Abridged version

KAWASAKI STEEL TECHNICAL REPORT

No.25 (September 1991)

Special Issue on 'H-Shapes with

Fixed Outer Dimension' and 'Steel Pipe'

Corrosion of Steel Structured Wharves and Revetments and Their Maintenance

Kei Wada, Keisuke Shiota, Hideo Shinomiya, Yoshio Horinouchi

Synopsis :

This paper reports the inspection results of corrosion of port and harbor structures at Chiba Works and maintenance techniques for them. Differences in the corrosion rate of steel material between with and without corrosion protection was investigated. Electrode potential monitoring and visual inspection of aluminum alloy anode were proved to be effective in quality control of cathodic protection. The life of anode is expected to be extended by coating the structure at the tidal zone. For localized holes at steel pipe piles and steel sheet piles, some repairing methods have been developed and carried out. Finally the newly developed KPP (Kawasaki polyethylene or urethane resin coated pipe) pile is introduced as heavy-duty protective treatment.

The body can be viewed from the next page.

Corrosion of Steel Structured Wharves and Revetments and Their Maintenance*

Kei Wada
Staff Assistant Manager, Chiba Construction Engineering Sec., Construction Engineering Dept.

Keisuke Shiota
Research Engineer, Coastal Development Institute of Technology

Hideo Shinomiya
Staff Assistant Manager, Chiba Construction Engineering Sec., Construction Engineering Dept.

Yoshio Horinouchi
Chiba Construction Engineering Sec., Construction Engineering Dept.

Synopsis:

This paper reports the inspection results of corrosion of port and harbour structures at Chiba Works and maintenance techniques for them. Differences in the corrosion rate of steel material between with and without corrosion protection was investigated. Electrode potential monitoring and visual inspection of aluminum alloy anode were proved to be effective in quality control of cathodic protection. The life of anode is expected to be extended by coating the structure at the tidal zone. For localized holes at steel pipe piles and steel sheet piles, some repairing methods have been developed and carried out. Finally the newly developed KPP (Kawasaki polyethylene or urethane resin coated pipe) pile is introduced as heavy-duty protective treatment.

1 Introduction

Steel materials such as sheet piling, steel pipe pile and interlocked steel pipe pile have advantages of high strength, easy installation and effectiveness in soft ground, and are extensively used in harbor construction.[1] When steel materials are used for harbor construction, it is necessary to employ sufficient protection against corrosion.[2] The tranditional method for handling corrosion was to design with a thickness allowance for corrosion. However, severe localized corrosion (sometimes called concentrated corrosion) is liable to occur in the area just below M.L.W.L. Since it was difficult to foresee the causes of this concentrated corrosion and to predict its rate, and since the total-surface corrosion rate varies considerably with sea area, the problem of corrosion became conspicuous in the 1980s.[3]

At the Chiba Works, which has steel harbor structures of 12.3 km in total length, corrosion has been handled by cathodic protection and sacrificial corrosion allowance, and it has been found in recent years that the corrosion of non-protected structures was particularly severe. Consequently, a thorough corrosion investigation was carried out on all steel revetments and quays in 1985. After this investigation corrosion protection gathered momentum, and measures were instituted such as new applications of cathodic protection to non-corrosion-protected structures, repairs to severely corroded structures and the use of heavy-duty anticorrosion-treated steel.

This report summarizes the corrosion investigations, corrosion-protection measures and repair techniques to the steel harbor structures which the authors have so far carried out at Chiba Works.

2 Outline of the Harbor Structures at Chiba Works

Chiba Works is a coastal steelworks which was built

* Originally published in *Kawasaki Steel Giho*, 23(1991)1, 61–68

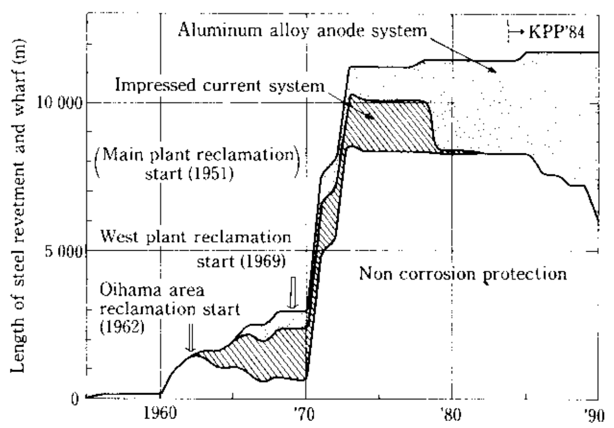

Fig. 1 History of corrosion protection method at Chiba Works

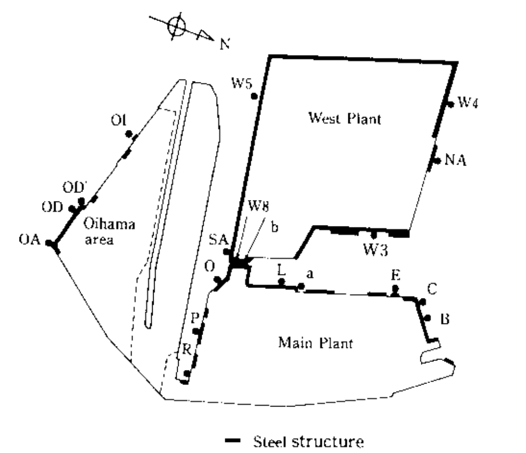

Fig. 2 General layout of Chiba Works and location of wharves and revetments

on land reclained from the sea to the south of Chiba City. Reclamation was started in 1951, and the site area amounts to 863 ha,[4] which includes the Main Plant, Oihama Area and West Plant. Initially mainly concrete sheet piling was used for the revetments and quays. The use of steel materials in the harbor structures was made for the temporary structures of Q-berth at the Main Plant for the first time in 1956. For the permanent structures, flat steel sheet piling was used at L-berth of the Main Plant, and interlocked steel pipe pile was used at O-berth of the Main Plant in 1961 for the first time. Later as Chiba Works expanded, more revetments and quays using steel materials were built so that today about 60% (12.3 km) of the current harbor structures amounting to 20.7 km in total involve steel structures.

Cathodic protection has been employed at Chiba Works as a corrosion protection method. Initially, the impressed current system was used, but this was gradually changed to the aluminium alloy anode system because of easier maintenance and improved performance of the aluminium alloy anode,[5] the aluminimum alloy anode system being universally used today. Heavy-duty, auti-corrosion-treated steel pipe piles, interlocked steel pipe piles and steel sheet piles, which are coated with polyethylen to render them maintenance-free, are now used for new installations or the replacement of existing harbor structures.

History of corrosion protection in the revetments and quays at Chiba Works is shown in **Fig. 1**. Cathodic protection by the impressed current system was adopted in 1963 for the first time (at A-berth), seven years after steel materials were used. Later, as reclamation progressed for the Main Plant and Oihama Area, the length of revetments and quays increased, and in 1966, the adoption of the aluminium alloy anode system began (at O-berth). In 1970, cathodic protection was adopted for 80% of the total length of 2.9 km. In the 1970s, reclamation work for the West Plant began, and a large quantity of steel material was used for the harbor structures. At that time, cathodic protection was employed only for the quays where cargo was handled, the other quays being designed to the thickness allowance for corrosion. In 1979, the greater part of the impressed current system was changed to the aluminium alloy anode system. The application of cathodic protection to the non-corrosion-protected structures has been carried out since 1986, although about 50% of the steel harbor structures have no corrosion protection. More than 17 years have now passed since these non-protected revetments and quays were constructed.

The positions of the revetments and quays which are taken up in this report are shown in **Fig. 2**, and their respective construction and the history of corrosion protection and repairs are shown in **Table 1**. As structural members, steel sheet piles, steel pipe piles and interlocked steel pipe piles are used, and their combinations and dimensions vary widely. For berths B, C and OA, and for W3 quay, cathodic protection was adopted at the same time as the structures were completed, but at some of the revetments and quays, cathodic protection was only adopted 3 to 20 years after the completion of construction. In addition, there are some places such as OD′ quay where the harbor structures have been left without protection for 22 years. At E-berth, the column for the jellyfish prevention net at the East seawater intake (point a), O-quay, P-berth, R-berth and the East-West connection bridge (point b) are being modified and repaired as mentioned in Sec. 4.

3 Corroded Condition of the Steel Materials

3.1 Corrosion Investigation at the West Plant and Oihama Area

In 1985, plate thicknesses were measured with an ultrasonic thickness gauge throughout the steel harbor

Table 1 Method of corrosion protection for wharves and revetments at Chiba Works

Symbol	Structural type (dia. (mm) × thick. (mm))	Finish of construction	Corrosion protection*[1]
B (Berth)	Steel walled pipe piles (863.6×10.3)	1965	①('65) ②('79)
C (Berth)	Steel walled pipe piles (1016.0×10.3)	1968	①('68) ②('79,'89)
E (Berth)	Steel pipe piles (762.0×7.1) (609.6×9.0)	1964	②③⑤ ('84)
a (Water entrance)	Steel pipe piles (318.5×6.9)	1972	③⑤('89)
L (Berth)	Steel sheet pile cell (KSP-F)	1961	①('64) ②('79,'89)
O (Revetment)	Steel pipe pile (300×6.4) Steel plate (t6)	1961	⑤('84) ②('90)
P (Berth)	Steel pipe pile (508, 660×7.9) Steel sheet pile (KSP-II)	1971	⑤('90)
R (Berth)	Steel walled pipe piles (508.8×9.0)	1962	②⑤('79)
OA (Berth)	Steel walled pipe piles (660×7.1)	1966	①('66) ②('79)
OD (Berth)	Steel walled pipe piles (1016.0×10.3)	1968	①('69) ②('82)
OD' (Revetment)	Steel walled pipe piles (1016.0×10.3)	1968	
OI (Berth)	Steel pipe pile (508.0×9.5) Steel sheet pile (KSP-IV)	1973	②④('86)
b (Bridge)	Steel pipe pile (914.4×12)	1971	②⑤('87)
W8 (Revetment)	Steel sheet pile (KSP-IV)	1971	②('88)
SA (Berth)	Steel pipe pile (609.6×12)	1973	②④('87)
W5 (Revetment)	Steel sheet pile (KSP-IV)	1971	
W4 (Revetment)	Steel sheet pile (KSP-IV)	1971	
NA (Berth)	Steel pipe pile (800~914.4×12~15.88)	1985	②,③('85)
W3 (Revetment)	Steel sheet pile (KSP-IV)	1971	②('71) ②④('86)

*[1] Corrosion protection method:
① Cathodic protection by impressed current
② Cathodic protection by aluminum alloy anode
③ Heavy duty polyethylene coated pipe (KPP)
④ Coating
⑤ Repair

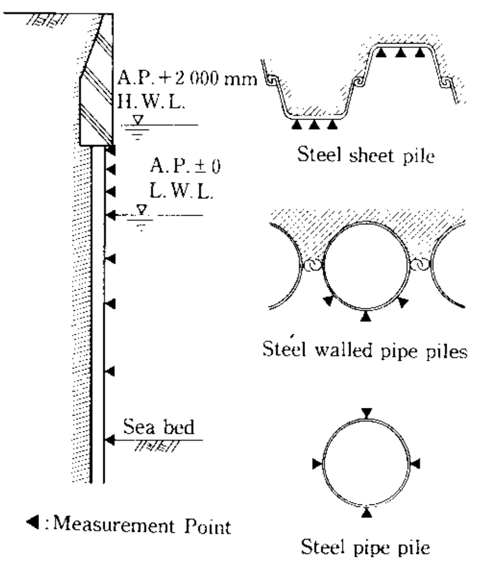

Fig. 3 Measurement point of steel plate thickness

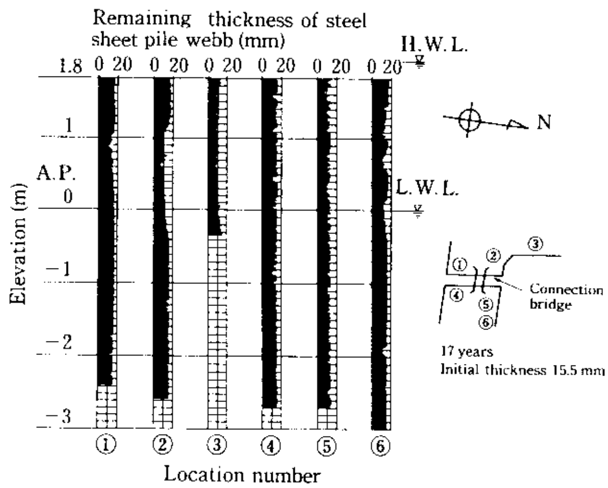

Fig. 4 Results of thickness measurement at W8 revetment

structures at the West Plant and over the entire Oihama Area. Measurement areas were set at an interval of about 50 m along the revetments and quays, the locations of the measuring points for plate thickness being shown in **Fig. 3**. The points to be measured were set at an interval of 0.5 m in the zone from H.W.L. to L.W.L., and at an interval of 1.0 m in the zone from L.W.L. to L.W.L.−2.0 m, thereby giving 5 to 9 points in total in each area. To measure plate thickness, three points were taken respectively on the convex and concave surfaces of the steel sheet piles, four points on the outer circumference for the steel pipe piles, and three points on the sea side for the interlocked steel pipe piles. These measurements of thickness were taken at each point and a mean value calculated.

In 1987, the vertical-direction continuous plate thickness distribution was investigated at W8-quay of the West Plant, using a measuring system employing an ultrasonic thickness gauge, which can give plate thickness data at an interval of 1 cm. The result is shown in **Fig. 4**, the measurement areas being locations ① to ⑥ in the steel sheet pile quays on both sides of the East-West connection bridge. These points had been left unprotected for 16 years since they were constructed, and all the measurements were taken on the convex side of the steel sheet piles.

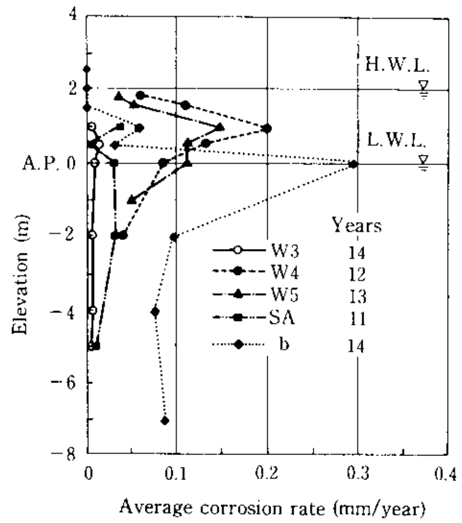

Fig. 5 Results of thickness measurement at West Plant

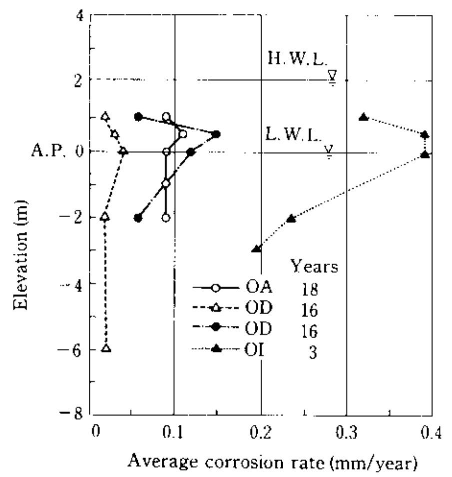

Fig. 6 Results of thickness measurement at Oihama area

Although the patterns for plate thickness decrease are different, the corrosion between AP −400 and AP +1 800 mm (the lower end of the concrete top to the steel sheet pile) was severe. At its worst, a thickness decrease of about 12 mm was observed aginst the nominal thickness of 15.5 mm, leaving very little material thickness. According to previous reports,[6,7] conspicuous corrosion (concentrated corrosion) is liable to occur immediately below the mean low water level (H.L.W.L.), and corrosion between the low and high water levels (L.W.L. and H.W.L.) is considered to be comparatively small; but in the present investigation, it is characteristic that concentrated corrosion was identified in L.W.L.–H.W.L. The results of the thickness measurements (1985) at the West Plant and Oihama Area are shown in **Fig. 5** and **6**, respectively. Because W3-revetment had been given cathodic protection by an aluminium alloy anode since it was constructed, the mean corrosion rate was as low as 0.008 mm/year. Different corrosion rates were observed at places such as the non-corrosion-protected W4 and W5 revetments, East-West connection bridge (point b) and SA-berth. The maximum value of the corrosion rate was found at a location between L.W.L. and M.S.L., its value being within the range of 0.04 to 0.3 mm/year. In the seawater-immersed portion of AP −2.0 m or below, the corrosion rate was below 0.1 mm/year. In the previous investigations,[6,7] it was reported that the mean corrosion rate on the convex surface of steel sheet piling was 0.057 mm/year near M.S.L., 0.126 mm/year near L.W.L. and 0.068 mm/year in the upper zone immersed in seawater. In the case of the W4 and W5 revetments, the same corrosion rates as thos in the previous investigations were obtained in the vicinity of L.W.L. and in the upper immersed zone, but near M.S.L., the corrosion rate was 1.6 times greater, thereby indicating that concentrated corrosion had occurred. In the steel pipe pile at point b, on the other hand, the peak value was seen at L.W.L., and the corrosion rate below L.W.L. was larger than that in the steel sheet pile, thereby giving a corrosion rate profile approximating to the value from the previous investigations. With the steel pipe pile at SA berth, no concentrated corrosion near the tidal zone was observed. The corrosion rates for non-corrosion-protected steel materials in "Technical Standard for Harbor Facilities and Commentaries[8]" are 0.3 mm/year in the splash zone above H.W.L., 0.1 to 0.3 mm/year in the tidal zone from H.W.L. to L.W.L., 0.1 mm/year in the seawater zone between L.W.L. and the sea bed, and 0.03 mm/year in the soil zone of the sea bed. These values near the maximum values of the mean corrosion rate in the non-corrosion protected areas shown in Fig. 5.

Regarding Fig. 6, OD-berth was given cathodic protection from the time of its construction; hence, its corrosion rate was nearly constant in the depth direction, being as low as 0.05 mm/year or less. Although OA-berth was given cathodic protection from the time of its construction, like OD-berth, its corrosion rate was higher at 0.09 mm/year. This may have been caused by the fact that the cathodic protection method by the impressed current system, which was installed at the time of its construction, was not of order for some time, thereby leaving OD-berth without corrosion protection. On the other hand, the interlocked steel pipe pile wall of OD-berth and OI-berth, which had no corrosion protection, were severely corroded in the tidal zone and showed the same trend as that at the West Plant. The corrosion rate at OI-berth was as high as 0.39 mm/year at the peak value, this steel sheet pile having a special construction with both sides exposed to seawater so that corrosion from both sides was progressing. If the corrosion rate from both sides was converted into a single-side corrosion rate, the corrosion rate in the tidal zone would be about 0.2 mm/year.

3.2 Corrosion Inspection at P-Berth of the Main Plant

When the steel plate thickness continues to decrease by corrosion, localized corrosion holes (pitting) soon occur in the material. As mentioned earlier, it is known that, in the tidal zone immediately below the mean low water level, severe localized corrosion will occur to a harbor structure.[9] At Chiba Works, some structures that had had no corrosion protection for more than 10 years were observed to have developed localized corrosion holes.

P-berth at the Main Plant was constructed in 1971. Since it was left without corrosion protection, the corrosion became severe. In about 1985, the steel sheet piles, which were exposed to seawater on both sides, developed localized corrosion holes. When repairs were made in 1990, the corrosion condition was investigated. Each steel sheet pile was of the II type. Out of 300 sheet piles, 270 had developed near-circular corrosion holes of about 20 to 150 mmϕ on both the concave and convex surfaces of the web, with a nominal original plate thickness of 10.5 mm, between L.W.L. and L.M.L. +1 200 mm (the lower end of the concrete at the sheet pile head). Further, out of 40 steel piles (508.0 mm in external diameter and 7.9 mm in wall thickness and 660.0 mm in external diameter and 7.9 mm in wall thickness) supporting the pillars of a building that overhangs the sea, eight had developed near-circular corrosion holes of about 100 to 700 mmϕ between L.W.L. and L.W.L. +1 200 mm (the lower end of pile head concrete). Since 19 years had passed since construction, the localized corrosion rate in the corrosion holes was considered to have reached 0.55 mm/year or more for both sides in the case of the steel sheet pile, and 0.42 mm/year or more in the case of the steel pipe pile.

From the plate thickness investigation, it was found that, excepting the corrosion holes in the tidal zone, (1) the steel sheet piles showed a mean residual plate thickness of 4.0 to 6.6 mm against a nominal original plate thickness of 10.5 mm, with a corrosion rate of 0.21 to 0.34 mm/year, and (2) the steel pipe piles showed a mean residual plate thickness of 4.3 to 6.0 mm against a nominal original plate thickness of 7.9 mm, with a corrosion rate of 0.1 to 0.19 mm/year.

A core sample was taken from the concrete at the top of the steel sheet piles near A.P. +1 300 mm/year to investigate the corrosion of the steel sheet pile inside the concrete. It was clarified that virtually no corrosion had occurred.

The corrosion holes in the steel sheet piles at P-berth are shown in **Photo 1**.

4 Corrosion Protection Measures

4.1 Cathodic Protection

Cathodic protection at present uses the aluminium alloy anode system in all cases, and a typical installation is shown in **Photo 2**. In terms of design, the life of the anode is set at 10 years. Regarding the protective current density at the start of cathodic protection, the design was based on the result of a preliminary electric current flow test at O-berth of 130 mA/m^2 in seawater, 30 mA/m^2 in the sea-bed soil and 60 mA/m^2 in the rubble mud. In calcuulating the design life of the anode, it is considered that the required corrosion-prevention current after the design life has elapsed will have dropped to about half the initial value. The electrode potential for cathodic protection is set at -800 mV vs. SCE. The consumption rate of the anode is liable to be different from the design consumption rate due to changes in the water quality and water depth. Thus, electrode potential monitoring is carried out once a year in order to confirm whether or not the potential of the anode after its installation is being kept at a lower potential than the electrical potential for cathodic protection. At any position where the anode potential was higher than the electrode potential for cathodic protection and where the elapsed years of the anode were approaching the design life, a diver was employed to

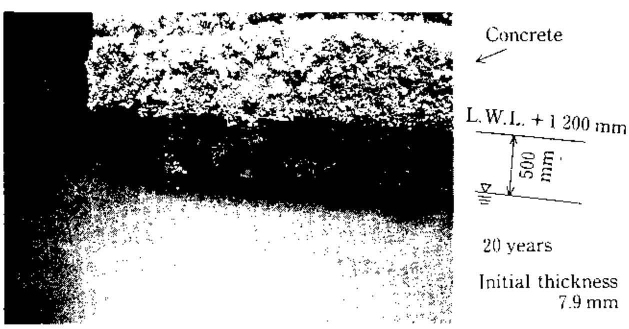

Photo 1 Corrosion of steel pipe piles at P-berth

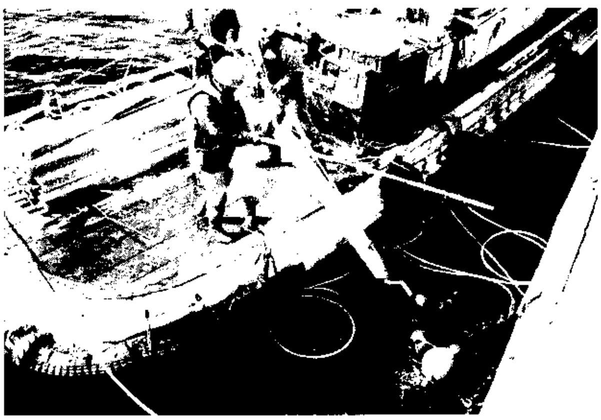

Photo 2 Aluminum alloy anode installation

remove deposits on the anode surface, to measure the shape and dimensions of the anode, and to investigate the remaining life of the anode, its consumption rate (consumed weight/years expired) and consumption ratio (actual consumption rate/design consumption rate).

In six areas where anodes were installed in 1979, an anode investigation was carried out in 1988. For C- and L-berths, the measured values for the anode consumption rate nearly agreed with the design consumption rate. However, at B-, D-, Q-, and OA-berths, it was found that one to four more years remained in addition to anode design life of ten years. Conceivable reasons for this are that (1) the unit effective quantity of electricity from the aluminium alloy anode, which had been estimated at 2 300 A · h/kg was found to be larger than this estimated value; (2) the protective current density by electro-coating had dropped significantly; (3) the water depth had become shallower than that at the initial stage of design and the surface area of the steel structure in the seawater had decreased; (4) the water quality had improved; and (5) there was an in-flow of protective current from nearby structures.

It is important to confirm the consumed state of the anode by potential measurement and anode investigation in order to estimate the renewal time for the anode and any changes in the environment.

4.2 Effect of Combined Cathodic Protection and Painting (Coating)

Cathodic protection, which is very effective in seawater, is not effective in the splash zone, and is only effective in the tidal zone when the steel structure is immersed in the water. Therefore, in the splash and tidal zones, corrosion protection by painting and coating becomes necessary. At Chiba Works, painting with tar-epoxy resin paint and other organic coatings has been employed for the splash zone, and since 1986, an underwater hardening type of resin coating has been applied to W3-revetment, OI-berth and SA-berth in the tidal zone.

When cathodic protection and painting (coating) are used in combination in the tidal zone, the protective current is rarely required. It has been reported that the consumption of the anode was suppressed and the life of the anode was extended.[10] At the SA-berth revetment, measurements were made of the potential and protective current when cathodic protection and coating were used in combination. The SA-berth revetment had had no corrosion protection since its construction in 1973. However, an anode was fitted in July 1987, and the underwater hardening type of resin coating was applied in the tidal zone in December 1987.

Daily variations in the potential and the protective current were compared before and after coating, the result being shown in **Fig. 7**. Before the coating was applied, the potential and protective current for the steel sheet piles changed, but after coating no changes in the

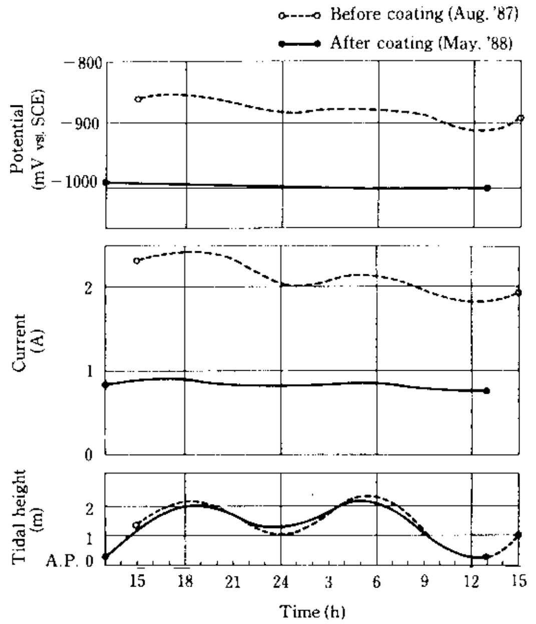

Fig. 7 Change of potential and current in a day

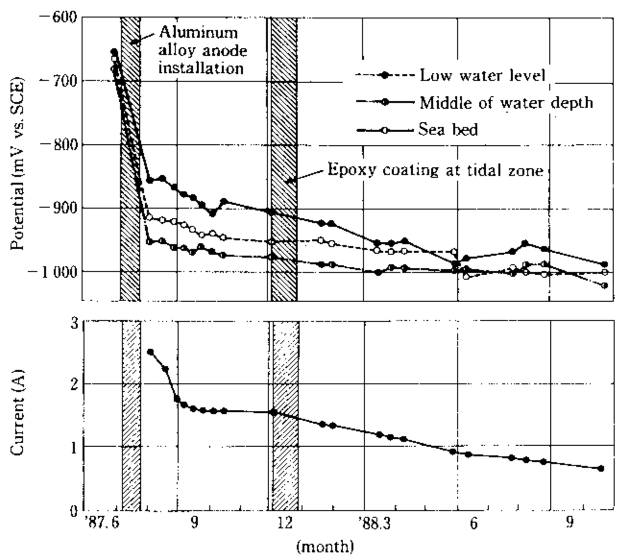

Fig. 8 Change in potential and current with time

potential and current were apparent. Compared with before coating, the potential was reduced by about 110 mV, and the protective current decreased by about 1.2 A (about 57%).

Changes in the potential and current with time are shown in **Fig. 8**. After the coating work in December 1987, the potential began to drop and the protective current also decreased, thereby demonstrating the effect of coating in the tidal zone.

When painting was carried out in the tidal zone in this way, the potective current for cathodic protection decreased and longer life of the aluminium alloy anode could be expected. It is considered that the protective current would increases depending upon the degree of deterioration of the coating. Conversely, it was possible to diagnose the soundness of the coating by measuring the potential and protective current.

4.3 Repairs to Corroded Steel Structures

Repairs were carried out on steel structures which had deteriorated by corrosion, a summary of these repairs being given in **Table 2**. Their common feature was that they had had no corrosion protection since their initial construction, until they were repaired. Repair methods were of two types: one involved fitting reinforcing steel plates and external pipes, as to the corroded parts of existing structures at R-berth, O-revetment, East-West connection bridge (point b) and P-berth, while the other involved removing the existing structures or constructing new structures adjacent to the existing structures as at E-berth, and constructing columns for jellyfish prevention nets at the East seawater intake (point a).

Table 2 Repairs made to wharves and revetments at Chiba Works

Name	Year	State of corrosion	Repairing method
R berth	1979	· Steel pipe piles heavily corroded · Some localized holes through steel plate at the piles	· Steel plate weld at the holes · Aluminum alloy anode installed
E berth	1984	· Steel pipe piles heavily corroded · Remaining wall thickness of piles were 7.5 mm to 8.5 mm (initial 9.0 mm) · Some localized holes through steel plate at the piles	· Protection by polyethylene coated pipes (KPP) · Additional KPP piles driven
O revetment	1984	· Steel pipe piles and steel plates heavily corroded · Some holes through steel plate at the plates	· Steel plate covering and cement mortal injection
Connection bridge (b)	1987	· Steel pipe piles heavily corroded · Remaining wall thickness of piles were 7.6 mm (initial 12.0 mm)	· Protection by urethane resin coated pipes and concrete injection · Aluminum alloy anode installed
Sea water entrance (a)	1989	· Steel pipes heavily corroded · Some localized holes through steel plate at the piles	· Replaced by KPP piles
P berth	1990	· Steel pipe piles and sheet piles heavily corroded · Remaining wall thickness of piles were 4.3 to 6.0 mm (initial 7.9 mm) · Some localized holes through steel plate at the pipe piles and sheet piles	· Protection by urethane resin coated pipes and cement mortal injection · Steel plate weld at the hole of the sheet piles

At R-berth, the interlocked steel pipe piles had developed corrosion holes, and the soil mound at the back caved in due to the out flow of sand. Reinforcing steel plates were welded over the corroson holes and cathodic protection was applied.

At E-berth, the corroded steel pipe piles were repaired by fitting a heavy-duty, anti-corrosion steel pipe pile (KPP pile) over the corroded steel pipe pile (the former being of a larger size than the latter), and by grouting the gap between the two pipe piles with concrete.

At O-revetment, the steel-plate earth-retaining wall developed corrosion holes, and the sand mound at the back caved in due to the out-flow of sand. Steel plates were bolted to the front of the existing earth-retaining wall and cement mortar was used to fill up the gap. The steel pipe piles for the piers of the East-West connection bridge (point b) had developed severe corosion near L.W.L. as shown in Fig. 5. Therefore, steel pipe halves coated with urethane resin was fitted in the tidal zone and joined by welding, before the annular gap was filled with underwater concrete to secure the outer pipe.

In the repair of the columns for jellyfish prevention nets at the East seawater intake (point a), heavy-duty anti-corrosive steel pipe piles were placed adjacent to the existing corroded piles, and the corroded piles were later removed.

At P-berth, the steel sheet piles and steel pipe piles had developed corrosion holes as mentioned in Sec. 3.2. Reinforcing steel plates were welded to the steel sheet piles, and the steel pipe piles were repaired by the double-pipe method, which used an urethane resin coating, after which the underwater joining method[11] was applied.

4.4 Double-Pipe Repairs to Corroded Steel Pipe Piles

Of the repair methods mentioned in Table 2, the double-pipe repair procedure is next described.

4.4.1 Full-scale test of the double-pipe repair[12]

When the steel pipe piles for the piers of the East-West connection bridge were repaired by the double-pipe method, a full-scale model test was carried out prior to the site work in order to confirm the reinforcing effect.

The structure types which were compared are shown in **Fig. 9**. Bending tests and compression tests were conducted on all four types. Type 1, whose corroded por-

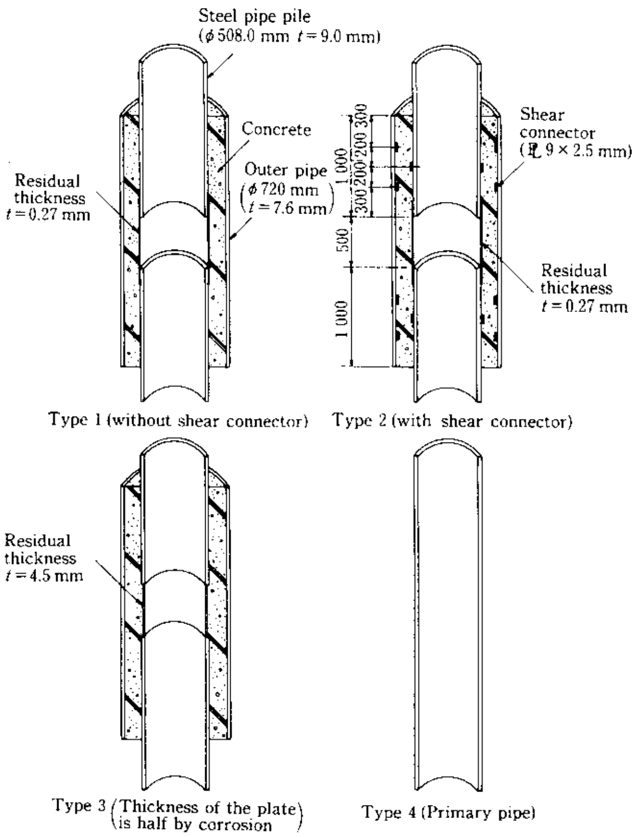

Fig. 9 Specimens for loading teste

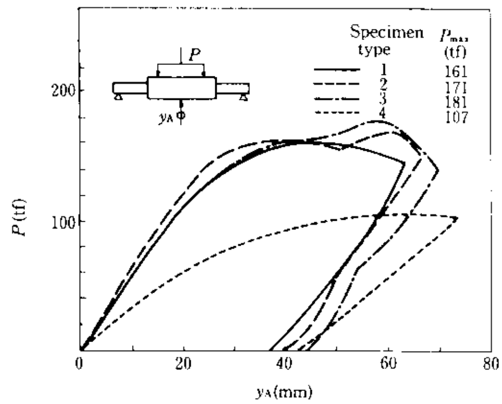

Fig. 10 Load (P)—displacement at the centre (y_A) in the bend test

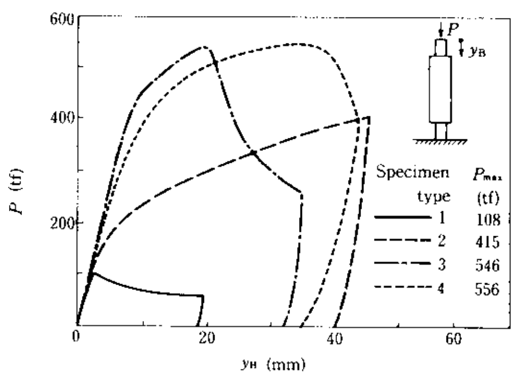

Fig. 11 Load (P)—displacement at the top (y_B) in the compression test

tion had no cross section at all, was reinforced against bending by the external pipe. With type 2, whose corrosion resulted in the loss of cross section like type 1, reinforcement against bending was provided by the outer pipe, and the axial force was handled by reinforcement with ribs. With type 3, whose corroded area was reduced to half the original thickness, bending and axial forces were handled by external-pipe reinforcement and the residual plate thickness together. Type 4 was a sound pipe. For the corroded steel pipe model, steel pipe with an external diameter of 508.0 mm and thickness of 9.0 mm was used. For the reinforcing pipe model, steel pipe with an external diameter of 720.0 mm and a thickness of 7.6 mm was used.

The relationship between the load and central displacement of the specimen in the bending tests is shown in **Fig. 10**. In the case of types 1, 2, and 3, whose corroded areas had been reinforced, displacement from the same load as that applied to type 4 was little, and the reinforcing effect on bending rigidity by the external pipe was demonstrated.

The relationship between the load in the compression test and the degree of head displacement is shown in **Fig. 11**. All the types showed the same trend, until load P rose to nearly 100 tf. Type 1, when compared with the sound type 4 pipe, showed a P_{max} value of about 20%, indicating that the reinforcing effect against axial load was small. On the other hand, type 2 with ribs, when compared with the sound type 4 pipe, had a larger displacement y_B under the same load, and the maximum P_{max} value was about 85% of that for the sound pipe, indicating the effect of axial load resistance by the ribs. From these experimental results, it was confirmed that repair by fitting an external pipe had a sufficient reinforcing effect against bending, and further, that the fitting of ribs had a reinforcing effect on axial force.

4.4.2 Repairs to P-berth steel pipe piles

The post-repair condition of the steel pipe piles of P-berth is shown in **Photo 3**. These steel pipe piles of P-berth had, as mentioned in Sec. 3.2, a residual thickness of 4.3 to 6.0 mm within the range of L.W.L. to L.W.L. + 1 200 mm, and in some locations, little thickness existed. Therefore, it was necessary to reinforce the piles against axial force and bending, after making a comparative examination of various reinforcing methods for their workability, economy, and reliability. As a result, it was decided to adopt the double-pipe repair

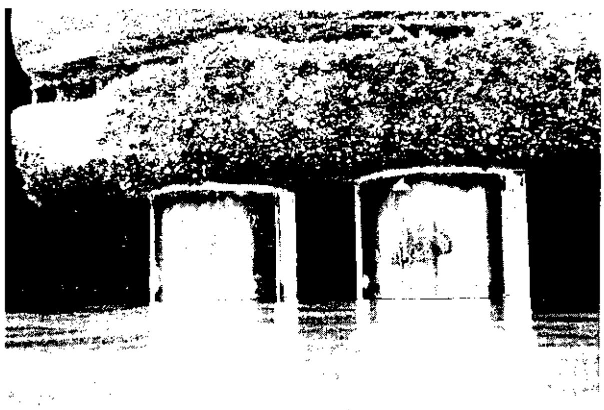

Photo 3 Repairing of steel pipe piles at P-berth

method which employs the underwater joining method.[11] Steel pipe halves, which had a larger external diameter than that of the corroded piles, were fitted around the external circumference of the corroded steel pipe, and the external pile joints were connected by bolting. Expanding concrete was then filled into the gap between the corroded pipe and external pipe to achieve consolidation between the two pipes. The corroded steel pipe numbered 34 with an external diameter of 508.0 mm and a thickness of 7.9 mm, and 6 with an external diameter of 660.0 mm and a thickness of 7.9 mm, giving 40 pipes in total. The diameter of the external pipe was set so that the gap between it and the corroded pipe would be 10 cm or more, and the length of the external pipe was set to that which would cover a length of 1.0 m more than the length of the corroded pipe. The external pipe was coated beforehand at the plant as an anti-corrosive measure with urethane resin, an underwater hardening type of resin being used for the joint.

4.5 Application of Heavy-duty Anti-corrosion Steel Pipe Piles (KPP Piles)

The KPP pile is a shot-blasted pipe which is wound over its external surface with a 2.5-mm-thick polyethylene sheet. One of the greatest features of this pipe is that it is maintenance-free for a long time, the polyethylene layer providing excellent corrosion resistance, weather resistance and impact rresistance. Kawasaki Steel started the full-scale manufacture and sales of this pipe in 1984 and has many application records both inside and outside the company.

The use of this pipe at Chiba Works is shown in **Table 3**. 51 t of this pipe were used for the first time for E-berth in 1984, and 5 914 t of KPP piles in total have been used during the seven years up to 1990. Particularly in the construction of the new NA-berth (1985),[13] 450 KPP piles with a diameter of 800 to 914 mm were placed, contributing greatly to the prevention of pile cover damage during driving, to decreasing the weight of superstructures on the revetment, and to accumulating KPP application techniques. The KPP pile is extremely effective as a non-corroding steel pipe pile when constructing a new revetment, and can also be used for refurbishing steel structures which have deteriorated by corrosion, as already mentioned in Sec. 4.3. **Photo 4** shows an example of KPP pile utilization at E berth. KPP piles were fitted over corroded steel pipe piles near the center to refurbish the corroded pipe piles of the pier.

Table 3 Application list of KPP piles at Chiba Works

Name	Year	Diameter (ϕ mm)	No. of piles (set)	Weight (tf)
E berth	1984	609.6~762.0	20	51
NA berth	1985	800~914	450	5 210
a	1989	318.5	31	29
OD berth	1990	609.6~1 016	43	624
Total				5 914

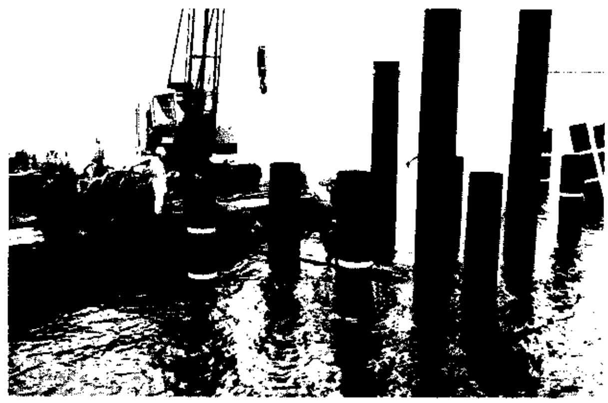

Photo 4 KPP pile installation for the renewal of E-berth

The demand for KPP piles looks set to increase because of their maintenance-free corrosion protection.

5 Conclusions

This paper has reported the corrosion condition of harbor steel structures at Chiba Works, corrosion protection techniques, and repair methods. The results are summarized as follows:

(1) Mean corrosion rate at non-corrosion-protection parts of steel pipe piles, interlocked steel pipe piles and steel sheet piles in the tidal zone at the West Plant and Oihama Area of Chiba Works was comparatively high at 0.1 to 0.3 mm/year. Concentrated corrosion in the tidal zone was observed in steel

pipe piles, interlocked steel pipe piles and steel sheet piles at the Main Plant, the corrosion rate being about 0.3 mm/year or more.

(2) The mean corrosion rate of steel material which had been given cathodic protection by an aoluminium alloy anode was 0.008 mm/year or less, thereby confirming the beneficial effect of cathodic protection.

(3) Control of this cathodic protection by electrode potential measurement and anode inspection is beneficial for monitoring the anode life and protective effect. When cathodic protection and coating in the tidal zone were used in combination, the protective current decreased and the anode life was prolonged.

(4) The double-pipe method for repairing corroded steel pipe piles proved its adequate reinforcing effect by a full-scale test. Its workability was also satisfactory to reinforce its effectiveness.

(5) Heavy-duty anticorrosion steel pipe piles (KPP piles) are maintenance-free for a long period and their coating cost is comparatively low. This type of pipe proved economical in the long term and a very useful structural material for constructing new or refurbishing harbor structures.

There still remain unporotected non-corrosion-protection steel quays and revetments left and it is necessary to promote the greater application of cathodic protection to these strucures.

Since cathodic protection is not sufficient in the tidal zone, other countermeasures such as coating and concrete covering should be used in combination. Development is required of anode replacement and surface coating methods that are more economical to apply.

Through periodical corrosion investigations and corrosion-protection effect surveys, it is important to constantly grasp safety against corrosion of various structures and to continue correct maintenance and control.

References

1) I. Fukuda and T. Takahashi: *Gekkan Kensetsu*, **32**(1988)5, 34–40
2) M. Hashimoto, K. Okamoto, and T. Morikawa: *Kawasaki Steel Giho*, **17**(1985)2, 185–192
3) K. Zen: "Corrosion and corrosion protection of port and harbour facilities", *Boshoku Gijutu* (*Corrosion Engineering*), **34**(1985)3, 185–192
4) M. Nagano, T. Sakaki, T. Kimura, K. Okamoto, K. Wada, and K. Shiota: *Kawasaki Steel Giho*, **20**(1988)4, 261–268
5) Coastal Development Institute of Technology: "Koowan Kozobutsu Boshoku Mannal (Manual for corrosion protection for steel structures in port and harbour facilities)", (1986)
6) T. Yokoi: "Actual states of corrosion and corrosion control methods of steel structures in marine environments", *Boshoku Gijutu* (*Corrosion Engineering*), **38**(1989)7, 390–395
7) T. Yokoi: Proc. of JSCE Conf., **403**(1989) VI-10, 85–92
8) Japan Port and Harbour Association: "Koowan no Shisetsu no Gijutsujo no Kijun · Kaisetsu (Technical standards for harbour facilities)", (1979)
9) T. Nakano: "Maintenance and Repair techniques for port harbour structures", Proc. of Port and Harbour Engineering Conference, 4(1987), 184–196
10) M. Abe and S. Yokoi: "Experiments on cathodic protection using together with coating", Technical note of the PHRI, (1985)537, 1–39
11) K. Tsutsumi, M. Nei and I. Joe: 25th Kokan-Koji Hokokukai, (1979), 217–222
12) Y. Horinouchi, K. Wada and K. Shiota: Proc. of 44th JSCE Conf., (1989), 852–853
13) M. Tominaga, E. Kenmochi, T. Kimura, and I. Okumura: JSCE Technical Report, **385**(1987), 116–125