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Long Term Performance of Cathodic Protection Applied on Deteriorated PC Girder Specimen due to Chloride Ingress

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ABSTRACT

In this study, long term performance of cathodic protection (here in after CP) was evaluated using actual PC girder which had deteriorated due to chloride ingress before the application. We have used two different types of anode in CP system by dividing the specimen into some parts. In order to investigate the influence of oversupply of current on hydrogen embrittlement of PC wires, 6 times more than normal current was supplied in some part of specimen. During the operation period, the specimen has been exposed in actual marine environment. After 10 years operation period, cover concrete was removed, conditions of PC wires in part of specimen and durability of pipes for CP system were examined. As a result, we confirmed that both anodes have long term performance to prevent the corrosion progress of PC wires in marine environment, without any risks of hydrogen embrittlement even in oversupplied current follow condition.

Keywords. Cathodic Protection, Anode System, PC girder, Chloride Attack, hydrogen embrittlement

INTRODUCTION

Cathodic protection(CP), an electrochemical technique for inhibiting corrosion of steel in concrete, is widely known and already used as one of the remarkable ways for both repair of

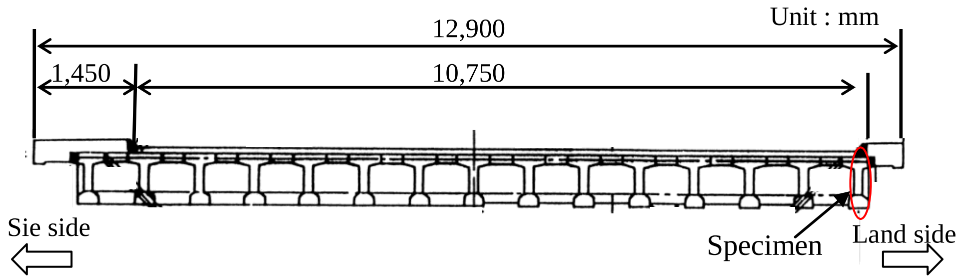


Figure 1. Outline of Removed Road Bridge

Table 1. Dimensions of Load Bridge

Type	Pretensioned girder
Length of bridge (Length of span)	14.14m（13.60m）
Effective width	10.75m
Completion	February, 1972

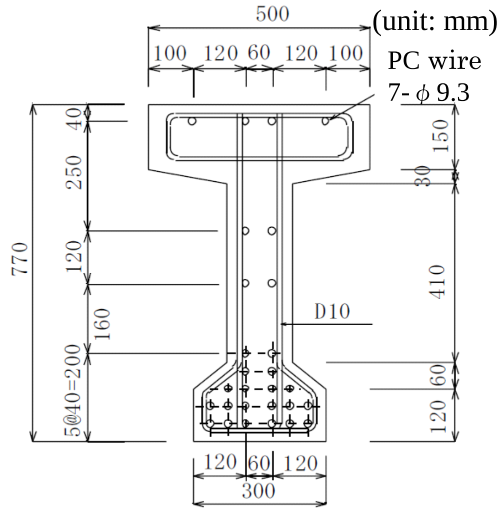


Figure 2. Cross-Section of PC girder

deteriorated concrete structure and maintenance of new concrete structures especially in marine environment. On the other hand, long term effect of CP system applied to concrete structures has not been examined in detail. Therefore, we have examined it using actual 25 years old PC girder as the specimen. After applying CP systems to this old PC girder, the specimen has been exposed in Tokyo bay, Japan for 10 years. In this paper, long term performances of CP system according to the experiment are reported. Moreover, in a detailed investigation, the conditions of the re-bars inside of the concrete were confirmed where CP system has been applied for 10 years.

OUTLINE OF EXPERIMENT

Preparation of Specimen. In this experiment, actual PC girder was used as specimen. This PC girder had been used for 25 years, and removed from the road bridge. Figure 1 shows outline of the bridge. During the service life of this bridge, it had been exposed to severe marine environment and undergone several repair works. Table 1 shows dimensions of the bridge. And we used No.15 PC girder of the bridge as a specimen which had been located at the most landward side in the bridge. Figure 2 shows the cross-section of the PC girder. This girder has 28 PC wires of diameter 7-9.3mm and stirrups of D10. From the chipping examination before application, covering depths of PC wire and stirrup were found as 33 ~ 37mm and 20 ~ 24 mm respectively. Also core samples were taken from web portion of PC girder, and neutralization depths and chloride contents were measured using those samples. From the result, the ranges of chloride contents at the depth of PC wire and stirrup were 3.8 ~ 4.6 kg/m^3 in sea side and 1.2 ~ 1.9 kg/m^3 in the land side respectively. The range neutralization depths were only 3.0 ~ 5.0mm. According to those investigations, main reason of the deterioration of this structure could be judged as chloride attack.

CP System. We used two types of CP system, one was titanium grid anode (here in after called “TG system”) and another was titanium mesh anode (here in after called “TM system”). Figure 3 shows scope of each CP systems.

In TG system, anodes shall be installed in the ditches which made on the concrete surface at regular intervals. In this study, the interval of TG anodes was set 150 mm in the part of web and bottom. On the under flange and side, TG anodes were installed at each centre position. Figure 4 shows outline of TG system. The ditch for TG anode was 25 mm in width and 15 ~ 25mm in length. For confirmation of effects of corrosion protection, reference electrodes (Lead) were installed in the seaside part of the web, and the both seaside and landside of the flange. Those reference electrodes were numbered as TGE1, TGE2 and TGE3 respectively. The initial protective current density was set at 6.0mA/m^2 considering the result of prior polarization test.

The outline of TM system is shown in Figure 5. TM anode was attached to the concrete surface through the web and the flange with plastic nails. The anode was covered with the overlay mortar of 15 mm thickness. Distance between two places installed TG system and TM system is about 300mm (Figure 3). Addition to that, TM system was installed in two separate parts, each area was supplied with different protective current density. One part is supplied normal protective current (here in after normal protective) to keep depolarization constant at 100 mV or more. Another part is supplied 6 times protective current density compared with the normal one (here in after over protective). For confirmation of effects of corrosion protection, a reference electrodes (Pb) were installed in both sea and land sides of

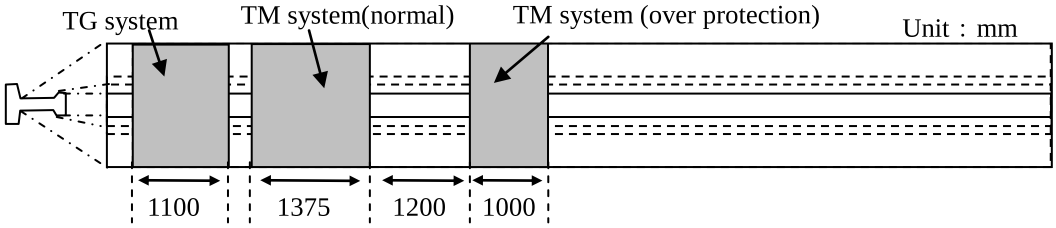


Figure 3. Scope of Each CP Systems

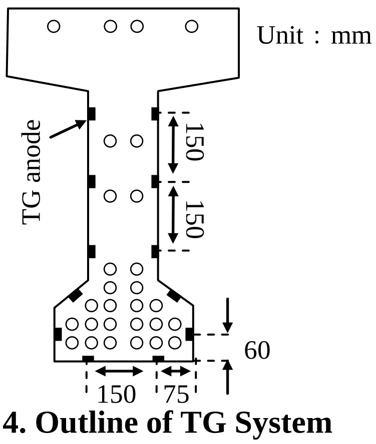


Figure 4. Outline of TG System

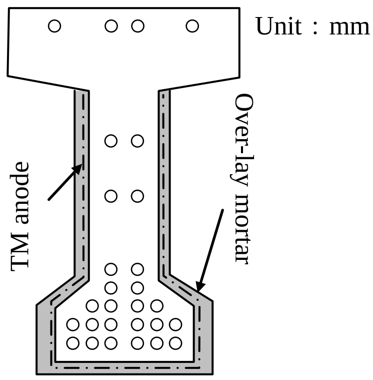


Figure 5. Outline of TM System

the flange. Reference electrodes were numbered as TME1 and TME2. The initial protective current density was set at 6.6mA/m^2 in normal part, considering the result of prior polarization test.

OUTLINE OF SURVEY

Chloride content and Neutralization depth. In this study, core samples were taken from the web part of girder. Firstly, neutralization depth was measured by phenolphthalein method. Then, each core sample was sliced at every 20 mm thickness from sea side surface to land side surface. Figure 6 shows the cut positions in core sample. As for each sliced specimen, the total chloride content was measured according to JIS A 1154[Methods of test for chloride content in hardened concrete].

External observation and chipping investigation. After 10 years operation period, we investigated the external observation on the concrete surface, conditions of wires and pipes for CP system, and DC power source. And then, cover concrete was removed to observe the conditions of PC wire.

Effects of corrosion protection. The confirmation of effects of corrosion protection was done by measuring voltage of DC power source, protective current density, and depolarization after 24 hours disconnection of protective current. PC wires were arranged as shown in Figure 7. Distribution of current density for each PC wires was measured by using the resistor with 10Ω of constant electrical resistance.

Soundness of anode system. After 10 years opeation period, we carried our visual inspection on over-lay mortar of anode system. Afterwards, TG anode and TM anode were removed in order to evaluate the soundness of anode system by using the accelerated life test according to NACE standard. In this test, since anode samples were few, the accelerated test solution was performed only with 40g/l NaOH solution. The neutralization of concrete and over-lay mortar around anodes was evaluated by phenolphthalein method.

Risk of Hydrogen embrittlement on PC wire. In this study, we evaluated risks of hydrogen embrittlement on PC wire. After disconnecting the protective current, PC wires of approximately 1000 mm in length were taken from the girder. Diffused hydrogen content from the refrigerated PC wire was measured by gas chromatography. In addition, to examine the effect on delayed fracture, tensile strength of PC wire was measured in the

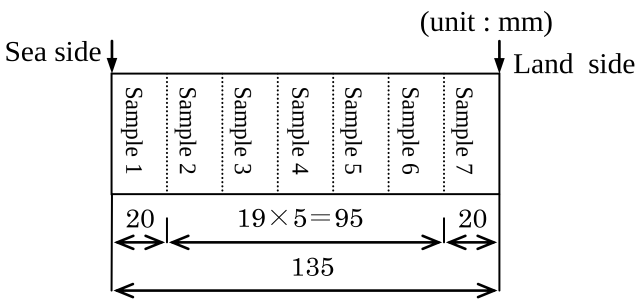


Figure 6. The Cut Position of Core Sample

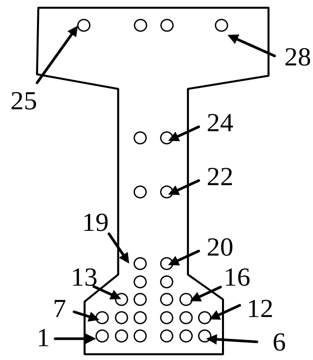


Figure 7. Number of PC Wire

condition of slow rate strain control (1.6 E-5/sec).

RESULTS AND DISCUSSIONS

Chloride content and neutralization depth. Distribution profiles of chloride content in concrete before and after 10 years operation of TM and TG systems are shown in Figure 8~10. Regarding chloride content before CP systems, high chloride content (3.8 ~ 4.5kg/m^3) could be seen in every sea side parts and it tended to decrease to the range of 1.5 ~ 2.0kg/m^3 in the land side parts. The peaks could be confirmed at the depth of 20 ~ 40mm from concrete surface of sea side, where PC wires and stirrups were embedded. However, after 10 years operation of CP systems, chloride content clearly decreased in the sea side areas,.

In TG system, it can be assumed that the chloride ion that had been drawn to the anode might go out due to the rainfall effect, because anodes in TG system have been installed only in the ditches on the concrete surface. On the other hand, in the case of TM system with normal protective level, 0.8 kg/m^3 of chloride content was observed in over-ray mortar . It suggests that chloride diffusion from the girder concrete to the over-lay mortar can occurred during the operation period of CP system. This effect can expected more with the increase of

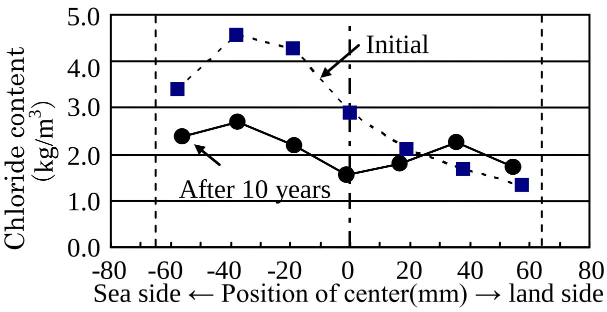


Figure 8. Chloride Content（TG system）

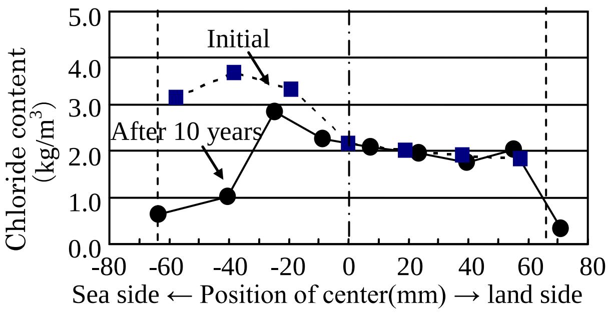


Figure 9. Chloride Content (TG system : normal protective)

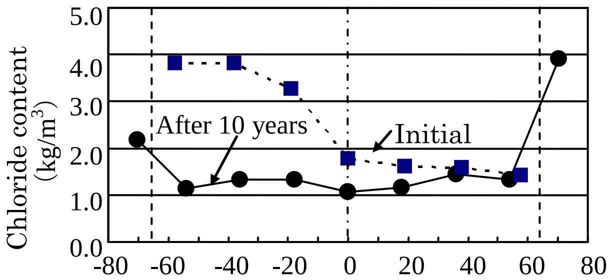


Figure 10. Chloride Content (TG system : over protective)

protective current, as shown in the case of TM system with over protective level. In the case, Chloride contents were remarkably decreased not only in the both sides but even in the centre of girder.

Table 2 shows neutralization depths before and after CP systems. In TG system which needs no over-lay mortar, neutralization depth tended to increase a little, compared with before application. However, in the case of TM system, no neutralization depth was observed after application. It can be assumed the effect of the migration of alkaline component from over-lay mortar to concrete during operation period.

From the visual inspection on TG system area after application, cracks were found in joint mortar. In TM system, micro hexagonal pattern cracks were observed on the surface of the over-lay mortar. Especially, in sea side flange where TM system with normal protective level has been applied, crack was generated along the PC wire and its width was about 0.35mm, as shown in Photograph 1.

PC wires taken out from the part of TG and TM system (normal protective level) after CP application are shown in Photograph 2 and 3. Comparing the appearance of those PC wires with those before application, it can be confirmed that corrosion progress has been kept in the same level during operation period. . Therefore, it was thought that the drying shrinkage of mortar is a main cause of those cracks, except large crack in Photograph 1 which occured due to the crack opening in the base concrete.

Photograph 4 shows pipes after 10 years operation. In this exposed condition, some pipes received direct sunshine every day; therefore, pipes made of the resin caused some cracks due to ultraviolet deterioration. For the application of CP system, it is very important to consider the suitable arrangement and orientation for pipes to avoid the deterioration due to ultraviolet ray.

Confirmation of effect of corrosion protection. Table 3 shows depolarization and instant off potential during operation period. Depolarization meant here is a value after 24 hours disconnection of protective current. From these results, the range of depolarization in TG system was 91 ~ 384 mV and one in TM systems (normal protective level) was 264 ~ 628 mV. Therefore, the effect of corrosion protection could be expected because of excess of 100 mV protective standard in both CP systems. On the other hand, depolarization in TM system (over protective level) was found to be a too large level, such as 612 ~ 1,075 mV. And instant off potential of over protective part was -911~ -984 mV (vs. sat. CSE) after 1 year

Table 2. Neutralization Depth

Unit：mm

		Initial（Ave.）	After 10 years（Ave.）		
			TG system	TM system	
				normal	over
Sea side		4.0	4.9	0.0	0.0
Land side		3.5	3.4	0.0	0.0
Interface	Sea	—	—	0.0	0.0
	Land	—	—	2.8	0.0

interface：between over-lay mortar and concrete operation period, and -1,361 ~ -1,057 mV(vs. sat CSE) after 10 years operation period. Since the latter potential range is ignobler than -1,050 mV (vs. sat. CSE) that is hydrogen evolution potential, that hydrogen gases has possibly been generated around the re-bar surface in concrete during operation period.

onfirmation of distribution of protective current. Figure 11 shows supplied protective

Photograph 1. Crack of Over-lay Mortar (TM system : normal protective)

Photograph. 4 Condition of Pipes (after 10 years)

Photograph 2. Corrosion Condition of PC Wire (TG system : after 10 year)

Photograph 5. Mortar around Anode (TG system : after 10 years)

Photograph 3. Corrosion Condition of PC Wire (TM system : normal protective : after 10 year)

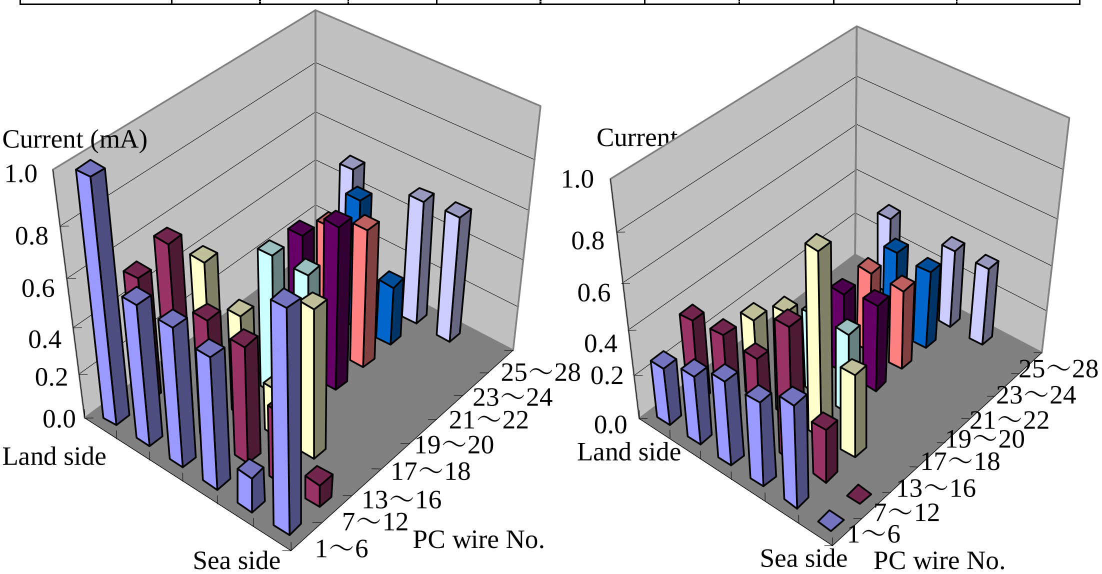
Photograph 6. Mortar around Anode (TM system : after 10 years)

current of each PC wire, when we supplied protective current only to TG system. After about 1.7 years operation period, the amount of protective current supplied to No.1 and No.6 PC wire which embedded in the bottom and the side of the PC girder was 3 ~ 4 times of other wires. However, protective current could be supplied uniformly to whole re-bar from the anode system after 10 years operation. This phenomena suggested the environment of the PC wires could be improved according to the increase of hydroxide ions (OH^-) around re-bar surface in concrete due to CP system.0 mV of protective current seen in No.6 and No.12 PC wire after 10 years is caused by electrical disconnection due to deterioratrion of electric wires. Similar phenomena could be found in TM system.

Soundness of anode system. Neutralization depths of mortar around anodes in TG and TM system are shown in Photograph 5 and 6. Around both anodes, neutralization depth was approximately 1mm. It caused because of electrochemical reaction occurred around anode surface. However, we evaluated that the anode system was sound after 10 years operation, because the supplied condition and the effect of corrosion protection were still active. Figure 12 shows the result of the NACE standard accelerated life test. For both anodes, same

Table 3. Depolarization and Instant off potential for operation period

	Depolarization（mV）							Instant off potential（mV vs. sat. CSE)	
Operation period	TG system			TM system（normal）		TM system（over ）		TM system (over)	
	TG E1	TG E2	TG E3	TM E1	TM E2	TM E3	TM E4	TM E3	TM E4
6 months	243	185	189	365	264	707	794	－1020	－1059
9 months	384	281	91	628	427	961	1120	－1293	－1392
12 months	167	212	261	343	264	612	745	－911	－984
10 years	225	262	361	311	265	1075	746	－1361	－1057



(a) after 1.7 years **(b) after 10 years**

Figure 11. Supplied Protective Current of Each PC wires (TG system)

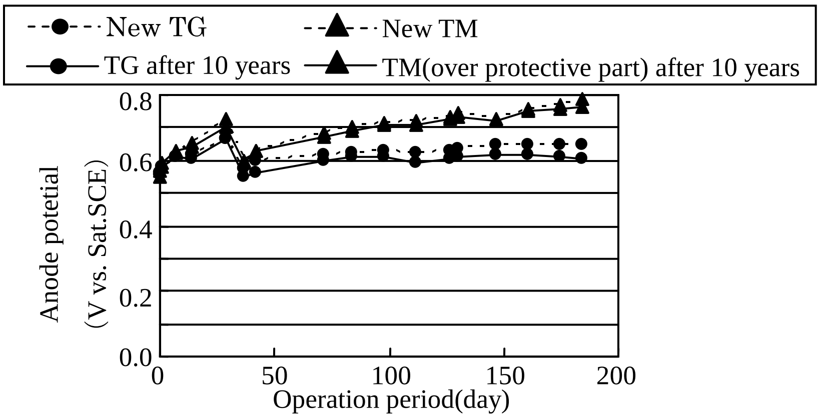


Figure 12. The result of the accelerated life test(NACE)

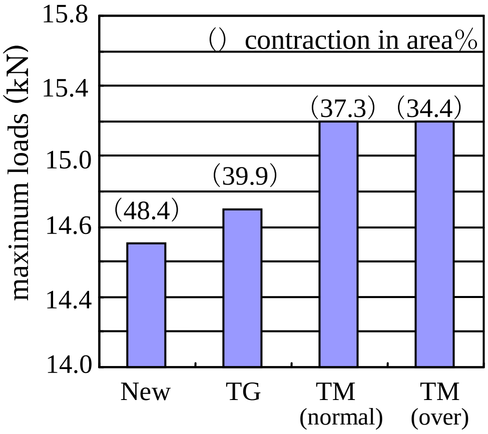


Figure 13. maximum loads and contraction in area

performance comparing to new one even after 10 years operation was confirmed.

Risk of Hydrogen embrittlement on PC wire. In PC wires of normal protective part and over protective part, each diffusion hydrogen content were less than 0.01ppm which is detection limit. It seems that it is because the depolarization test was done before taking out PC wire from concrete, then Hydrogen was discharged or oxidized after protective current was stopped. Figure 13 shows the result of the slow strain rate tensile strength test. In sampled PC wire, the value of contraction in area tended to decrease compared with new one. But this was not only PC wire from over protective part. The reason can be thought corrosion holes of steel observed in some breaking areas. However, since all maximum loads of sampled PC wire were more than new one, it can be judged, within this study, that there was no hydrogen embrittlement of PC wire.

CONCLUTIONS

(1) We applied CP (TG system and TM system) to PC girder which had been damaged by chloride attack. As a result, the effect of corrosion protection of CP was confirmed after 10 years operation period.

(2) Chloride ions around the re-bar in concrete were decreased by applying CP, because they were drawn to the anode side.

(3) In this study, both anodes (TG anode and TM anode) had satisfied the durability against accelerated life test in NACE standard after 10 years operation period.

(4) Mortar and concrete around the anode were neutralized by electrochemical reaction. However, it did not influence on the effect of corrosion protection and appearance.

(5) The influence of over current on hydrogen embrittlement of PC wires was investigated. As a result, it was judged that there was no risk of hydrogen embrittlement of PC wire in the experiment.

(6) Pipes made of the resin caused some cracks by ultraviolet deterioration; therefore, it is very important to consider the arrangement and orientation of pipes and the installation methods to avoid the deterioration due to ultraviolet ray.

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