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Investigation on the Critical Conditions of Chloride Attack in Subway Tunnels

Tsutomu Yamamoto[1], Yoshihiko Mutou[2], Norihiko Ogura[3], Kazuhiro Kuzume[4] and Nobuaki Otsuki[5]

[1]*Infrastructure Maintenance Dept., Tokyo Metro Co., Ltd., 19-6, Higashi-ueno 3-chome, Taito-ku, Tokyo, Japan. t.yamamoto@tokyometro.jp*
[2]*Infrastructure Maintenance Dept., Tokyo Metro Co., Ltd., 19-6, Higashi-ueno 3-chome, Taito-ku, Tokyo, Japan. y.mutou@tokyometro.jp*
[3]*Tokyo Office, Kokusai Structural Engineering Corp., 1-13-5, Kanda Sudacho, Chiyoda-ku, Tokyo, Japan. ogura.nori@kokusai-se.co.jp*
[4]*Kokusai Structural Engineering Corp., 1-7-8, Nishi Honmachi, Nishi-ku, Osaka, Japan. JDD01055@nifty.com*
[5]*Department of International Development Engineering, Graduate School of Engineering, Tokyo Institute of Technology, 2-12-1, Ookayama, Meguro-ku, Tokyo, Japan. nobuakiotuki2000@yahoo.co.jp*

ABSTRACT

Subway tunnels in Tokyo cross under rivers in many places. Some of them are exposed to leak water which contains a high concentration of chloride ions and found prone to possible future chloride attack or already with signs of it. The authors carried out field survey and measurement on reinforced concrete rectangular tunnels under tidal rivers (aged 36 to 55 years from construction). The results revealed that significant corrosion could occur in existing subway tunnel structures when the chloride content in concrete was about 3.0 kg/m^3 or more. In addition, minimum corrosion amount to cause spalling of concrete was determined from the field survey results. The estimated minimum corrosion amount was adequately higher than the critical corrosion amount to cause corrosion cracking estimated by a conventional equation.

Keywords. Chloride attack, Subway tunnels, Chloride concentration, Cover, Reinforcing steel corrosion level

INTRODUCTION

Tokyo Metro Co., Ltd. maintains and operates a subway system of about 195 km which consists of nine lines. Tunnels account for about 80%, and most of them are located under the center of Tokyo. They cross under or run near rivers, channels, canals and reclaimed lands (hereinafter collectively referred to as “rivers”) in up to 75 sections.

Of the 75 sections under rivers, 49 sections have rectangular (cut-and-cover or caisson) tunnels and 29 sections have shield tunnels, including three sections with both types.

Some sections were previously found with serious deterioration induced by chloride attack due to water leakage in the tunnels, and close survey and repair work were carried out at some locations. Except for them, most sections do not exhibit significant problems attributable to chloride attack at present.

However, it is expected that with the progress of chloride attack a sudden decrease may occur in durability of the currently sound sections. In order to determine proper preventive maintenance for them from middle- and long-term perspectives, field survey and measurement were carried out on the rectangular tunnels of Tokyo Metro subways.

This paper reports analysis and examination on the field data, with the focus placed on the following three points of the existing subway tunnels: water leakage and the range of its effect; reinforcing steel corrosion level and its relationship with causal factors; and the minimum corrosion amount to cause spalling of concrete.

HISTORY OF THE SURVEY AREAS

Cases with Chloride-induced Deterioration and Their Repair Work

Some of the shield tunnels constructed in the early years of Tokyo Metro subways suffered frequent water leaks and exhibited serious deterioration due to chloride attack. These sections had been repaired by secondary lining, bolt replacement or surface coating (Otsuka et al., 2006; Teito Rapid Transit Authority, 2005).

In rectangular tunnels constructed by pneumatic caisson method under tidal rivers (rivers influenced by tides), serious chloride-induced deterioration was detected due to water leakage though the caisson joints. These sections had been repaired by cross section restoration or surface coating (Sezutsu and Yamamoto, 2010).

Overview of Previous Surveys

Leak water samples were collected in the subway tunnels, and chloride content in them was measured. Table 1 shows the measurement results. The chloride content in leak water was as high as about one fourth that of seawater in a tunnel crossing under the Sumida River about 14 km inland from the mouth of the river, while the value was very low in an ordinary section which was not under rivers.

Chloride content was also measured in the surfaces of tunnel body concrete in the above ordinary section, which resulted in a very low average of 0.12 kg/m^3. These results suggested that the possibility of chloride attack would be extremely low in the sections not under rivers.

Table 1. Chloride Content in Leak Water

Leak water sampling locations	Cl^- concentration
Crossing under the Sumida River on the Tozai Line (about 3 km from the river mouth)	16,100 mg/l
Crossing under the Sumida River on the Chiyoda Line (about 14 km from the river mouth)	4,300 mg/l
Near Tawaramachi Station on the Ginza Line (not under rivers)	37 mg/l
Reference: seawater	About 19,000 mg/l

FIELD SURVEY

Field surveys have been conducted since 2008 on rectangular tunnels, particularly on those under tidal rivers. The survey in 2010 was carried out at 30 locations in seven sections on five lines shown in Table 2.

According to the design documents at the time of construction, specifications of the concrete used in the current survey sections were as follows: design strength of 21 N/mm^2; W/C of 53% in the specified mix proportions; and cement content of 320 kg/m^3.

Standard survey in 2010 was conducted on side walls at selected typical locations with significant water leaks or trace of water leakage. The survey included visual observation of the appearance, hammering test, chloride content measurement on core samples, cover thickness measurement, and corrosion level inspection on reinforcing bars exposed by concrete removal.

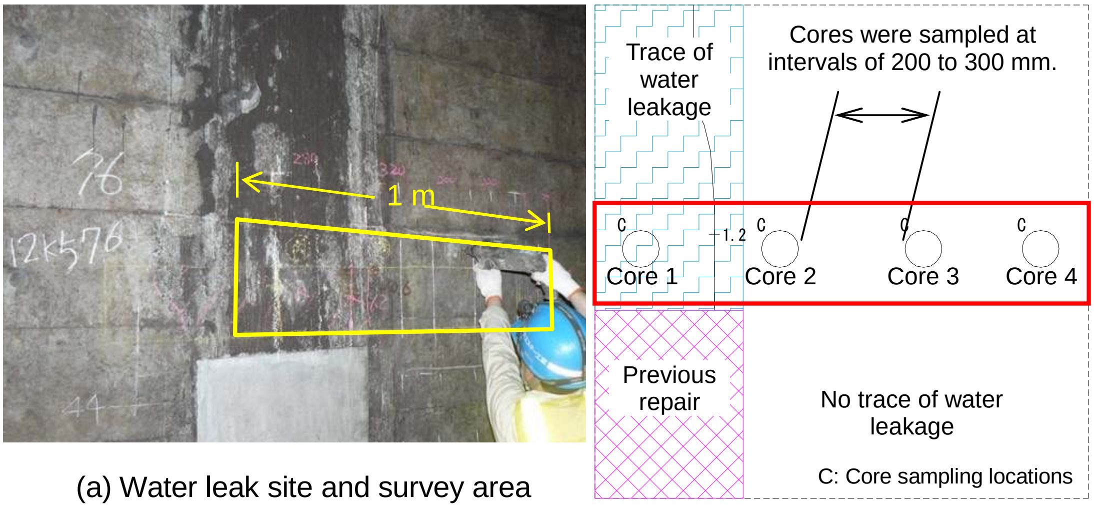
Figure 1-(a) shows an example of a site of water leak and an area of the standard survey, and Figure 1-(b) shows an example of core sampling locations and visual observation results.

In order to determine the range of the effect of chloride content in the leak water, four cores were taken at intervals of 200 to 300 mm gradually away from the site of water leak or trace of water leakage, avoiding the reinforcing bars. Each core was sliced at 20 mm intervals to make five specimens for chloride content measurement.

Additional survey was carried out in the same year to obtain an adequate number of samples for the reinforcing steel corrosion level inspection. The survey included visual observation, hammering test, cover thickness measurement, and reinforcing steel corrosion level inspection by concrete removal, excluding chloride content measurement which was performed in the standard survey. Like in the standard survey, typical sites with water leaks or trace of water leakage were selected. Chloride content data from previous measurements were also used in this study, where available.

Table 2. List of Field Survey Sections

Sections	Subway line names	Rivers crossed	Tunnel structures	Year of construction (age in 2010)	Number of survey areas	
					Standard	Additional
M1	Marunouchi Line	Nihonbashi River	Cut-and-cover	1955 (55)	1	2
H1	Hibiya Line	Kanda River	Cut-and-cover	1962 (48)	1	2
H2		Nihonbashi River	Pneumatic caisson	1962 (48)	1	4
T1	Tozai Line	Kamejima River	Cut-and-cover	1966 (44)	1	2
T2		Sumida River	Pneumatic caisson	1966 (44)	1	6
C1	Chiyoda Line	Nihonbashi River	Cut-and-cover	1969 (41)	1	2
Y1	Yurakucho Line	Kanda River	Cut-and-cover	1974 (36)	1	5



(a) Water leak site and survey area

(b) Core sampling location

Figure 1. An Example of Survey Area

ANALYSIS AND DISCUSSION ON SURVEY RESULTS

The field survey data was analyzed and examined, with the major focus placed on the following three points: water leakage and the range of its effect; reinforcing steel corrosion level and its relationship with causal factors; and the minimum corrosion amount to cause spalling of concrete.

Water Leakage and the Range of Its Effect

Figure 2 shows the chloride content distribution in the cores from the standard survey. Chloride concentration naturally tended to be the highest in Cores 1 which were taken from immediately below the site of water leak or trace of water leakage, exceeding 10 kg/m^3 in the surface layer (0 to 20 mm from the surface) or 3.0 kg/m^3 in the 80 to 100 mm range at some locations. Cores 3 and 4 taken from the locations with no water leak or trace of water leakage on the concrete surface exhibited a chloride concentration less than 2.0 kg/m^3 even in the surface layer, except for T2. The value further decreased to around 0.5 kg/m^3 or below at depths greater than 60 mm.

Reinforcing steel corrosion level was determined in accordance with the grades specified in the guideline by the Japan Concrete Institute (Japan Concrete Institute, 2009), by removing the concrete and visually inspecting the exposed reinforcing bars. Table 3 shows the criteria used for the determination.

The reinforcing steel corrosion level inspection revealed that corrosion of level C or above emerged only in the vicinity of Cores 1, while corrosion near Cores 3 or 4 was ranked B or below, except for T2.

Section T2 was located near a joint in a rectangular tunnel constructed by pneumatic caisson method. The waterproof layer of this section was found not functioning properly at almost all locations and likely to have allowed penetration of a considerable amount of water for a long time.

Unlike in T2 which was constructed by pneumatic caisson method, the effect of chloride ions contained in leak water was found limited to a local range in the cut-and-cover tunnels, primarily immediately below the site of water leak or trace of water leakage or the range within 200 to 300 mm from them.

The results revealed that damage induced by chloride attack in cut-and-cover subway tunnel sections would be locally limited to the vicinity of the site of water leak in most cases, unlike the common chloride-induced deterioration found in seaside structures where airborne salt attack extends over the entire structure members.

Table 3. Visual Determination of Reinforcing Steel Corrosion Level

Corrosion level	Description
D	Significant corrosion with obvious reduction in the cross section (IV*)
C	Shallow pitting corrosion, or corrosion with minor reduction in the cross section (III*)
B	General superficial corrosion (II*)
A	Spot rusting, or superficial corrosion (I*)
0	No corrosion (I*)

*Symbols in the brackets represent the corrosion level evaluation in the Standard Specifications for Concrete Structures by the Japan Society of Civil Engineers.

(Japan Concrete Institute, 2009; Japan Society of Civil Engineers, 2008)

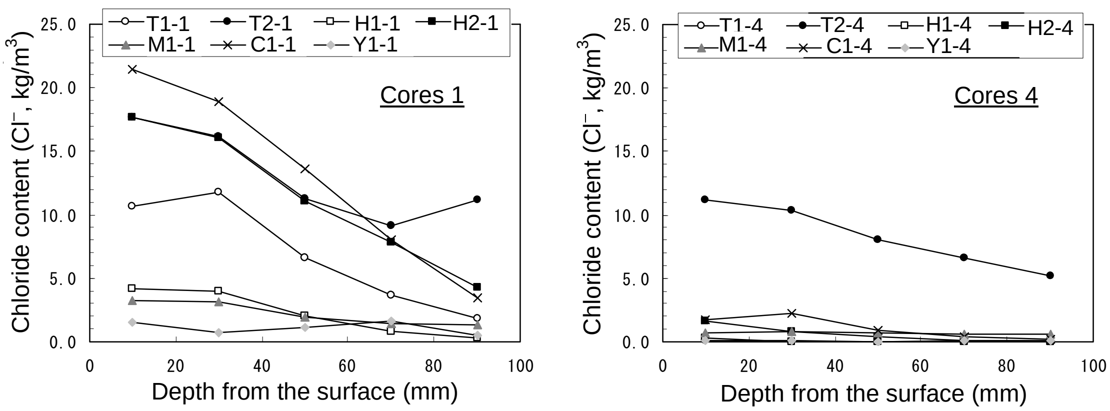


Figure 2. Chloride Content Distributions in Individual Cores

Reinforcing Steel Corrosion Level and Its Relationship with Causal Factors

Figure 3 shows the relationship between the reinforcing steel corrosion level, cover thickness, and chloride concentration at the locations of the reinforcing bars at the site of water leak or trace of water leakage and in its vicinity in the standard and additional surveys.

Depending on the condition of material storage at actual construction sites, reinforcing bars may already have spot rusting or minor corrosion in their surfaces before assembly. It is possible that minor corrosions found during the concrete removal inspection were those initiated during construction. As shown in Figure 3, corrosion of level B can be divided into two groups by chloride content: below 1 kg/m^3, and above 4 kg/m^3. The authors made an assumption that corrosion of the first group (hereinafter referred to as “B1”) was from the rust generated during construction, while the rust in the second group (hereinafter referred to as “B2”) was induced by chloride attack. Corrosion of level B2 was found distributed above 3.0 kg/m^3 which was the lowest chloride content in the concrete where corrosion of level C emerged.

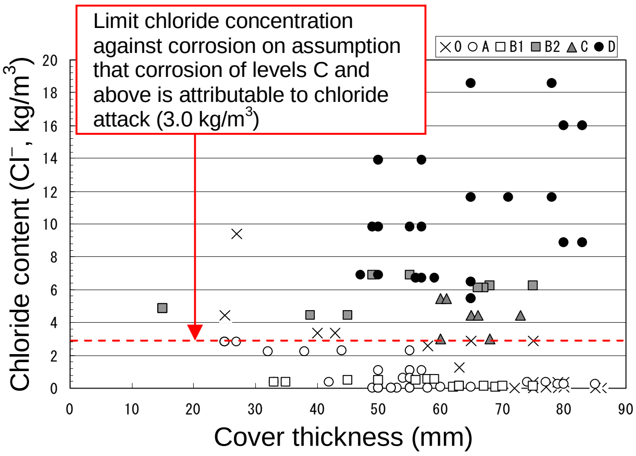


Figure 3. Relationship between Reinforcing Steel Corrosion Level, Cover Thickness and Chloride Concentration

Since corrosion level was determined by visual inspection as shown in Table 3, there were variations in the actual corrosion amount among the steel bars ranked to the same level. Also referring to the previous research (Ishibashi et al., 2002), the authors decided to carry out analysis on the assumption that corrosion of level B1 or below was from the rust generated during construction, while corrosion of level B2 or above was the corrosion induced by chloride attack.

It is generally said that reinforcing steel corrosion starts when the chloride concentration at the location of the steel reaches a certain limit. Chloride-induced corrosion of reinforcing steel is known to be governed by various factors including chloride concentration, cover thickness, reinforcing steel diameter, mix proportions, temperature and humidity. However, the limit chloride concentration against corrosion which marks the end of the incubation period is shown in a wide range from 1.0 to 2.5 kg/m^3 in the current guidelines (Japan Society of Civil Engineers, 2007; Tokyo Port Terminal Corporation, 2004; The Ports and Harbours Association of Japan, 2007; Public Works Research Center, 1989), with different values presented depending on the environmental and other conditions.

Therefore, an analysis was made on the limit chloride concentration against corrosion, using the current survey results.

Figure 4 shows the distribution of chloride concentration at the location of reinforcing steel in the samples with corrosion of levels B2, C or D in the standard and additional surveys. An analysis was made on the basis that the distribution showed a logarithmic normal curve.

The analysis revealed that, based on the current field survey results, corrosion of level B2 or above would emerge at a chloride concentration of 3.4 kg/m^3 with a reliability of 95% or more. The reliability would increase to 97% at 3.0 kg/m^3 which was the minimum chloride concentration to cause corrosion of level C observed in the field survey.

Consequently, limit chloride concentration against corrosion in rectangular subway tunnels was assumed to be around 3.0 to 3.4 kg/m^3 under the above given conditions.

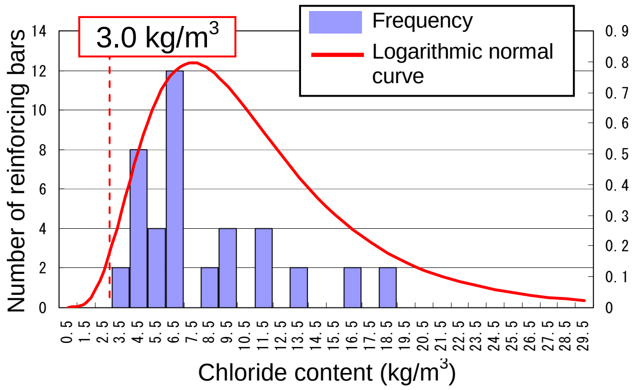


Figure 4. Chloride Content Distribution for Corrosion Levels B2, C and D

Minimum Corrosion Amount to Cause Spalling of Concrete

a) Relationship between reinforcing steel corrosion level and spalling of concrete

Figure 5 shows the relationship between the corrosion level of individual reinforcing bars inspected in the standard and additional surveys, cover thickness, and presence or absence of spalling in the surface concrete before removal for inspection. Using this diagram, critical conditions were analyzed for crack initiation in concrete induced by the progress of corrosion in reinforcing steel.

Cracks due to reinforcing steel corrosion are detected in most cases as spalling of cover concrete in subway tunnels including the current survey sections. For that reason, the authors used the information of presence or absence of spalling obtained by hammering test for the determination of the minimum corrosion amount for crack initiation in this study.

Spalling of concrete occurred where cover thickness was 80 mm or less. This suggests that, where cover thickness is more than 80 mm, corrosion which has progressed to level C or D may still remain latent, without causing obvious spalling.

Consequently, the line drawn in Figure 5 between the largest cover thickness with spalling of concrete with corrosion of level C and that with corrosion of level D was considered to represent critical cover thicknesses above which no spalling of concrete would occur, at least according to the current survey results.

b) Examination of the minimum corrosion amount to cause spalling of concrete

The vertical axis in Figure 5 represents the corrosion level qualitatively. The corrosion level was converted to the amount of corrosion in order to compare the relationship obtained from the survey results between the corrosion level, presence or absence of concrete spalling (cracks in concrete) and cover thickness against the critical corrosion amount to cause corrosion cracking estimated by the conventional equation.

The conversion from the corrosion level to corrosion amount of reinforcing steel was made in accordance with the guideline by the Japan Concrete Institute shown in Table 4 (Japan Concrete Institute, 2009). Figure 6 shows the relationship of the converted corrosion amount of the reinforcing steel with concrete spalling against the cover thickness. The values of critical corrosion amount estimated by the equation are also plotted in Figure 6.

Reinforcing bars with corrosion of level 0, A or B1 as well as those of B2 which are all without concrete spalling are not shown in Figure 6 in order to focus on the spalling of concrete attributable to chloride-induced corrosion only.

The equation used to estimate the critical corrosion amount for corrosion cracking initiation in this study for the comparative purposes was that proposed by Yokozeki et al. [Yokozeki et al., 1997; Equation (1)] which used the cover thickness as a variable. With the focus placed on the reinforcing bars closest to the surface in the current study, the calculation was made using the bar diameter and spacing of 16 mm and 125 mm, respectively, based on the field survey results.

$$W_{cr} = -1.841\varphi(\varphi - 8.661) + 145.1\alpha^{-1.194} + 3809D^{-0.8351} + 10.60X_1 - 72.30 \qquad (1)$$

where, W_{cr}: critical corrosion amount (mg/cm^2); φ: creep coefficient [assumed to be 0.4 (Kawamura et al., 2005; Maruya and Uji, 1989)]; α: volumetric expansion ratio when steel is converted to corrosion products (= 3.2); D: angle of corrosion (assumed to be 360°); and X_1: shape function [(cover thickness / bar diameter) or {1.75 × (bar spacing – bar diameter) / (2 × bar diameter)}, whichever is smaller].

Corrosion amount in 16 mm-diameter reinforcing bars was calculated to be 220 mg/cm^2 for level C and 345 mg/cm^2 for level D from the relationship between the corrosion level and the mass loss ratio shown in Table 4 from the field survey. Figure 6 shows the relationship between these calculated corrosion amounts and the cover thicknesses of the reinforcing bars where concrete spalling was found during the field survey. The line connecting the largest cover thicknesses for the two corrosion levels, i.e., 61 mm for level C and 78 mm for level D, was considered to express the relationship between the cover thickness and the minimum corrosion amount to cause spalling of concrete in the current study.

This limit line appeared above the equation proposed by Yokozeki et al., showing the validity of the equation used and adequate safety margin in the prediction made by the equation.

The discrepancy between the approximation of the current field survey and the equation proposed by Yokozeki et al. was larger with the increase in cover thickness. However, it should be noted that initiation of microcracks in early stages might not have been detected in the current field survey where crack initiation was determined depending on the presence or absence of spalling of concrete. It is also possible that corrosion in some of the survey sections which were aged 36 to 55 years from construction might have advanced during the considerable time since the initiation of corrosion cracks.

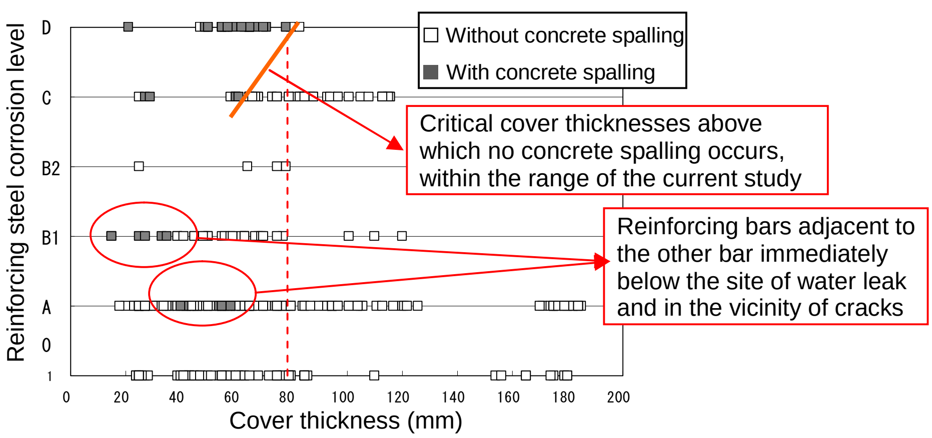


Figure 5. Relationship between Reinforcing Steel Corrosion Level, Cover Thickness and Spalling of Concrete

Table 4. Relationship between Reinforcing Steel Corrosion Level and Mass Loss Rate

Corrosion level	Reinforcing steel mass loss rate (%)	
	Mean value	Standard deviation
D	11.0	4.5
C	7.0	3.5
B	4.5	3.0
A	2.0	1.0
0	0.8	0.2

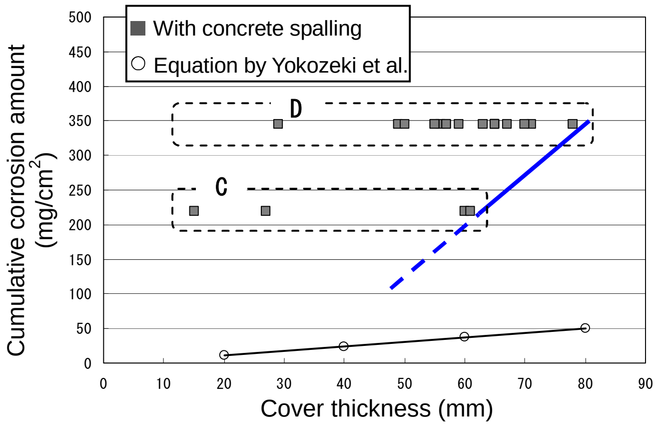


Figure 6. Crack Initiation Corrosion Amount vs. Cover Thickness

CONCLUSION

Field survey and measurement were carried out on rectangular subway tunnels under tidal rivers and various influential factors related to chloride-induced deterioration were examined by analyzing the field data for the purpose of clarifying the critical conditions for the occurrence of chloride attack in rectangular subway tunnels. The findings are summarized as follows.

(1) Damage induced by chloride attack in cut-and-cover subway tunnels would be locally limited to the vicinity of the site of water leak in most cases, unlike the common chloride-induced deterioration found in seaside structures where airborne salt attack extends over the entire structure members.

(2) However, it should be noted that the range of the effect of water leakage is larger in such sections that had been constructed by pneumatic caisson method and have experienced significant water leaks.

(3) All reinforcing bars observed to have corrosion of level C or above with reduction in the cross section were found to have a cover thickness of 125 mm or less.

(4) On the assumption that corrosion of level B2 or above was the rust induced by chloride attack, limit chloride concentration against corrosion in this survey was 3.4 kg/m^3 with a reliability of 95%. The reliability would increase to 97% at 3.0 kg/m^3 which was the minimum chloride concentration where corrosion was observed in this survey.

(5) A comparison between the minimum corrosion amount for the initiation of corrosion cracks by observation and the estimation by the conventional equation proposed by Yokozeki et al. revealed that all limit values obtained from the current survey were plotted above the conventional equation, showing the validity of the equation and adequate safety margin in the prediction made by the equation.

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REFERENCES

Ishibashi, T., Furuya, T., Hamazaki, N. and Suzuki, H. (2002). "Investigation of falling on concrete fragments from RC structures." *Proceedings of Japan Society of Civil Engineers*, No. 711/V-56, 125-134 (in Japanese).

Japan Concrete Institute. (2009). *Practical Guideline for Investigation, Repair and Strengthening of Cracked Concrete Structures -2009-*, Tokyo (in Japanese).

Japan Society of Civil Engineers. (2008). *Standard Specifications for Concrete Structures-2007, Maintenance*, Tokyo (in Japanese).

Japan Society of Civil Engineers. (2007). *Standard Specifications for Concrete Structures-2007, Design*, Tokyo, 119 (in Japanese).

Kawamura, C., Tanimura, Y., Sogabe, M., Tottori, S., Hasegawa, M. and Higashigawa, K. (2005). "Study on the penetration of chloride ions into concrete based on investigation of railway structures." *Proceedings of Japan Society of Civil Engineers*, No. 781/V-66, 193-204 (in Japanese).

Maruya, T. and Uji, K. (1989). "Prediction of diffusive salt penetration into concrete." *Proceedings of the Japan Concrete Institute*, 11-1, 597-602 (in Japanese).

Otsuka, T., Sezutsu, S. and Tasoko, N. (2006). "Soundness investigation of segment that chloride ion under water leak influences." *Proceedings of tunnel engineering, JSCE*, 16, 419-426 (in Japanese).

Public Works Research Center. (1989). *Report of Research Results on Public Works, Development of Durability Improvement Technology of Concrete, Comprehensive Technology Development Project in Ministry of Construction*, Tokyo, 67 (in Japanese).

Sezutsu, S. and Yamamoto, T. (2010). "The inspection and remedial measure against chloride induced deterioration of the caisson subway tunnel which crosses the river." *Proceedings of tunnel engineering, JSCE*, 20, 395-402 (in Japanese).

Teito Rapid Transit Authority. (2005). *History of the Engineering Department, Civil Engineering*, Tokyo, 735-745 (in Japanese).

The Ports and Harbours Association of Japan. (2007). *Technical Standards and Commentaries for Port and Harbour Facilities in Japan*, Tokyo, 489 (in Japanese).

Tokyo Port Terminal Corporation. (2004). *Deterioration Investigation and Repair Manual for Piers*, Tokyo, 32 (in Japanese).

Yokozeki, K., Motohashi, K., Okada, K. and Tsutsumi, T. (1997). "A rational model to predict the service life of RC structures in marine environment." *Proceedings of the Fourth CANMET/ACI International Conference on Durability of Concrete*, SP 170-40, 777-798.