A STUDY ON THE EFFECT OF CATHODIC PROTECTION FOR REINFORCING BAR IN RC PIER UNDER TIDAL AND SPLASH MARINE CONDITION

TADO, Hiroto
Port and Airport Research Institute, materials Investigation Group

Yamaji, Toru
Port and Airport Research Institute, materials Investigation Group

Hiroyuki KOBAYASHI
Nakabohtec Corrosion Protecting Co., LTD

濱田, 秀則
九州大学大学院工学研究院社会基盤部門 : 教授

https://hdl.handle.net/2324/4481619

出版情報：Advances in Construction Materials Proceedings of the ConMat'20, 2020-08-27. 日本コンクリート工学会
バージョン：

A STUDY ON THE EFFECT OF CATHODIC PROTECTION FOR REINFORCING BAR IN RC PIER UNDER TIDAL AND SPLASH MARINE CONDITION

Hiroto TADO [1], Toru YMAJI [2], Hroyuki KOBAYASHI [3] and Hidenori HAMADA [4]

[1] Port and Airport Research Institute, materials Investigation Grope, tado@p.mpat.go.jp
[2] Port and Airport Research Institute, materials Investigation Grope, t-yamaji@p.mpat.go.jp
[3] Nakabohtec Corrosion Protecting Co., LTD, Acting Section, h. kobayashi2@nakabohtec.co.jp
[4] Kyushu University, Department of Civil Engineering, Professor, h-hamada@doc.kyushu-u.ac.jp

Abstract

When sections of port structures in water (such as piers) are steel structures such as steel pipe piles, it is common to apply cathodic protection to the steel pipe piles using a galvanic anode system. However, rebars during the construction of the upper part of the pier are electrically conducted with the steel pipe piles in the sea. If the upper construction concrete sinks into the sea, protective current from the galvanic anode in the sea flows into the rebars in the concrete. Moreover, during construction on the upper part of the pier during the tidal zone, if cathodic protection is applied using an impressed current system, the wetting situation within the same parts will differ and the distribution of the protective current will become uneven. In this study, we installed a long RC specimen in a tidal environment, imitating a part of a peer, to grasp the potential and protective current distribution for cases of conductance from the electrodes in the upper section construction, conductance from the galvanic anodes in the lower construction section and conductance from both the upper and lower section construction. Moreover, by evaluating the corrosion status of the rebars in the concrete, we examined the effects of cathodic protection. Based on these results, we can see that, in this test, while conducting to the lower section construction through the galvanic anodes, even when the application of cathodic protection to the upper section construction was HWL or above, there were prevention effect in the steel materials within the concrete near the tidal zone.

Keywords: Pier, Cathodic protection, Corrosion rate, Tidal zone, Prevention effect, Depolarization quantity

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Hiroto Tado
Port and Airport Research Institute
3-1-1Nagase
Yokosuka City,Kanagawa 2390826
Japan

E-mail Adress: tado@p.mpat.go.jp
Telephone Number: +81-46-844-5103

1. INTRODUCTION

As port structures, such as piers, are in severe salt environments, cathodic protection may be applied using the impressed current system as a salt damage measure for upper section rebar concrete (hereafter, upper section construction). Moreover, when the lower section is a steel structure (hereafter lower section construction), it is typical for cathodic protection to be applied using the galvanic anode system for steel structures in the sea. As both the upper section construction and lower section construction are electrically conductive, if the upper section construction is sunk in the seawater, the protective current will flow to the rebar. However, there are few cases that allow us to grasp the impact of the wetting environment because of the tide on the rebar potential and protective current distribution if cathodic protection is applied to the upper section construction and lower section construction. Therefore, if cathodic protection is applied to the lower section construction, the scope of application of cathodic protection on the upper section construction is unclear. Furthermore, the effects of cathodic protection on the upper section construction are based on the potential change quantity known as "depolarization quantity 100 mV or more" [1] as a standard value. However, because, in wetting environments such as tidal zones, the supply rate of dissolved oxygen on steel surfaces is slower; furthermore, the potential change gently occurs [2], and this depolarization quantity may not be satisfied.

In this study, we install a long RC specimen imitating part of a pier in a water tank that imitates the tides. This specimen electrically conducts concrete imitating upper section construction and steel materials that imitate lower section construction. Then, cathodic protection is applied to the lower section construction using the galvanic anode system and conductance occurs from the electrodes buried in the upper section construction to the steel materials in the concrete. Under these conditions, by examining the potential of the steel materials in the concrete and the protective current distribution, we reviewed the impact of the protective current from the galvanic anodes in the lower section construction. Furthermore, as a judgement indicator for the prevention effects in a wetting environment, we examined the application of repassivation potential and the corrosion rate during conductance. About the corrosion rate, this is the estimated corrosion rate at the time of conductance of the intersection point with the Tafel slope straight line extrapolated from the potential directly after stopping conductance (instant OFF potential) and anode polarization curve at the time of conductance.

2. TEST METHOD

2.1. Specimen overview

Table 1 lists the concrete formulation. The cement is normal Poltland Cement, the fine aggregate is natural sand, and we used macadam for the coarse aggregate (maximum aggregate dimension = 20 mm). The target slump is 10 ± 2.5 cm, and the air quantity is 4.5% ± 1.5%. For the concrete, sodium chloride is used when kneading together, and chloride ions are mixed in to make it 10 kg/m^3. The specimen's shape is shown in Figure 1(a)(b) . Eight round steel bars installed in the concrete and the sea SR19 are wired such that they are integrated together via galvanic anodes and switches, providing resistance to adjust the generated current. Furthermore, conductance from within the concrete is through linear titanium steel electrodes (hereafter MMO electrodes) buried within seven areas of concrete. The round steel bars, before being buried in the concrete, had their black film removed through sandblasting processing; furthermore, after one month of seawater spray, they were used after

Table1. Concrete formulation

W/C (%)	s/a (%)	Unit quantity（kg/m^3）				
		W	C	S	G	AE Water reducing agent
50.0	46.0	168	336	808	975	1.19

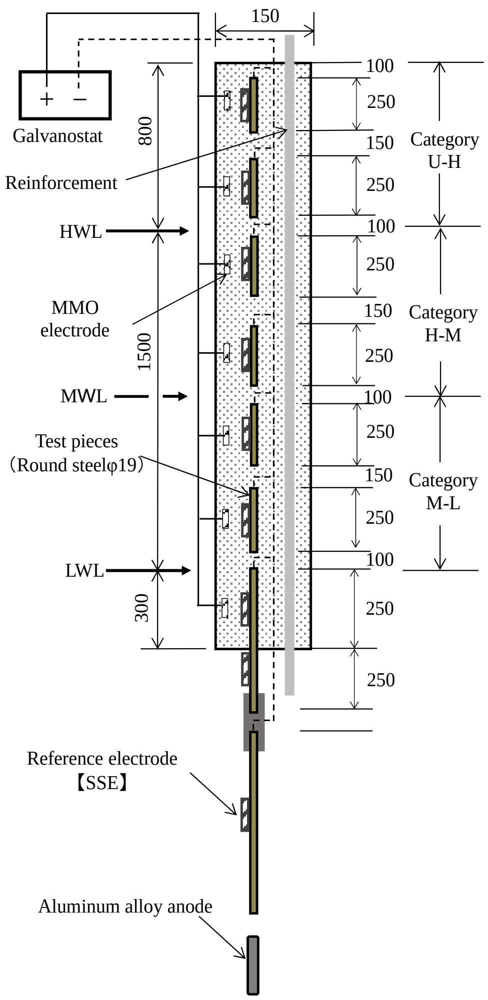

Figure 1(a). General drawing of a specimen

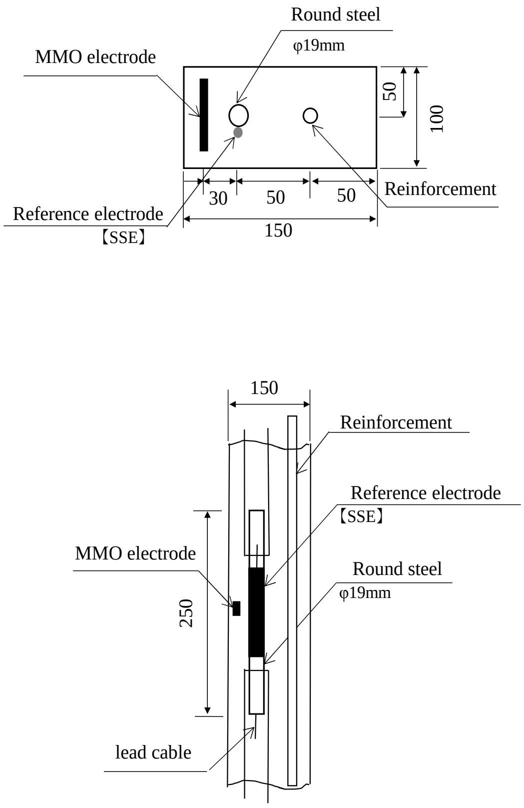

Figure 1(b). Cross-sectional drawing

corrosion was generated. For reference electrodes, a saturated silver chloride electrode (hereafter “SSE”) was buried next to the steel materials. Moreover, the surface connected to the seawater had two surfaces of concrete placement surface and bottom surface, and the four other surfaces had epoxy resin applied.

2.2. Conductance method

Table 2 lists the cathodic protection conductance case for the specimen. Case P shows the case when conductance occurs only on the galvanic anodes in the lower section, case A-P shows the case when, while conducting via the galvanic anodes in the lower section construction, conductance occurs from all MMO electrodes installed in the upper section construction, and case H-P shows cases where conductance occurs from MMO electrodes installed at HWL (full tide position) or above in the upper section construction. Furthermore, Figure 2 shows an image of the protective current flowing to the upper section construction from the lower section construction galvanic anodes because of high tide. Conductance to the upper section construction is performed using the constant current system, and the galvanostat is used as a DC power supply. The conductance current from the MMO electrodes is the current value at which steel materials of HWL or above can maintain depolarization quantity of approximately 100 mV without conducting lower section construction galvanic anodes. Furthermore, the lower section construction, in relation to the steel materials exposed to seawater, has the initial protective current density set to the typical protective current density of 100 mA/m^2. Measurement in each case starts after the potential of the steel material in the lower section construction reaches steady state. At this time, the conductance current from the lower section galvanic anodes is reduced to

Table2. Conductance Case List

Case	In concrete		Underwater	Current density（mA/m²）	
	All electrode	Electrode over HWL		In concrete	Underwater
P	—	—	●	0	100
A-P	●	—	●	10	100
H-P	—	●	●	10	100

●: Applicable

Current density in the sea : Represents the initial current density

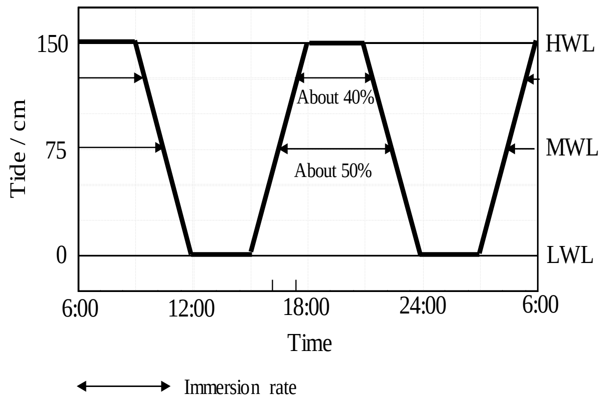

Figure3. Tide cycle diagram

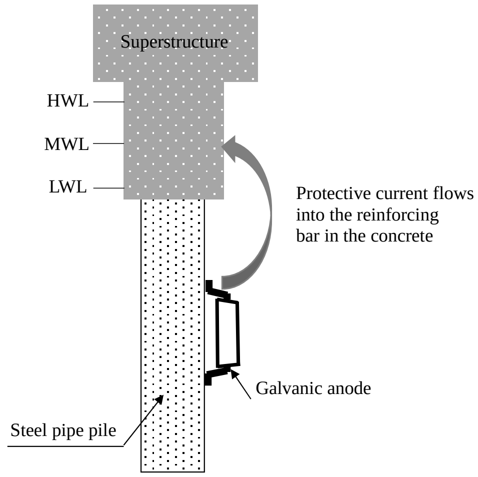

Figure2. Image of protective current inflow

~70%. The conductance time for each case was set to approximately two weeks. After each case was completed, a non-conductance period of approximately one week was set, and after the potential depolarized, the conductance for the separate case was started.

2.3. Exposure environment

The specimen was placed within the Port and Airport Research Institute. The tide cycle is an environment that is repeated twice every day (tidal variation = 1.5 m), and this cycle is shown in Figure 3.

2.4. Measurement items

(a) Steel material potential

The steel material potential was measured using SSE. Within this document, this is shown in a form after conversion to the saturated copper sulfate electrode standard (hereafter “CSE”).

(b) Incoming flow current to steel materials.

For the incoming flow current to the steel materials, the measured voltage was converted to current and shown after inserting a resistor (1 Ω) into the steel materials.

(c) Steel material depolarization quantity

The depolarization quantity is the difference between the instant OFF potential immediately after conductance stops and the potential 24 h after conductance stops. The depolarization quantity measurement results, for each case, are after the potential change has become steady. The measurement was conducted at a low tide.

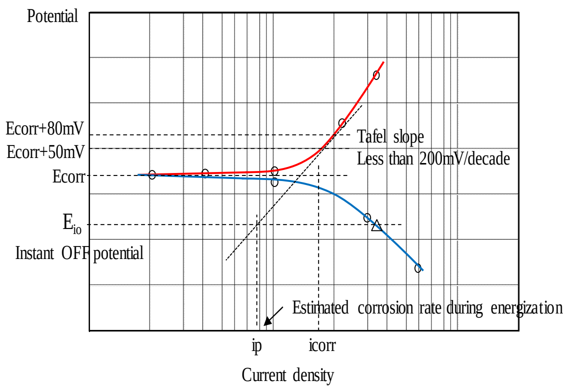

Figure4. Overview diagram of steel corrosion rate estimation

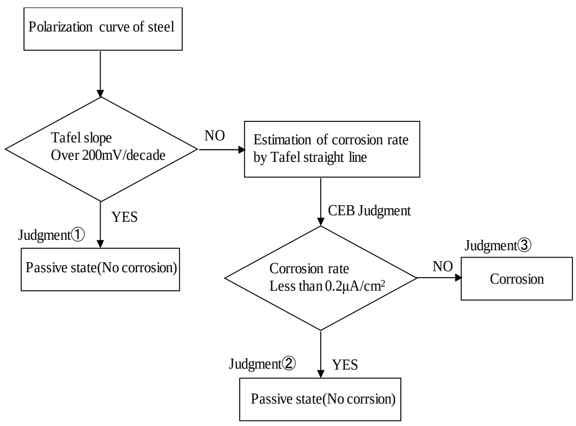

Figure5. Corrosion judgment flow of steel on wetting environment

(d) Corrosion rate at the time of conductance

We measured the ON potential (Eon), instant OFF potential (Eio), and conductance current (I) before starting the measurement. Next, using a Potentiostat, we measured the ON potential at the time of conductance and by changing the potential in the direction of the anode at a rate of 20 mV/min measured the steel polarization curve when cathodic protection was applied. The potential on completion was set to the potential after polarizing the potential after switching from the cathode current to the anode current (natural potential: Ecorr) at approximately 120 mV in the + direction. We obtained environmental resistance Rs (mainly concrete resistance) based on the formula(1), and calculated the voltage drop IR from the environmental resistance and force current at the time of polarization measurement.

$$Rs = \frac{|Eon - Eio|}{I} \qquad (1)$$

Figure 4 shows the obtained polarization curve and the intersection with the straight line of the Tafel slope straight line extrapolated from the instant OFF potential, and anode polarization curve is the estimated corrosion rate at the time of conductance. In this study, based on the reference document [4], the anode polarization curve Tafel straight line was set within the range of 50–80 mV changed in the +direction from the natural potential. According to the reference document [4], because the relationship between the steel material corrosion weight loss obtained from the corrosion rate estimated when applying cathodic protection and the actual corrosion weight loss measured from the recovered steel materials is an equivalent relationship, which can be utilized as a method of evaluating the corrosion rate when applying cathodic protection. Furthermore, based on reference documents [5] and [6], if the Tafel slope from the polarization curve shown in Figure 5 exceeds 200 mV/decade, and the steel materials are considered to be passivated. If the Tafel slope is within 200 mV/decade, the estimated corrosion rate is judged according to ① to ③ considering the steel material corrosion status using the CEB standard (draught) [7].

3. TEST RESULTS

3.1. Potential measurement

Figure 6 shows the results of potential measurement at the time of low tide in each case and at a high tide in Figure 7. The potential in the HWL to MWL (hereafter, category H-M) is in the direction for high tide compared to low tide. This is thought to be because, as it moves towards high tide, the protective current flows from the galvanic anodes in the lower section construction. Here in case the corrosion occurs because of chloride ion in the passivated steel materials, this corrosion can cause

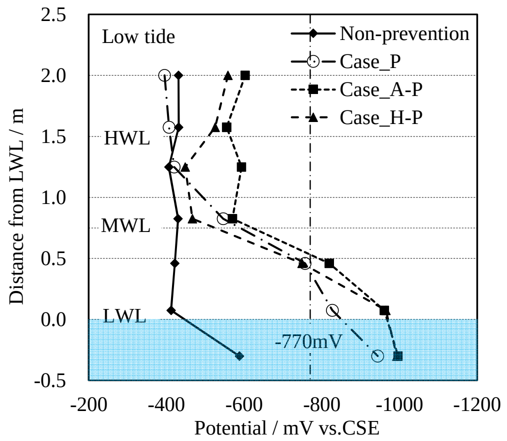

Figure6. Potential at low tide

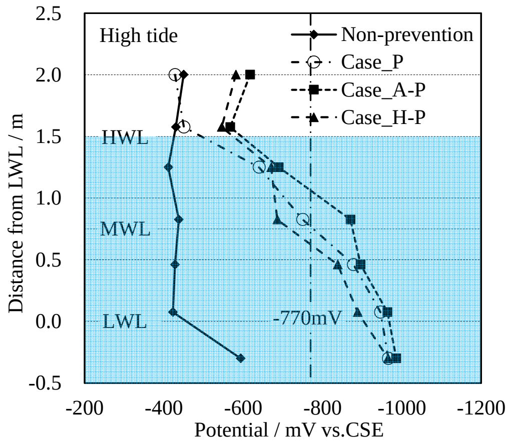

Figure7. Potential at high tade

pitting or crevice corrosion. To prevent this corrosion, cathode polarization should be performed until it reaches the potential where the passivated film once broken is reformed. Following [1], if the measured potential is at the repassivation potential, it is judged the steel materials are not in the corroded state. In this study, the -770 mV vs. CSE[8] is used as a reference for repassivation potential. Furthermore, as the potential at high tide is at + direction compared to low direction, this is evaluated according to the potential measured at low tide. Using Figure 6, at +0.5 m or below, for all cases, it was below the repassivation state. In other words, we learned that category M-L steel materials were not in the corroded state.

3.2. Flowing current

Figure 8 shows the results of measuring the current flowing to the steel materials at low tide for each case and Figure9 shows those for high tide. At low tide, for cases A-P and H-P, we confirmed that the respective designated currents were being conducted; however, at high tide, for cases A-P and H-P, the inflow quantity increased within the category H-M range. However, no change was directly seen in the inflow quantity for steel materials above LWL. Moreover, in the case of category H-M at high tide, the maximum inflow current values were virtually the same for case P and cases A-P and H-P. In this case, nearly all of the current flowing in at high tide is considered to be protective current from galvanic anodes in the lower section construction.

3.3. Depolarization quantity measurement

Figure 10 shows the depolarization quantity measurement results in cases A-P and H-P at low tide. For HWL and above (hereafter category U-H), the depolarization quantity was virtually satisfied.

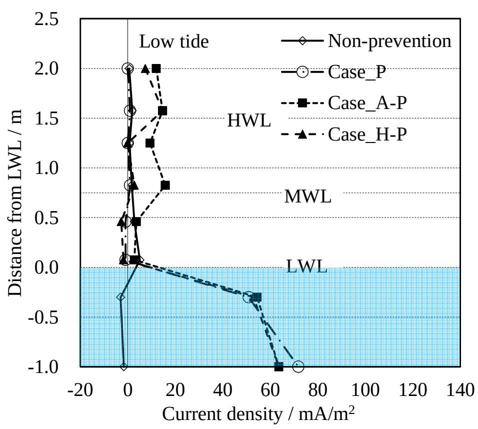

Figure8. Current distribution at low tide

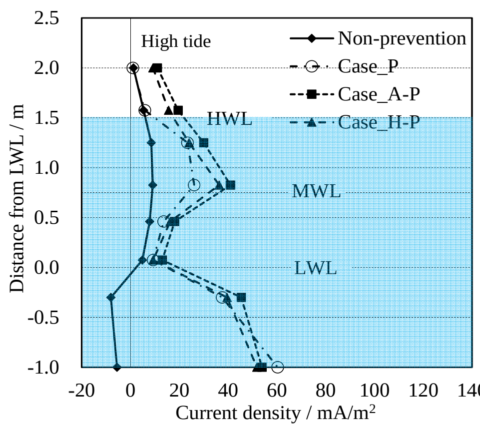

Figure9. Current distribution at high tide

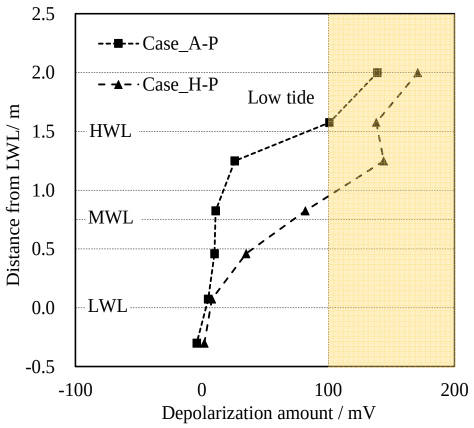

Figure10. Depolarization quantity change

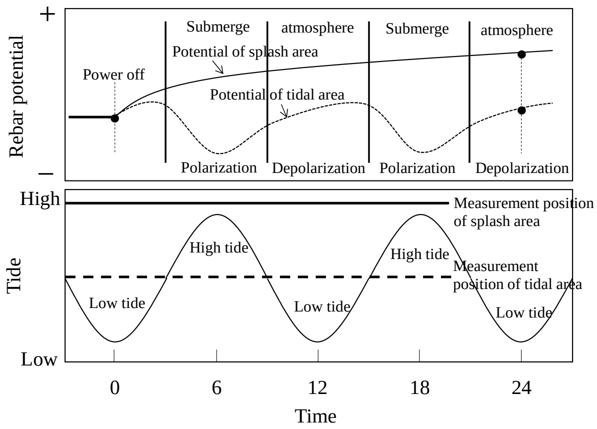

Figure11. Potential change in case of galvanic anodes in the lower section construction

Category H-M, at a high tide, has approximately twice the inflow of flowing current for the category U-H, ; moreover, even at low tide, there is the inflow of flowing current with the impressed current system because the depolarization quantity of 100 mV was not met for either of the cases. The cause of this is explained using Figure 11. If the MMO electrode conductance is stopped at a low tide, the steel material potential (natural potential) changes in the + direction; however, depending on inflows of protective current from galvanic anodes in the lower section construction because of tide level increases, the steel material potential (conductance potential) may change to the direction. If the current inflows drop again because of a drop in the tidal level, the potential will change to the + direction; however, in the tidal section, compared to the center of the atmosphere, the supply rate of dissolved oxygen to the steel material surface will slow down. Then, the potential change will ease, and it is considered that, compared to the splashing section that does not receive impact from the galvanic anodes in the lower section construction, and the depolarization quantity is measured as a small amount.

3.4. Evaluation of the steel material corrosion status on conductance

Figure 12 shows the Tafel slope and estimated corrosion rate obtained from the steel material polarization curve at conductance in each case. Furthermore, we evaluated the corrosion status of the steel materials from Figure 5 based on these results. For case P, at HWL and above, steel materials are judged to be in a corrosion state; however, category H-M steel materials were judged to be in a passivation state. We can see that this is because with the inflow of protective current from the galvanic anodes installed in the lower section construction at +1.25 m (Immersion rate = ~40%) or below because of the inflow of protective current from the galvanic anodes within the sea, and the corrosion of in the steel materials within the concrete can be inhibited.

However, in regard to cases A-P and H-P, it was judged that the steel materials in category U-H and H-M

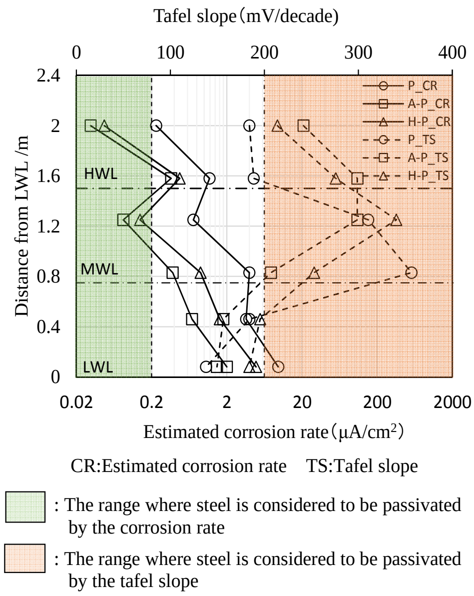

Figure12. Corrosion situation evaluation results for each case.

will be in passivation state; moreover, its prevention effects were confirmed. However, the category M-L steel materials maintained at or below repassivation potential were judged to be in a state of corrosion. A factor in this is surmised to be that because even at a low tide, they are somewhat submerged. Note that as the cathode potential was close to the hydrogen generated potential, the area around the steel materials was a deaerated environment. In this manner, we consider that if the immersion rate increases, the impact of the cathode reaction grows in an extreme manner; therefore, we consider it is necessary, moving forward, to review whether the corrosion rate can be estimated from the cathode polarization curve when the immersion rate is high.

4. OBSERVATIONS CONCERNING PREVENTION EFFECTS

We installed a specimen imitating a section of a pier in a water tank imitating the tide and changing the conductance cases, evaluated the steel material potential, protective current distribution, depolarization quantity measurement, and the steel material corrosion status. We have made observations based on the results for each category, and made observations on the specimens as a whole.

(a) Category U-H（HWL or above）

The inflow of protective current from the galvanic anodes in the lower section construction was seen temporarily during high tide; however, as almost no change in potential was seen, it was considered that its impact did not reach the galvanic anodes on the lower section construction. For cases A-P and H-P, we learned that by maintaining the depolarization quantity of 100 mV through conductance adjustment and prevention effect can be evaluated by depolarization.

(b) Category H-M（HWL to MWL）

For cases A-P and H-P, at high tide, there was almost twice the inflow of current than the category U-H inflow current; therefore, depolarization of 100 mV was not satisfied. A factor in this is considered to be that the area around the steel materials in the concrete was in a deaerated state. However, for case P, deeper than +1.25 m (immersion rate = ~40% from Figure 3), which was evaluated to be in a passivated state. Therefore, it is suggested that most of the steel materials in category H-M only obtain prevention effect from galvanic anodes in the lower section construction.

(c) Category M-L（MWL to LWL）

Because of the protective current from the galvanic anodes in the lower section construction, the steel materials were almost all at repassivation potential or below. However, when reviewing this using the polarization curve, it was judged to be in a state of corrosion. A factor in this is surmised to be that because, even at low tide, they are somewhat submerged; furthermore, as the cathode potential is close to the hydrogen generated potential, the area around the steel materials is a deaerated environment. In this manner, we considered that if the immersion rate increases, the impact of the cathode reaction grows in an extreme manner; therefore, we consider it is necessary, moving forward, to review whether the corrosion rate can be estimated from the cathode polarization curve when the immersion rate is high.

(d) Specimens in general（all categories）

For cases A-P and H-P, the corrosion state of the steel materials was evaluated as being in a passivated state. From this test, we learned that even when applying cathodic protection to the upper section construction while conducting using galvanic anodes from the lower section construction, we suggested that there are prevention effect in regard to the steel materials in the tidal zone.

5. CONCLUSION

A long RC specimen imitating a section of the pier was installed in a water tank imitating the tide, and by changing the conductance case, we evaluated the steel material potential, distribution of protective current, depolarization quantity measurement, and corrosion state of the steel materials in categories U-H (HWL or above), categories H-M (HWL to MWL), and categories M-L (MWL to LWL). Therefore, we obtained the following conclusions.

(a) In this test, at +1.25 m (immersion rate = ~40%) or less, the corrosion in the steel materials in the concrete was inhibited by the protective current from the galvanic anodes in the seawater, and then a prevention effect was obtained.

(b) In this test, when applying cathodic protection to the upper section construction while conducting using galvanic anodes from the lower section construction, it was suggested that there are prevention effect in regard to the steel materials in the tidal zone even at HWL or above.

(c) As an indicator for the results of judging prevention effect in a wetting environment, such as the tidal zone, the possibility that the repassivation potential, Tafel slope, and corrosion rate obtained from the polarization curve be applied has been suggested; however, further validation is required moving forward.

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