Numerical Simulation of Deterioration Process of Concrete Structures of Electric Power Facilities due to Chloride Attack

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1. INTRODUCTION

Reinforced concrete electrical power facilities are critical infrastructure designed to generate, transmit, and distribute electricity. Recent inspections of underground service tunnels have revealed significant deterioration, including cracks, concrete spalling, and steel reinforcement corrosion.[1] Investigations on the tunnels have confirmed high chloride content in the concrete of these facilities. (See **Fig. 1**)

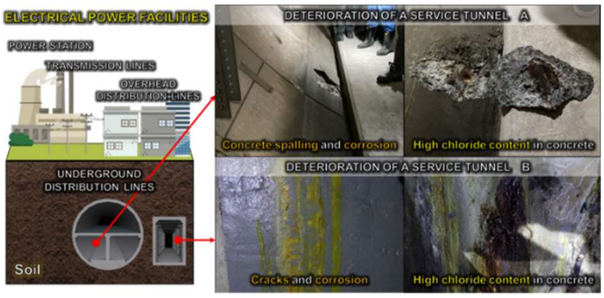


Fig. 1 Deterioration in Reinforced concrete service tunnels

There are multiple cases of electrical power facilities exhibiting similar deterioration, making it essential to clarify the deterioration mechanism from a durability and maintenance perspective. For this reason, the objective of this study is to clarify the deterioration mechanism of the reinforced concrete structures of electric power facilities by numerical simulation.

2. NUMERICAL SIMULATION MODEL [2]

Reinforced concrete structures are typically subjected to drying and wetting processes. In this context, diffusion and capillary suction are the primary mechanisms governing moisture and chloride ion transport in concrete.

In this study, the capillary suction process is the primary transport mechanism analyzed through a coupled moisture-chloride model. This model considers concrete pore size distribution and water phases in partially saturated concrete to estimate chloride ion movement within the material.

3. CASE STUDY: TOYOSU SERVICE TUNNEL

3.1 Introduction

The reinforced concrete service tunnel, completed in 1998, connects the Shin-Toyosu Substation in Tokyo to the Shin-Keiyou Substation in Chiba (see **Fig. 2**). The structure is entirely underground, with a depth ranging from 7.5 to 17.2 meters and a total span of 40 km. It has a circular cross-section with an external diameter of 8.15 meters. Internally, the tunnel is divided into three sections: an upper section and two lower sections.

Fig. 2 Location of the service tunnel in Toyosu, Tokyo

In July 2024, a visual inspection of the lower left section of the Toyosu service tunnel revealed multiple signs of deterioration in the reinforced concrete structure, including reinforcement corrosion and concrete spalling (see **Fig. 3**). The inspection covered a 0.6 km segment from the Shin-Toyosu Substation entrance in Tokyo.

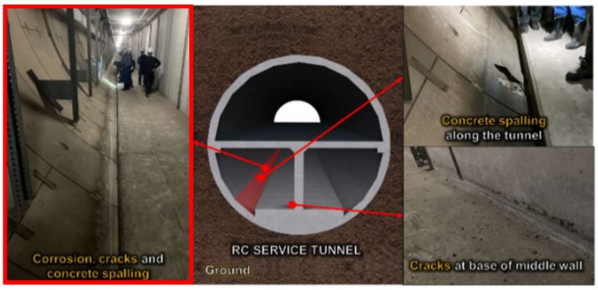


Fig. 3 Deterioration in the left section of the service tunnel

3.2 Objective and deterioration hypothesis

This case study focuses on the lower left section of the tunnel, near a drainage system, where water infiltration marks were observed (highlighted in red in **Fig. 3**).

A review of previous investigations on the tunnel led to the hypothesis that reinforcement corrosion resulted from the infiltration and accumulation of chloride-rich external water. This hypothesis is supported by a 2009 report, which states that the drainage pump in that section of the tunnel failed, leading to water accumulation inside. The pump was repaired after two months, but the exact duration of exposure to external water remains unclear. Also, no records indicate another major drainage failure after 2009.

A decade later, in 2019, chloride content surveys confirmed the presence of chloride ions in areas where water infiltration marks had been previously observed[1]. More recently, a 2024 survey detected chloride ions in both the drainage system water and in a spalling concrete fragment, further indicating prolonged exposure to chloride contamination.

The objective of this case study is to estimate, through inverse calculation, the conditions that led to the observed level of concrete deterioration.

3.3Numerical Simulation

3.3.1 Environmental condition model

To conduct the numerical analysis of the flooded area in the tunnel, it is essential to determine a model that realistically simulates the conditions to which the concrete was exposed. Field data and past inspections confirm that chloride ingress in the Toyosu service tunnel occurs exclusively through external chloride-laden water, with no airborne chloride contribution. Consequently, the model assumes that chloride ions enter the concrete only when its surface is in direct contact with water.

3.3.2 Analytical results

The material parameters governing moisture and chloride ion transport in concrete [2],[3],[4],[5] are listed in **Table 1**. The size of the discretized element was 4 mm × 4 mm, and the time step was set to 1 hour.

Table 1 Material parameters

Vo (m^3/m^3)	B	C	Kv	Kl	Klp	Kcl
0.126	25008	0.5	0.036	0.00072	0.021	0.0072

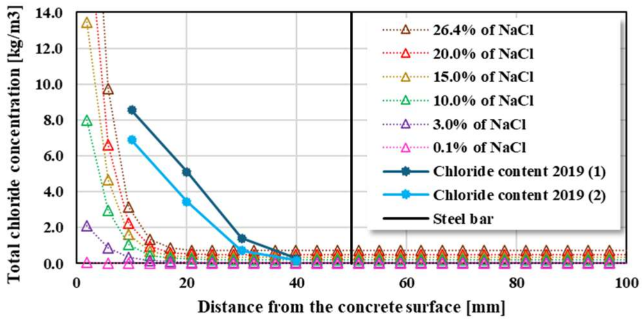
Table 2 Calculation conditions

W/C (%)	Temp (°C)	RH (%)	NaCl solution (%)	Dry-wet Condition	Exposure Time (months)
35	20	85	26.4, 20, 15, 10, 3, 0.1	Always wetting	1, 6, 12, 18, 24

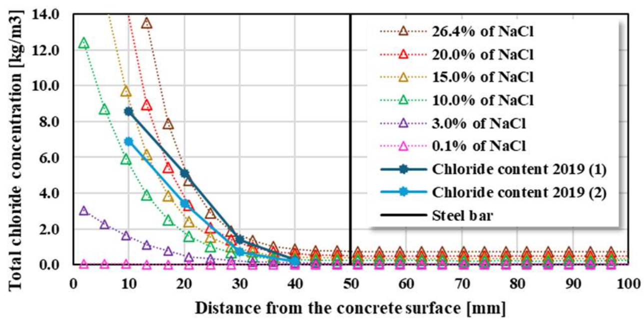
Fig. 4 presents the test series under continuous wetting conditions for cases (a) to (e). Six NaCl solutions were compared in all simulations: 26.4% (saturated concentration), 20.0%, 15.0%, 10.0%, 3.0%, and 0.1% (based on field measurements).

The 'continuous wetting' condition assumes uninterrupted exposure to chloride-rich water. During the first month, external water infiltrates the concrete surface, rapidly increasing chloride concentration in the outermost layer. As exposure progresses, accumulation slows, reaching near-saturation after six months, after which chloride ions begin penetrating deeper, as observed in cases (c), (d), and (e). Case (c), corresponding to 12 months of exposure, closely replicates the chloride profiles measured in 2019, with the best fit obtained using a 10.0% NaCl solution.

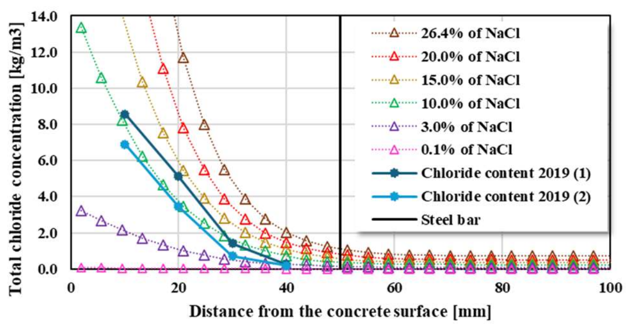
This suggests that the tunnel, under continuous wetting, experienced prolonged exposure to external water with approximately 10% NaCl. Since chloride redistribution under drying conditions is very slow, it is reasonable to assume that the 2019 profile still retains characteristics of the 2009 exposure, supporting the hypothesis that chloride contamination was a sustained process over time.



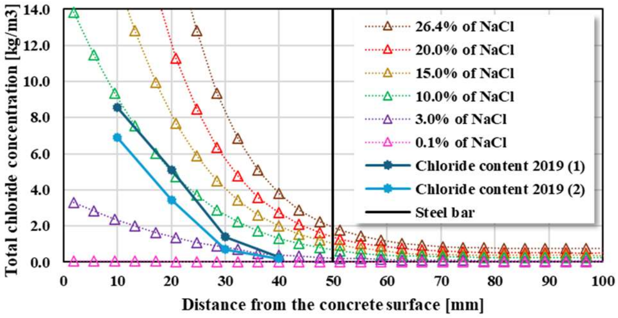
a) Chloride concentration profile (1 month)



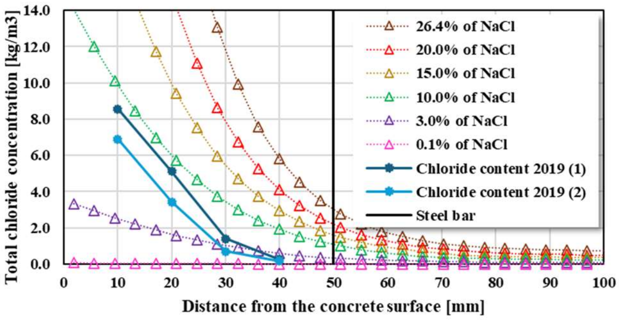
b) Chloride concentration profile (6 months)



c) Chloride concentration profile (12 months)



d) Chloride concentration profile (18 months)



e) Chloride concentration profile (24 months)

Fig. 4 Test series under continuous wetting conditions for cases (a), (b), (c), (d), and (e).

3.4 Conclusions

This study examined the deterioration of the Toyosu Tunnel in Tokyo, primarily linked to external water infiltration during a drainage system failure. The numerical calculations estimate the chloride ion concentration in the infiltrated water and the duration of concrete exposure during this event.

In this regard, only cases where the primary transport mechanism for moisture and chloride ions occurs through capillary suction have been simulated. The results indicate that an exposure period of one year to a 10% NaCl solution successfully replicates the chloride ion concentration profiles measured in the concrete during the 2019 inspection. This confirms the predictive capability of the numerical model under these specific conditions and supports the proposed hypothesis regarding the deterioration process.

However, a 10% NaCl solution represents a higher chloride concentration than seawater, raising the need to clarify how the accumulated water in the tunnel reached such levels. Additional investigations are required to determine whether the high chloride concentration resulted from a single event or from recurrent infiltration episodes. Establishing a timeline for chloride ingress will be essential to distinguish between short-term and long-term deterioration effects.

3.5 Recommendations for Future Research

In the original thesis of this study [6], various NaCl concentrations and exposure durations were analyzed, including scenarios with prolonged moisture periods followed by drying phases. However, the results indicate that chloride redistribution occurs faster than expected, highlighting the need to refine the numerical model for a more precise evaluation of this phenomenon.

The present analysis considers chloride ion transport primarily through capillary suction but does not account for redistribution during the drying phase. Future research should therefore focus on integrating both capillary suction and diffusion under alternating moisture and drying conditions to better understand chloride migration in dry concrete and refine hypotheses about the deterioration process.

Current calculations suggest that chloride redistribution occurs more rapidly than anticipated, which does not accurately reflect the true diffusion behavior. To address this, the numerical model must be adjusted to properly simulate chloride transport during extended drying periods. Once these refinements are implemented, a dynamic simulation approach can provide a more precise assessment of deterioration and deeper insights into how environmental fluctuations influence chloride penetration and corrosion in reinforced concrete structures, such as the Toyosu Tunnel.

REFERENCES

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