Study on Maintenance System for Cut and Cover Tunnels Showed Signs of Deterioration by Chloride Attack

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ABSTRACT: While maintaining subway tunnels, some of them already showed signs of deterioration by chloride attack. Therefore, it was investigated the mechanism of deterioration by chloride attack, features of sections of deterioration by chloride attack, methods of determining repair range and appropriate repair method. Furthermore, as a method of determining the detailed repair range, silver nitrate spraying method was developed. Because of examination of the repair method, it was revealed that the combined use of sacrificial anode construction method and surface impregnation method is appropriate depending on the progress by chloride damage. Based on the results, we have been doing construction for 5 years ago. The field test conducted a monitoring survey for 5 years 9 months and carried out a chipping out. This report describes the result of chloride damage investigation, construction status of repair work and monitoring result.

KEYWORDS: Subway tunnel, Chloride induced deterioration, Chloride damage, Silver nitrate spraying method, Monitoring result

1. INTRODUCTION

Tokyo Metro Co., Ltd. ("Tokyo Metro") is a railway operator with nine subway lines and 195.1 km of track. With a ridership of roughly 7.58 million passengers per day, the lines are the main arteries of transportation in the Japanese capital of Tokyo. Tunnels comprise 166.8 km, or 85%, of structures owned by Tokyo Metro, and we maintain their safety through daily maintenance. Subway tunnels in urban areas are primarily made of reinforced concrete, and thus have different characteristics in terms of maintenance compared to tunnels through mountains, which are mainly lined with plain concrete. For example, reinforced concrete carries the risk of peeling caused by corrosion of the rebar. Peeling typically occurs when concrete covering material is pushed outward by the corrosion and expansion of rebar and other steel material in box elements, which is caused by chloride damage and neutralization. Reinforced concrete in subway tunnels is not immune to this damage.

Previously, it was believed that chloride damage does not occur in tunnels due to the absence of impact from airborne salt. However, reports of chloride damage in tunnels have surfaced. In addition, recent surveys have revealed the progression of neutralization to an extent in box tunnels 80 years or older, but also confirmed that urgent measures are not required due to the low moisture content of the concrete.[1]

In light of the above, Tokyo Metro has conducted detailed surveys and investigations of chloride damage in earnest since 2008.[2,3] Tokyo Metro has used the findings of these surveys and investigations to prioritize chloride-damaged sections, and is performing chloride damage repair work based on a combination of sacrificial anodes and surface impregnation.

The sacrificial anode method is a method of electrical corrosion prevention under which zinc or other metals with a stronger tendency to ionize than steel are connected to the steel inside concrete, thereby limiting the corrosion of the steel. The metals "sacrifice" themselves by corroding faster than the steel, and form a circuit through which a protective current flow to the steel, thereby limiting the corrosion of the steel. Regarding the duration of the effects of the sacrificial anode material used in repair methods for chloride damage prevention, tests and the like have revealed the need to replace the sacrificial anodes after roughly 10 years.[4]

In response, nondestructive monitoring surveys have been conducted within the scope of experimental work in order to confirm the sustainability of the corrosion prevention effects of our methods of repairing chloride damage.[5] Peeling surveys were also conducted in areas where roughly five years and nine months had passed since the repair work was performed. In this paper, we present the results of destructive and nondestructive monitoring of the sacrificial anode method.

Table 1: Tunnel Specifications

Item	Explanation
Location of work	Tozai Line between Kayabacho Station and Monzen-nakacho Station (Under the Sumida River)
Structure type	RC box tunnel, double-track
Work method	Caisson method
Earth covering	Under the river: Roughly 2-6 m; On land: Roughly 20 m
Geology	Soft silt layer
Construction period	June 1963-April 1966
Concrete design strength	25 N/mm^2

Table 2: Results of Preliminary Study

Item		Result
Appearance		Deformations caused by flaking near joints
Chipping survey		Corrosion present
Neutralization depth		Progressed to roughly 5-15 mm throughout
Chloride ion content	Up to 40 mm	Roughly 1.0 kg/m^3 (Maximum 5.2 kg/m^3)
	40-60 mm	Roughly 0.4 kg/m^3
Moisture content	Surface	1%-2%
	Inner	3%-5%

2. CONSTRUCTION WORK OVERVIEW

2.1 Tunnel Specifications and Scope of Experimental Work

Table 1 shows the tunnel specifications. Figure 1 is a plan view of the experimental work locations. The work locations were in a tunnel section of the Tokyo Metro Tozai Line that crosses the Sumida River. The scope of the work was four rectangular locations measuring 500 mm x 500 mm. It is worth noting that two of the locations included tunnel joints.

2.2 Preliminary Study

We conducted studies of chipping, neutralization depth, chloride ion content, and surface/inner moisture content prior to construction work. Table 2 shows the results. In order to previous our studies, it is said

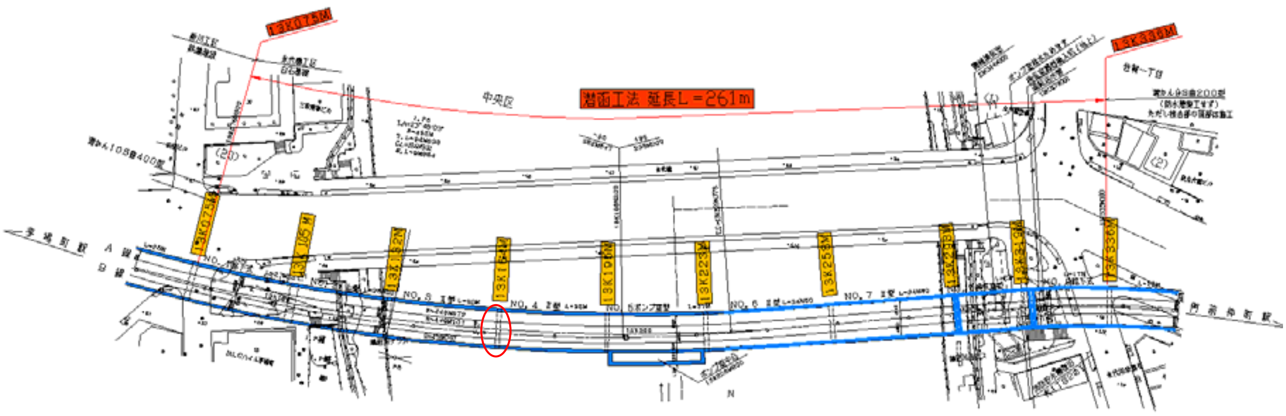

Figure 1: Plan View of Experimental

Table 3: Repair Methods in Experimental Work

No.	Rust-Proofing Agent	Patch Repair Material	Sacrificial Anode Material	
			Zinc Content	Backfill Material
1	Chloride content-absorbing nitrite-type hydrocalumite	Powdered resin, short-fiber premixed PCM	160 g	Lithium hydroxide
2			None	
3	None		38 g	Bromide + lithium nitrate
4	Chloride content-absorbing nitrite-type hydrocalumite		38 g	Bromide + lithium nitrate

to that the rust limit is about 3.0 kg/m^3 in our tunnels. But the results of chloride ion content ware roughly 0.4 kg/m^3.

2.3 Methods Applied

Table 3 shows the repair methods applied in the experimental work. Four different patterns were tried—either using or not using a saline matter adsorbing rust-proofing agent, either using or not using sacrificial anodes, and changing types—but the patch repair materials were kept the same for each.

We noted the workability of these patterns during the experimental work in the field, and excluded the application of the rust-proofing agent from our method of chloride damage repairs; we presently use No. 3 for chloride damage repairs.

2.4 Experimental Work in the Field

2.4.1 Field Surveys

Silver nitrate solution was sprayed in places where daily inspections revealed deformations in order to confirm whether chloride ions had adhered to the surfaces of those structures. In places where the color changed to white, hammering tests were conducted to check for flaking by checking dull sounds. In places where chloride damage may have occurred, the scope of patch repairs was recorded through field measurements and marking, and used to create a repair development view. In addition, in places where no discoloration of silver nitrate and no chloride damage was observed, the scope of surface impregnation material application was also indicated on the repair development view in an effort toward preventive maintenance. Figure 2 shows hammering test/visual inspection.

2.4.2 Concrete Chipping

First and foremost, tarpaulins, line shields, concrete panels and the like must be used to protect the rigid overhead rails of the operating lines, the telecommunication and electrical cables, and the track surface. Because the patch repair was performed in tunnels between stations, the materials used had to be transported from temporary material storage areas to the worksites each night.

In addition, an electric chipping hammer was used for the chipping work to facilitate the transportation of machinery and

Figure 2: Hammering test/Visual inspection

Figure 3: Images of Concrete Chipping

equipment. In order to secure space for the work, chipping was performed to a depth of roughly 20 mm behind the existing rebar. Figure 3 shows images of concrete chipping.

2.4.3 Installation of Sacrificial Anodes

Mild steel wire was used to attach the sacrificial anodes to the existing rebar exposed by the chipping work. To improve the electrical continuity between the sacrificial anodes and the mild steel wire, the surfaces of the rebar where the wire was to be connected were thoroughly prepared. Sacrificial anode spacing was determined based on calculations of the surface area of rebar per square meter of structure and the corrosion prevention radius (Figures 4, 5, and 6).

Figure 4: Images of Sacrificial Anode Materials and Installation

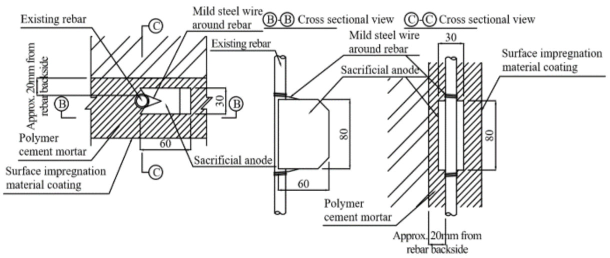

Figure 5: Diagram of Sacrificial Anode Installation

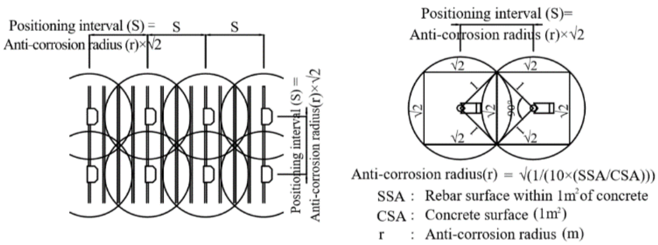

Figure 6: Scope of Sacrificial Anode Impact

Figure 7: An Installed FRP Grid

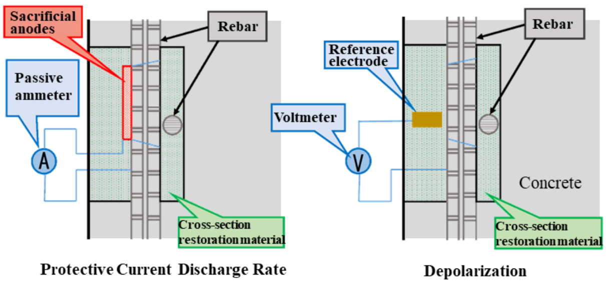

Figure 8: Reference Electrode Measurement Concept

Table 4: Rebar Corrosion Level Evaluation Criteria (ADTMC876)

Electric Potential Measurement	Evaluation
-200 mV < E	90% or greater probability of no corrosion
-350 mV < E < -200 mV	Indeterminate
E <350 mV	90% or greater probability of corrosion

2.4.4 Patch Repair of Concrete

To restore the durability of concrete structures, patch repairs were performed in places where damaged concrete was removed by chipping. The patching concrete material was made to use polymer cement mortar because of the combination with the cathodic protection method and the materials' adhesion to the existing structures, workability, impact on operating trains and other factors were considered. Before applying the mortar, a primer was applied to the existing structures in order to improve adhesion.

In addition, an FRP grid was used to prevent the mortar from peeling or falling off, and anchor bolts and washers were used to secure the FRP grid to the existing structure. The use of carbon fibers, which conduct electricity, in the FRP grid was avoided to prevent the protective current from leaving the target area. When the depth of the patch repairs to be repaired was 80 mm or less, single layers of FRP grid and mortar were used; when the depth exceeded 80 mm, two layers of each were used. Figure 7 shows an installed FRP grid.

2.4.5 Surface Impregnation Material Application

Surface impregnation materials were applied to prevent chloride ions from infiltrating concrete framework, and as a measure of preventive maintenance. Surface impregnation materials were applied as a measure of preventive maintenance even in places where patch repairs have already been performed, and in places where silver nitrate spray did not result in discoloration.

Silane materials were used as the surface impregnation materials. These materials are water repellent, adhere easily to concrete to form water repellent surfaces, and cause the surface impregnation materials to re-penetrate the concrete even as it degrades due to age. Rollers were used to apply the silane materials to the surface.

3. MONITORING SURVEYS

3.1 Nondestructive Surveys

In order to confirm the sustainability of the corrosion prevention effects of each work, nondestructive monitoring surveys were conducted one or two times each year from the construction period in November 2012, to September 2018.

3.1.1 External Appearance

In order to confirm the status of the surface, we conducted close visual inspections to survey the condition of the surface at and around repaired parts. In addition, we carried out hammering tests to confirm the presence or absence of flaking and other deformations.

3.1.2 Protective Current Discharge Rate

We measured the protective current that flows from the sacrificial anodes to the rebar. We embedded individual-type reference electrodes near the sacrificial anodes, and used lead wires to connect the anodes, the rebar, the reference electrodes, and measuring boxes mounted on the concrete surfaces. Figure 8 shows reference electrode measurement concept.

We confirmed whether a protective current of roughly 1-30 mA per square meter of concrete is flowing as required in the "Recommendation of Design and Construction of Electrochemical Corrosion Control Method (Draft)."

3.1.3 Self-Potential

We used a self-potential measuring device (potentiometer) to observe the potential gradients of repaired parts and unrepaired parts in order to confirm the mitigating effects of the sacrificial anodes on potential gradients and estimate the state of rebar corrosion. Our method of determination adheres to the evaluation criteria for corrosion of rebar set out in ASTM (ASTMC876). Table 4 shows rebar corrosion level evaluation criteria.

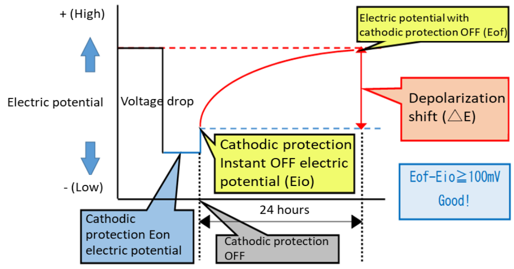

Figure 9: Extent of Depolarization Measurement Concept

3.1.4 Extent of Depolarization

We measured the extent of depolarization in order to confirm the corrosion prevention effects. We measured electric potential when the electricity is on and the sacrificial anodes and rebar are electrically connected, electric potential immediately after turning the electricity off, and electric potential of the rebar 24 hours after the electricity is turned off. Figure 9 shows extent of depolarization measurement concept. To measure the extent of depolarization, we embedded individual-type reference electrodes near the sacrificial anodes, and used lead wires to connect the anodes, the rebar, the reference electrodes, and measuring boxes mounted on the concrete surfaces. We used an external power supply system to confirm the delivery of the corrosion prevention reference value of 100 mV.

3.2 Results of Nondestructive Surveys

3.2.1 External Appearance

Figure 10 shows the external appearance of the experimental work. We observed the return of water leakage from some of the places after the work. With close-up confirmations of the state of the concrete surfaces, we were able to confirm that peeling and other damage was not serious, but we believe that the return of water leakage can cause more chloride damage that leads to corrosion of rebar.

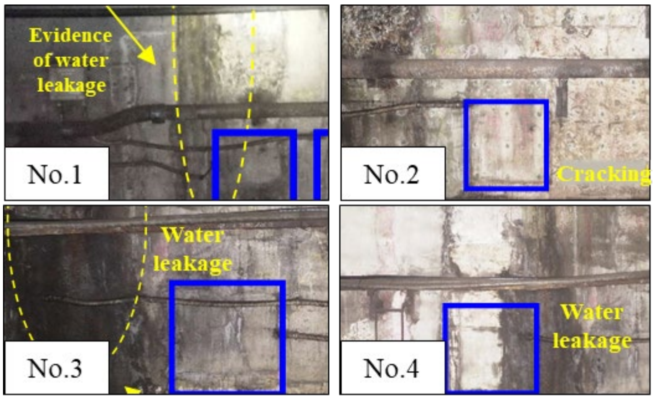

Figure 10: Resulting External Appearance

3.2.2 Protective Current Discharge Rate

Figure 11 shows how the protective current discharge rate changed over time. For No. 3 and No. 4, where the volume of zinc was low, the current discharge rate was high immediately after power was supplied, fell below 1 mA/m^2 after 600 days, and was ultimately 0.66 mA/m^2. It is known that the current discharge rates of sacrificial anodes are generally high when the power is initially supplied, and tend to decrease over time. However, the protective current discharge rate for No. 1 did not show any substantial decrease from the time immediately after power was supplied, staying between 1 and 3.3 mA/m^2 and generally not falling below 1 mA/m^2; therefore, it is believed that corrosion has not occurred there.

In addition, No. 3 and No. 4 exhibited the same trend, which made it clear that, when the zinc content is identical, the presence or absence of the rust-proofing agent had no effect on the protective current discharge rate.

3.2.3 Self-Potential

Figure 12 shows how self-potential changed over time.
At No. 1, which has the highest zinc content, traces of water leakage were noted on the left side of the experimental work area, and the overall self-potential shifted to the low side below -650 kV, which suggests a 90% probability that corrosion of rebar has occurred.

The central part of No. 2, which was only coated with the rust-proofing agent, exhibited a shift to the low side in 2015 and 2016. However, in and after 2017, the overall measurement was 200 mV, which suggests a low probability of corrosion. It is worth noting that during the measurement taken on August 1, 2018, traces of water leakage were noted on the lower left side of the experimental work area, and that the self-potential in that area shifted to the low side below -350 mV. At No. 3, which only has sacrificial anodes, water has leaked into the left half of the measurement area since 2017, and the self-potential in that area shifted to -650 mV, which suggests a 90% or higher probability of corrosion.

In addition, at No. 4, which was both coated with the rust-proofing agent and implanted with sacrificial anodes, water has leaked into the right half of the measurement area since 2017, and the self-potential in that area shifted to -650 mV, which suggests a 90% or higher probability of corrosion.

These observations show that the self-potential shifts to the low side when water leaks into monitoring areas. Given the strong impact of water leakage, it appears to be difficult to use self-potential to predict corrosion of rebar.

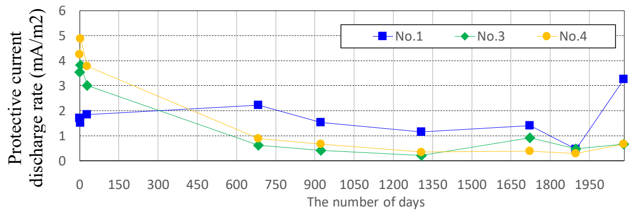

Figure 11: Changes in Protective Current Discharge Rate

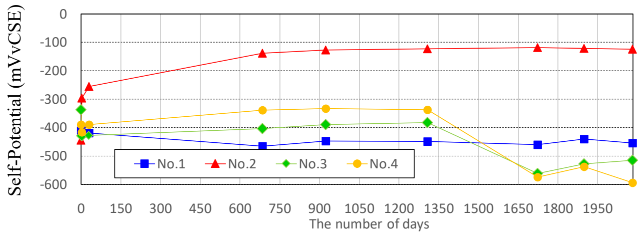

Figure 12: Changes in Self-Potential Over Time

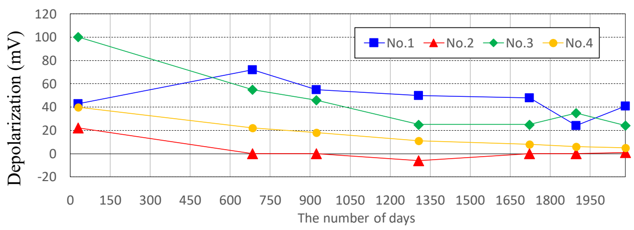

Figure 13: Changes in Extent of Depolarization Over Time

3.2.4 Extent of Depolarization

Figure 13 shows how the extent of depolarization changed over time. No. 3, which was not coated with the rust-proofing agent, only satisfied the target of 100 mV immediately after power was supplied. The coating of the rust-proofing agent exhibited the tendency to degrade the corrosion prevention effects. However, the extent of depolarization of No. 1, which has the highest zinc content, increased to 72 mV over 700 days, exhibiting the same tendency with the protective current discharge rate.

At all measurement points other than No. 3 immediately after power was supplied, the corrosion prevention reference value of 100 mV was not exceeded using an external power supply system.

3.3 Overview of Chipping Surveys

In order to confirm the rust-proofing effects of the chloride damage repairs, we conducted chipping surveys roughly five years and nine months after the repairs were performed in the four places shown on Table 2. We used a hammer drill to chip away the protective covering and expose the rebar in the 500 mm x 500 mm scope of repairs in each place, and an additional 100 m above each place. We confirmed the state of the corrosion of rebar visually according to the guidelines set out by the Japan Society of Civil Engineers and the Japan Concrete Institute.[6,7]

We also removed the sacrificial anodes we embedded in three places and measured the decrease in mass by taking actual measurements of the mass of remaining zinc. Furthermore, we calculated an aggregate discharge rate from actual measurements of discharge rates, and used Faraday's law (Formula 1) to calculate a theoretical decrease in mass.

$$w = \frac{Ite}{26.8} \quad (1)$$

Here, w = Mass of zinc (g), I = Electric current (A), t = time (h), and e = Chemical equivalent weight of zinc (32.69)

3.4 Results of Chipping Surveys

3.4.1 External Appearance

Figure 14 shows the state of the rebar. Our visual inspections did not reveal any corrosion of rebar at or around the places where sacrificial anodes were installed at No. 1, No. 3, and No. 4. However, we did confirm significant corrosion of rebar in some places within the scope that were not repaired. At No. 2, where only the rust-proofing material was used, we confirmed that the patch repair of some of the rebar in the scope of repairs had decreased, and we noted the same trend at places within the scope that were not repaired at No. 1, No. 3 and No. 4.

3.4.2 Decrease in Mass of Zinc

Table 5 shows the decrease of the mass of zinc in the sacrificial anodes. We noted decreases in actual measurements of mass as well, regardless of whether the rust-proofing agent was used. In addition, although it is generally accepted that the discharge rate increases as the mass of zinc increases, we confirmed similar decreases in the amount of zinc, regardless of the initial mass of the zinc. Both the actual measurements of discharge rates and the decreases in mass we derived from theoretical values were lower than half the actual measured values of the zinc. This is possibly because we only measured the discharge rates once or twice per year, and thus were unable to fully understand how finely the discharge rates change over time.

3.4.3 Estimation of Duration of Effects of Sacrificial Anodes

Table 6 shows the estimated duration of the effects of sacrificial anodes derived from the decrease in the mass thereof. For No. 3 and No. 4, where the volume of zinc was low, our actual measurement-based estimate of the duration of the corrosion prevention effects of the sacrificial anodes was roughly seven years and seven months to seven years and 10 months; as of the chipping surveys, we estimate that the anodes can prevent corrosion for roughly two more years. Although we estimated in investigations to date that sacrificial anodes could remain effective for roughly 10 years,[5] our surveys revealed that the effects last less than eight years. This is likely because the temperature and humidity in underground structures remain high throughout the year. The results suggest that further destructive

No. 1: Saline Matter Adsorbing Rust-Proofing Agent + Large Sacrificial Anodes

No. 2: Saline Matter Adsorbing Rust-Proofing Agent Only

No. 3: Small Sacrificial Anodes Only

No. 4: Saline Matter Adsorbing Rust-Proofing Agent + Small Sacrificial Anodes

Figure 14: State of Rebar Corrosion

Table 5 Decrease of Sacrificial Anode Mass

No.	Initial Mass (g)	Decrease of Mass (g) (Rate of Decrease)	
		Actual Measurements from Destructive Tests	Calculations from Actual Measurements of Discharge Rate
1	160	29.5 (18.4%)	23.85 (14.9%)
3	38	27.8 (73.2%)	9.27 (24.4%)
4	38	28.4 (74.7%)	9.37 (24.7%)

Table 6 Duration of Effects of Sacrificial Anodes

No.	Initial Mass (g)	Duration of Effects	
		Calculations from Actual Measurements of Destructive Tests	Calculations from Actual Measurements of Discharge Rate
1	160	Roughly 31 years	Roughly 38 years and four months
3	38	Roughly seven years and 10 months	Roughly 23 years and five months
4	38	Roughly seven years and seven months	Roughly 23 years and two months

monitoring and investigations of matters such as setting times to replace sacrificial anodes are necessary.

4. CONCLUSION

We gained the following knowledge from the results of these surveys.

1. The results of monitoring surveys of protective current discharge rates show that, when the zinc content is identical, the presence or absence of the rust-proofing agent had no effect on the protective current discharge rate.
2. Regarding monitoring surveys of self-potential, given the strong impact of water leakage, it appears to be difficult to use self-potential to predict corrosion of rebar.
3. In the surveys of the extent of depolarization, the divergence between evaluations using corrosion prevention reference values and the results of visual inspections in chipping surveys suggest that it is difficult to use reference values to predict the corrosion of rebar.
4. The results of chipping surveys did not reveal any corrosion of rebar at or around the places where sacrificial anodes were installed at No. 1, No. 3, and No. 4. This proves that the present chloride damage repair method can be expected to have corrosion prevention effects on existing rebar.
5. Actual measured values of zinc were twice as large as the decreases in mass calculated from actual measurements of discharge rates. In

addition, although we estimated that sacrificial anodes could remain effective for roughly 10 years, our surveys revealed that the effects last less than eight years.

5. REFERENCES

Kawakami, K., Mutou, Y., Oizumi, M., Hosumi, S., Morohashi, Y. (2014) "*Neutralization progression projections in box-type subway tunnels*" JSCE 69th Academic Seminar, V-165, pp. 329-330.

Mutou, Y., Nitta, Y., Ogura, N. (2018) "*Report on Determining Priority Rankings and Repair Methods for Chloride Damage Prevention in Subway Tunnels"*. JCI Annual Journal of Concrete Engineering, Vol. 40, No. 1, p. 759-764.

Sezutsu, S., Yamamoto, T. (2008) "The inspection and remedial measure against chloride induced deterioration of the caisson subway tunnel which crosses the river" JSCE Collection of Tunnel Engineering Reports, Vol. 20, p. 395-402.

Mutou, Y., Oizumi, M., Morohashi, Y., Kuzume, K., Otsuki, N. (2014) "Study on the Effective Prevention Method Against Chloride Attack in the Subway Tunnel" (Proceedings of the Concrete Structure Scenarios, JSMS, Vol. 14, p. 287-294.

Kamei, K., Abe, T., Noguchi, M., Tsujiguchi, T. (2017) "Chloride Attack Countermeasure Construction of Subway Caisson Tunnel Under the River" JSCE Council on Underground Spaces, Vol. 22, A2-1, p. 41-48.

Japan Society of Civil Engineers: *Standard Specifications for Concrete (Maintenance)*, enacted in 2013.

Japan Concrete Institute: *Diagnostic Techniques for Concrete '17 (Foundation)*.