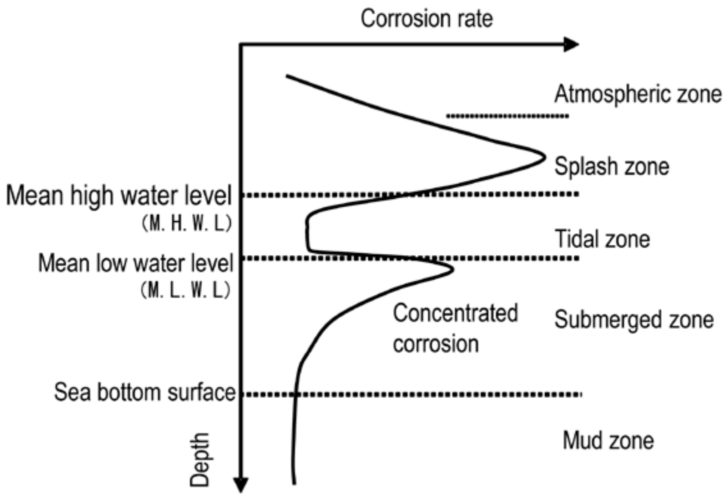

Fig. 3 Representative Examples for Vertical-direction Corrosion Rate of Steel Pipe and Sheet Piles

i) Atmospheric zone

In most cases, because common piers and steel sheet pile mooring quays are covered with a concrete upper structure, steel products in this zone are seldom exposed directly to the atmosphere. Further, the corrosion rate (corrosion loss) for such structures is mostly around 0.1 mm/y.

ii) Splash zone

Because the splash zone is constantly subjected to splashing seawater, great amounts of both seawater and oxygen are supplied. Additionally, any layer of rust on the surface of the steel peels away due to wave impact. Accordingly, the splash zone is the most corrosive environment. In general, corrosion rate in this zone reaches the high level of 0.3 mm/y. According to surveys made in the Okinawa area, there are examples of corrosion rate reaching 0.5~0.6 mm/y due to the additional effect of high temperatures and humidity in that area.

iii) Tidal zone

The tidal zone is where structures undergo periodic immersion into seawater and exposure to the atmosphere due to tidal action. It is notable in this zone that, while corrosion rate in the vicinity of the mean seawater level (hereinafter referred to as M.S.L.) is small, corrosion rate in the vicinity just beneath the M.L.W.L. is extremely large. The reason for this is that a macro-cell is formed in which the area of the M.S.L. becomes the cathode (high dissolved oxygen concentration) and the vicinity just beneath the M.L.W.L. becomes the anode (low dissolved oxygen concentration). There are cases, depending on the circumstances, when corrosion rate in the vicinity just beneath the M.L.W.L. exceeds that in the splash zone. This phenomenon is called "concentrated corrosion."

When concentrated corrosion occurs and further develops without corrective action in steel pipe sheet pile structures or in steel pipe pile sheet pile structures, there are cases in which the extent of the corrosion is great enough to cause structural collapse. In steel pile sheet pile structures, pits form in the protruding sections of the piles due to concentrated corrosion in the vicinity just beneath the M.L.W.L., and because the back-filled sand flows out through these pits, the area behind the sheet piles is hollowed out. In steel pipe pile structures, the wall thickness of the pipe piles rapidly decreases due to concentrated corrosion in the vicinity just beneath the M.L.W.L., and the seel pipe pile structure causes buckling due to the occurrence of pits. As a result, there are cases in which the upper structure causes subsidence.

iv) Submerged and mud zones

Corrosion in the submerged zone is nearly uniform, aside from the section just beneath the M.L.W.L. where extensive concentrated corrosion occurs. According to the survey results, corrosion rate at depths below –1 m or more is about 0.1~0.2 mm/y. In the mud zone, because of reduced oxygen supply compared to the submerged zone, corrosion rate becomes smaller: about 0.03~0.05 mm/y.

3. Corrosion-protection Technologies for Port and Harbor Steel Structures

3.1 History of Corrosion-protection Technologies

When corrosion surveys were conducted in 1967 on a wharf constructed in 7.5 m of water at the Port of Toyama, it was found that the tie rods recovered were wrapped in two layers of coal-tar impregnated jute (thickness: about 3 mm). By the way, no corrosion was found in the tie rods.

The above example is a special case, because the most prevalent concept of corrosion protection in those days was based on the provision of "corrosion allowance." Accordingly, the wall thickness of steel products was increased beforehand by a margin for corrosion loss that would conform to the desired number of durable years.

It was in 1953 that cathodic protection was first applied on a harbor steel structure; this was the Port of Amagasaki in which an anodic system employing magnesium alloy anode was applied. At this port, cathodic protection by means of an external current source system was applied in 1954.

Entering the 1960s, attempts were made to use cathodic protection (external current source system) in various port and harbor structures. But the diffusion of cathodic protection did not show progress. Some major reasons contributing to this was that recognition of the need for periodic inspection of corrosion-protection current density and electric potentials and other maintenance measures after completion of a harbor facility was insufficient, and that expenditures for the maintenance of public facilities was inadequate.

Around 1960~1965, oil paint and tar epoxy resin paint were developed and increasingly adopted for corrosion protection in zones above the submerged zone.

Entering the decade starting from 1965, it was thought that corrosion rate in port and harbor steel structures in the submerged zone was equal to that of steel specimens immersed in seawater. While there was steady recognition that long steel products extending through multiple corrosion environments (tidal, submerged, and mud zones) caused macro-cell corrosion, the actual state of macro-cell corrosion was not yet clear. To correct this situation, the Port and Harbor Research Institute started a nationwide survey of the actual state of corrosion in existing steel structures that, one, lacked corrosion-protection measures and, two, had been in service for many years. At first, efforts were directed at developing a steel product thickness gauge that could be applied in the submerged zone, which led to the development of an ultrasonic flaw thickness gauge.

In coating/lining corrosion protection, zinc-rich paint was developed and used as an undercoat for tar-epoxy resin coating. Further, attempts were made to cover the upper section of pier steel pipe piles with concrete as a corrosion-protection method for structures above seawater level where the effect of cathodic protection could not be obtained. However, at that time, because underwater non-separation concrete had not yet been developed and because the structures that were covered with concrete were still washed using seawater, the concrete-covering method did not necessarily produce satisfactory results. In addition, there were cases in which the concrete covering cracked and peeled off. Accordingly, the concrete-cover method was not realized in terms of corrosion-protection performance.

Around 1970, chlorinated rubber paint was developed, followed by the development of urethane paint in 1972.

In cathodic protection, high-performance aluminum alloy anodes were developed, and the full-scale application of anodic corrosion protection started. Also around 1970, underwater welding technology was developed to reduce the work period and increase safety when attaching aluminum alloy anodes. However, in those days, the provision of corrosion allowances remained the main corrosion-protection method.

Entering the decade starting from 1975, the application of cathodic protection for steel structures newly installed in the submerged zone was clearly designated in the "design standards for port and harbor facilities." Further, starting in 1980 and for some years afterwards, diverse kinds of highly durable coating/lining corrosion-protection methods were developed, among which were the cement-mortar/FRP cover method, the petrolatum lining method, and the underwater hardening-type lining method. Around 1982, polyethylene lining and polyurethane lining (the so-called heavy-duty corrosion protection method) were developed. In the coating-type system, ultra heavy/thick type epoxy resin paint and fluorine resin paint having high weather resistance were developed.

However, even in those days, corrosion-protection systems were not necessarily applied for all port and harbor facilities, and in reality many steel structures relied on the "corrosion allowance" system.

As a result, in 1983, an accident occurred at the Port of Yokohama involving the subsidence of a harbor facility. Triggered by this accident, cathodic protection was established in 1984 as the standard method of corrosion protection for existing steel structures in the submerged and mud zones, and coating/lining protection as the standard method of corrosion protection for existing steel structures in the tidal, splash, and atmospheric zones.

During the same period, the practical application of titanium as a corrosion-protection material began in the form of titanium cladding for steel plates, as did the use of corrosion-resistant stainless steel linings. Titanium materials had already been adopted for actual structures such as the bridge piers of the Trans-Tokyo Bay Highway (for water depths ranging between –2 m and +3 m) and the Yumemai Bridge (floating, revolving-type). Seawater-resistant stainless steel linings were applied as a corrosion-protection measure for the jacket-type quays used to improve the Ooi Quay (for water depths of –1 m and above).

Further in the *Technical Standards for Port and Harbor Facilities* revised in April 1999, corrosion-protection methods based on corrosion allowance was eliminated, and as a rule cathodic protection was stipulated for zones below the mean tidal level and the coating/lining protection method for all zones upwards from 1 m below the mean tidal level.

As stated above, corrosion-protection technologies for port and harbor steel structures have undergone a series of transitions, and, currently, there are many corrosion-protection and corrosion-repair methods with practical applicability that have been put into actual use (Fig. 4).

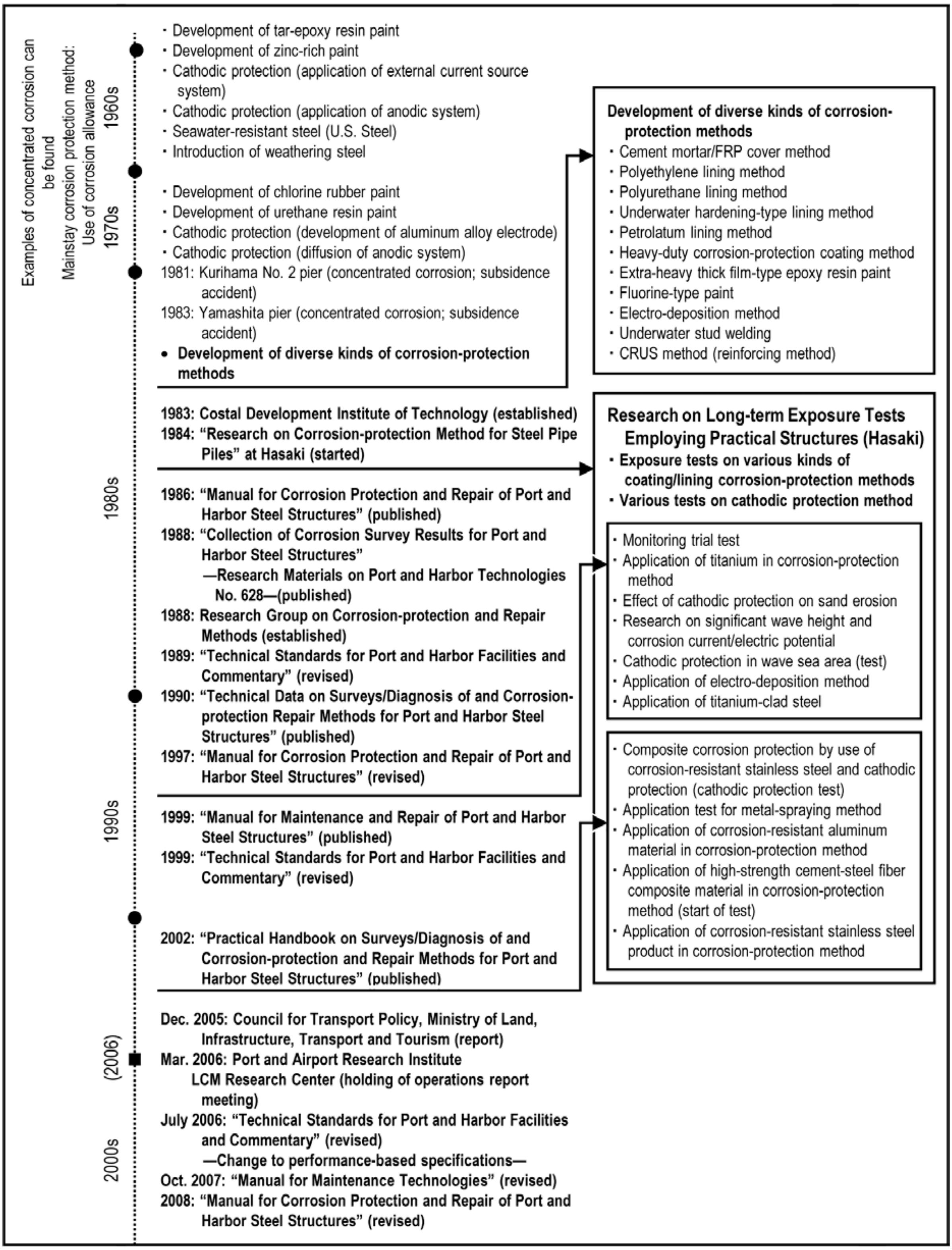

Fig. 4 Transitions in Corrosion-protection Technologies for Port and Harbor Steel Structures

3.2 Concepts for Standard Corrosion-protection Methods

Needless to say, it is necessary to provide appropriate corrosion-protection measures for port and harbor steel structures. In particular, regarding concentrated corrosion occurring in the vicinity just beneath the M.L.W.L., it is difficult to visually find it and, further, to repair it by the use of coatings, and thus it is necessary to implement appropriate countermeasures. Three standard corrosion-protection methods are established to treat concentrated corrosion (Fig. 5).

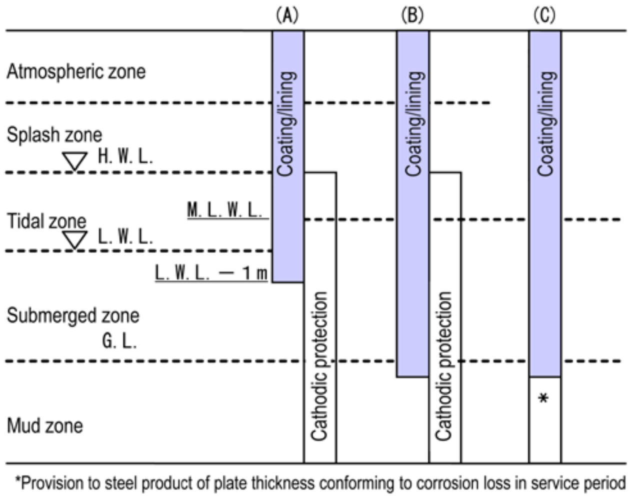

Fig. 5 Standard Corrosion-protection Methods for Port and Harbor Steel Structures

(A): This method applies coating/lining corrosion protection to the section above L.W.L. –1 m and cathodic protection to the section below the M.L.W.L.; it is also the most widely applied method. Because the section from the M.L.W.L. to L.W.L. –1 m is the site where concentrated corrosion is liable to most frequently occur, both the coating/lining method and cathodic protection are applied. Further, the combined use of both methods is effective in environments where high waves occur and river water mixes with great amounts of rainwater.

(B): This method applies the coating/lining corrosion protection of method (A) to sections deeper toward the sea bottom. This method is most economical and effective in cases where the large corrosion-protection current density of cathodic protection is necessary in open seas and in areas subject to the flow of high tides. The same is true in environments where the seawater electric resistance ratio is subject to wide seasonal deviation, for example, floodgates and revetments installed at the mouths of rivers. There are many examples of method (B) being applied to long-span bridges and floodgates.

(C): This method applies coating/lining corrosion protection to those parts of the splash zone where the severest corrosion occurs, tidal zone, submerged zone, and mud zone. In general, this method is applied to steel sheet pile revetments installed in areas of shallow water. In such applications, the coating/lining method should possess particularly excellent corrosion protection and durability. In most cases, polyethylene linings and urethane-elastomer linings are applied to newly installed structures, and petrolatum linings and mortar linings to existing structures. In most cases, the limit application depth for the coating/lining method is up to G.L. –1 m. The corrosion-protection method is not applied to the mud zone at G.L. –1 m or below. In such an application, it is necessary to adopt a steel product having increased wall thickness sufficient for the corrosion loss expected in the corresponding sea area.

In general, method (A) is the corrosion-protection method that is applied to revetments and quay structures built using steel pipe piles, steel sheet piles, and steel pipe sheet piles. For large-scale structures and structures installed in river-mouth areas, there are cases in which method (B) is effective. Accordingly, it is necessary to determine the most economical method through comparison studies.

For structures having a short service life (temporary structures, etc.), no particular corrosion-protection methods are generally applied, although there are cases in which corrosion protection is implemented by means of increased wall thickness (corrosion allowance).

3.3 Materials for Coating/Lining Corrosion Protection

Diverse kinds of corrosion-protection materials and methods have been put into practical use so that they can accurately meet the respective application conditions of port and harbor steel structures. Five major coating/lining corrosion-protection methods are applied to port and harbor steel structures—coatings, organic linings, petrolatum linings, mortar linings, and metallic linings.

A representative coating system uses heavy/thick film-type zinc-rich paint plus epoxy resin paint.

Compared to coatings, organic linings have certain problems in terms of lining efficiency, ease of repair, and lining cost, but they also have higher corrosion resistance. Among the organic linings applied to port and harbor steel structures are polyethylene linings, urethane elastomer linings, extra-heavy/thick film-type linings, and underwater linings. Stable lining quality can be obtained with polyethylene linings and urethane elastomer linings that are factory processed using special equipment. Further, application of these two lining systems is increasing due to the reduced cost brought about by mass production.

Underwater linings are available in two types—the putty type in which the lining material, in a putty-like state, is applied by manual cladding; and the painting type whereby the lining material is applied using rollers and brushes. One of the features of the underwater lining system is that the lining can be applied to complex-shaped structures such as the sections where steel sheet piles are joined.

Petrolatum lining has many recorded applications and is effective as a corrosion-protection method for port and harbor steel structures. In this system, petrolatum-type corrosion-protection material is tightly bonded to the steel product surface, which is protected by the use of plastic or reinforced plastic covers and corrosion-resistant metallic covers. There are cases in which a buffer material is inserted between the petrolatum material and the cover. Further, there is another available method whereby the petrolatum material, buffer material, and cover are integrated. The integrated system features underwater applicability, comparative ease in surface grinding, and no need for a curing period after lining.

Mortar lining is a method whereby corrosion protection is attained by forming a dense passive film on the surface of a steel product by fully utilizing the alkaline in cement. When lining with concrete, the method is frequently called mortar lining. Mortar lining has long been applied in the corrosion protection of port and harbor steel structures. When the deterioration of lined mortar occurs in the form of cracking, peeling-off, or neutralization, the corrosion protection performance drops. To remedy this, various countermeasures are adopted—increased lining thickness, mixing of organic polymers and steel fibers, surface coating, and the use of protectors that are also used as FRP and metal molds.

Metallic lining is particularly superior in impact resistance and abrasion resistance over other lining systems, and is high in corrosion resistance. However, because there is the possibility that galvanic corrosion may occur at the points where the lining is connected to the targeted steel structures, it is necessary to fully examine the measure to prevent that from happening. Highly corrosion-resistant stainless steel and titanium are used as the metallic lining materials.

3.4 Cathodic Protection

(1) Principle of Cathodic Protection

In steel products that are developing corrosion, the anode section and the cathode section are separated. Because the anode section and the cathode section are electrically shorted, a corrosion cell is formed. As a result, a corrosion current (icorr) flows from the anode section to the cathode section, thereby causing corrosion of the anode section. In order to prevent this, either the anode or cathode section is eliminated so as not to form a corrosion cell. That is, the direct current that overcomes the corrosion current flowing from the steel product into the electrolysis (seawater) is continuously flowed from an external source into the steel product so as to prevent ionization (corrosion) in steel products. (See Fig. 6)

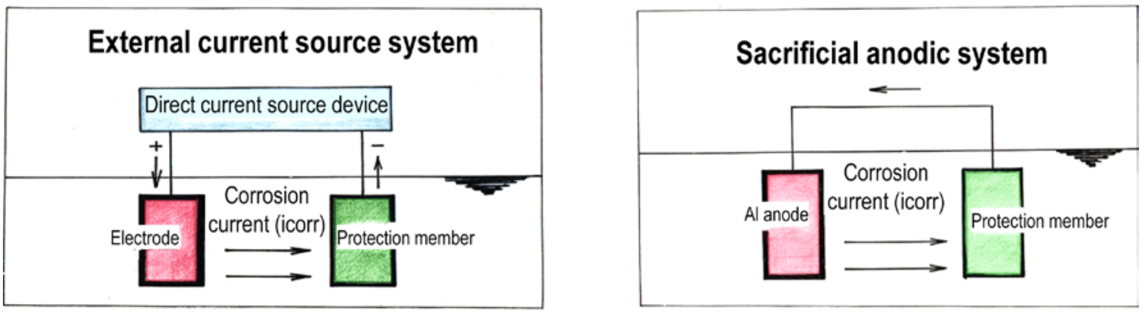

Fig. 6 Principle of Cathodic Protection

There are two types of cathodic protection—the external current source system and the sacrificial anodic system. In the external current source system, an electric circuit is formed by the combined use of a direct current device, an insoluble electrode, and the steel product to be protected; the protective current flows from the direct current source to the steel product via the insoluble electrode (electrode). In the sacrificial anodic system, large/small and/or high/low trends toward the ionization of metallic materials is utilized in such a way that metallic materials such as aluminum, zinc, magnesium, etc. are connected to the steel and are ionized (corroded) instead of the steel so as to protect the steel product against corrosion.

(2) Application of Cathodic Protection

In the current application standard, the prescribed application range for cathodic protection is the section extending from the M.L.W.L. downward. Cathodic protection is very effective in preventing concentrated corrosion from occurring in steel products located just beneath the M.L.W.L.

In 1976, the Ministry of Transport clearly stated in the design standard that cathodic protection (aluminum alloy anodes) be used in newly installed port and harbor steel structures. In 1988, its application was stipulated as the method for repairing existing structures as well.

In cathodic protection as currently applied, the sacrificial anodic system using aluminum alloy anodes is almost exclusively adopted. The major reasons for this are the many advantages offered by the sacrificial anodic system—no need to use a current source once the system is installed (in contrast to the external current source system), no need for power expenditures, and the possibility of inspection and maintenance by periodically measuring electric potential.

4. Newest Topic on Corrosion Prevention Technology (Tokyo International Airport (HANEDA Airport))

Fig. 7 shows a new Haneda Airport with 4th Runway, presently under construction. The feature of this runway is composed of reclaimed part (2020m in length) and wharf part (1100mm in length). As previous experience on Port and Harbor Steel Structure, well established corrosion prevention technology is required on wharf structures for long term design service life, in this case, 100 years. For this very important structure, steel piles composing steel jacket are all protected with stainless steel plate, 0.4mm in thickness at the part of tidal and splashing zone (Fig. 8). Steel beams composing of frame of the Upper structure are protected with epoxy resin coating (Fig. 9). The design service life of 100 years is a challenge for marine steel structures, exposing to very severe environmental condition. As just explained, highest level of corrosion prevention technology is adopted for jacket type steel structure. However, it is not thought that proper maintenance is necessary to achieve the service life of 100 years.

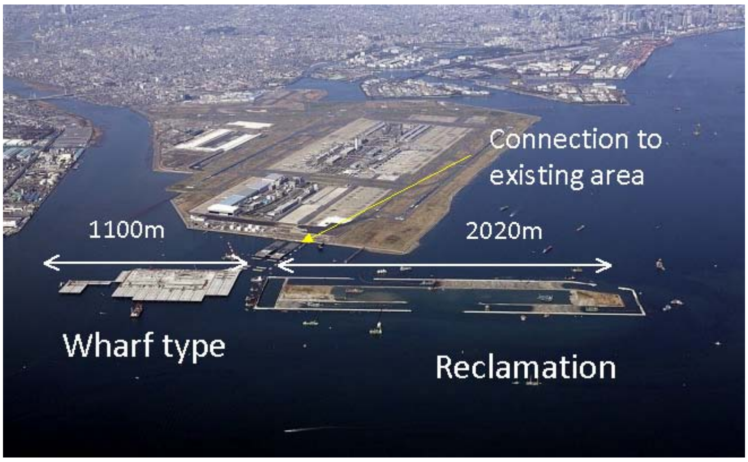

Fig.7 New Haneda Airport with 4^{th} Runway

Fig.8 Lower Structure of Wharf Type Runway

Fig.9 Upper Structure of Wharf Type Runway

5. Future Insight of Performance Driven Design and Maintenance of Corrosion Prevention Technology

Roughly speaking, in history of corrosion prevention technology in Japan, in 1980' the "corrosion allowance theory" was diminished and "corrosion prevention methods, such as, cathodic protection system, coating/lining system were established. In 2000', main part of infra structure preparation changed from new construction to maintenance of existing structures. And, design system was gradually changed from the "Specification" to the "Performance driven". Also, the design of corrosion prevention system was gradually shifted to the performance driven method. The definition of the performance of corrosion prevention system is "Within the design service life, to prevent steel corrosion (rusting)".

The design service life of general steel structures is mostly 50 years, except for new runway of Haneda airport, 100 years. Table 1 presents Lining or Coating Method and Expected Service Life. At present technological condition, the 50 years is the highest durability. Normally, 20 years and 30 years are expected level. This means the proper maintenance system is necessary to achieve the expected service life of more than 50 years for marine steel structures. In recent decade since 2000, major discussion was concentrated on the maintenance system of Port and Harbor Structures, both of concrete structures (RC, PC, Concrete- steel Hybrid) and steel structures (steel sheet pile, steel pipe pile, jacket type).

Table 1 Lining or Coating Method and Expected Service Life

Lining or Coating	Materials and method	Expected service life
Pre-coated type	Thick epoxy resin type painting Glass flake contained epoxy resin type	20 years
	Polyethylene lining type Polyurethane lining type Thick epoxy resin type lining	30 years
	Seawater resist type stainless steel lining Thin Titan plate clad type	50 years
Coated on site Type	Underwater-hardened resin type	20 years
	Resin covered petrolatum tape type Metal covered petrolatum tape type	30 years
	Reinforced concrete covered type Cement mortal covered with protective cover	30 years

Fig. 10 shows Performance Degradation Curve and Maintenance Effect. In this figure, also the three different maintenance levels are shown. Maintenance level is defined as the "level I" as the highest grade, "level II" for middle grade, and "level III" for the lowest grade. The level is set for each structure considering several important factors such as "important level of the structure", "environmental condition", "difficulty of the inspection/survey".

Maintenance work should be based on the LCM concept of individual structure. Fig. 11 shows the flowchart of the maintenance procedure. Fundamentally, a series of maintenance is composed of "periodic inspection", "required investigation", and "evaluation of deterioration or performance degradation", if necessary, "repair and reinforcement" and "data base construction for high level and low cost maintenance system".

At present 2010, to some degree, corrosion prevention technology is well developed. However, in future, following upgrades, 1) Performance-driven design system of corrosion protection system, 2) More higher level maintenance system, are still necessary to be established.

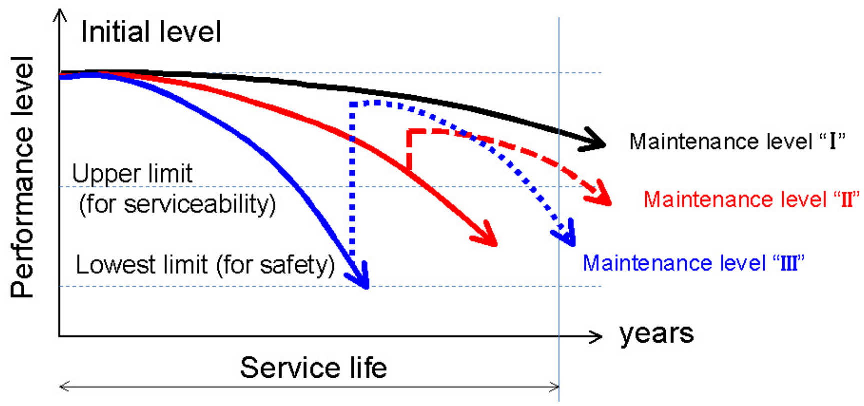

Fig.10 Performance Degradation Curve and Maintenance Effect

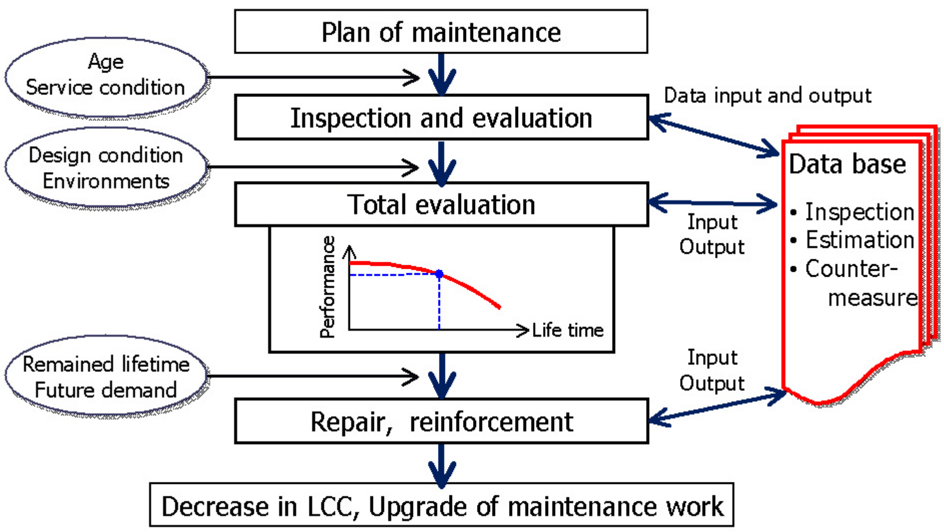

Fig.11 Maintenance Flow Based on LCM (Life Cycle Management)

Concluding Remarks and Acknowledgements

In my preparation of the above paper, the Port and Airport Research Institute, to which the author previously belonged, supplied many useful data and materials, for which I express my greatest thanks.

While it is clear that corrosion-protection technologies have made great strides, the current technologies are not necessarily perfect. In Japan, new R&D efforts are being promoted in this area, and the author hopes to contribute to this in one way or another. In this regard, I would be very grateful if I could collaborate with engineers and researchers in Vietnam and Indonesia pertaining to corrosion protection in the construction of port and harbor steel structures.