- Technical Paper -

STRUCTURAL DAMAGE PROCESS OF AN UNDERWATER SHIELD TUNNEL IN AN AGGRESSIVE ENVIRONMENT

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ABSTRACT

During the life cycle of an underwater shield tunnel, the long-term performance of the segmental linings will be affected by mechanical and environmental stressors, such as high water-soil pressure and aggressive agents. Therefore, the structural performance of a tunnel will deteriorate with time after its construction is completed. This paper investigates the damage process of segmental specimens under different load levels in an aggressive environment based on experiments of corrosion-accelerated specimens of a tunnel segment. In addition, an estimation method for determining the deteriorating damage of segmental linings is proposed.

Keywords: Underwater Shield Tunnel, Aggressive Environment, Deterioration, Damage

1. INTRODUCTION

Compared with urban subway tunnels, underwater shield tunnels undergo more serious environmental and mechanical stressors and thus require higher structural performance [1-2]. The complex stressors consist of two aspects. First, reinforced concrete (RC) tunnel linings are exposed to the diffusive attacks from aggressive agents. Aggressive agents, such as chlorides and sulfates, permeate into the lining with liquid and induce the corrosion of steel and cracking of concrete. Second, cracking and spalling of the tunnel lining induced by high water-soil pressure allow aggressive agents to permeate more easily and thus increase the corrosion rate and structural deterioration. Therefore, the structural performance assessment of underwater tunnel is particularly challenging due to the combined effects of high soil-water pressure and aggressive agents.

Over the past few decades, many researchers have qualitatively assessed and predicted the remaining life of underwater tunnel structures based on corrosion testing of the RC component and on-site monitoring. Izumi and Quo [3] performed a durability test of the highway shield tunnel crossing Tokyo Bay and studied the durability and anti-corrosion property of the tunnel. Lei et al. [4] proposed a lifetime prediction method of tunnel structure under the coupling effect of load and aggressive ions. Qu et al. [5] proposed a durability design of the subsea tunnel crossing Jiaozhou Bay using the chloride contents and chloride diffusion in concrete. Sun [6] proposed a methodology and corresponding testing methods for the durability design of a subsea tunnel. However, the deterioration process of the tunnel lining was found to depend on environmental and mechanical stressors. In terms of assessing the deteriorating performance of underwater shield tunnels, few studies have considered the combined effects of load and aggressive agents on the structural performance of underwater tunnels. Therefore, it is difficult to accurately assess the deteriorating damage level of an underwater tunnel during its life cycle, and further research is required to study the deteriorating mechanical performance of such a tunnel structure.

This paper conducts experiments using corrosion-accelerated specimens of a tunnel segment. Based on the experimental results, the damage process of segmental specimens under different load levels in an aggressive environment is investigated. Furthermore, a method evaluating the deteriorating damage of the segmental lining is proposed. The damage level is estimated by the load level and steel weight loss in the segmental lining; this estimation provides an approach for analyzing the deteriorating mechanical performance of an underwater shield tunnel in an aggressive environment.

2. ACCELERATED DETERIORATEION TESTING OF A BEARING SEGMENTAL SPECIMEN

2.1 Design of the Segmental Specimens

Segmental specimens that were designed based on the segmental lining in the shield tunnel of the Xiamen Metro Line No. 2 Project (Fig. 1) were used in the experiments to study the deteriorating characterization of a bearing segmental lining in an aggressive environment. Because it is difficult to use a prototype segment with loading to conduct an electrolytic experimental test, the segmental specimen shown in Fig. 2 was simplified by using a prototype segment that had the same material parameters, such as reinforcement ratio, concrete strength and concrete cover thickness.

As shown in Fig. 2, the specimen is 1,360 mm long, whereas the experimental zone is 660 mm long; for each

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Table 1 Material parameters of the rebar

Material	Diameter (mm)	Yield Strength (MPa)	Ultimate Strength (MPa)	Modulus of Elasticity (GPa)	Elongation (%)
HPB235	10	235	370	210	25
HRB335	22	335	455	200	16

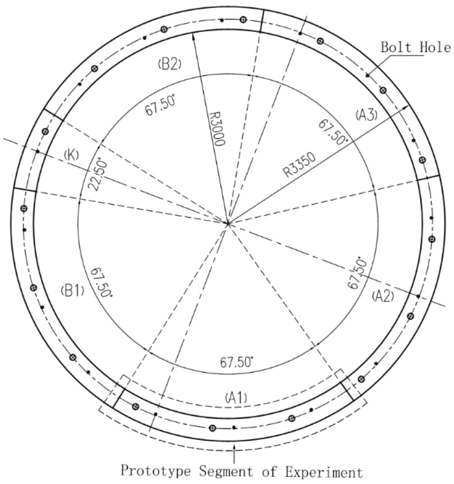


Fig. 1 Segmental lining of the shield tunnel

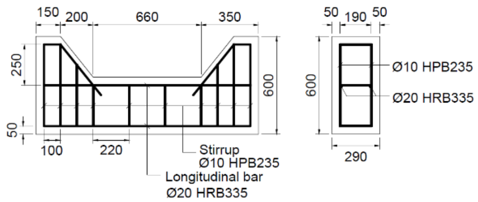
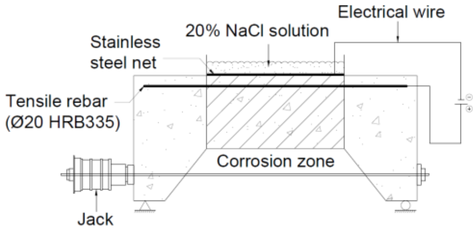


Fig. 2 Experimental Segmental Specimen



(a) Schematic diagram of an experimental corrosion specimen

(b) Photograph of the experimental setup for the bearing specimens

Fig.3 Experimental segment specimen

specimen, the cross section is 290mm × 350mm in the middle region, and the cross section in both end regions is 290mm × 600mm. Four deformed bars (two tensile bars and two compressive bars) with a diameter of 22 mm were used as longitudinal bars. The reinforcement grade was HRB335 (i.e., hot-rolled ribbed-steel bar), which has a yield strength of 335 MPa. The stirrups' diameter was 10 mm, and the steel grade was HPB235 (i.e., hot-rolled plain-steel bar), which has a yield strength of 235 MPa. The concrete used in the specimens had a compressive strength of 32.5 MPa and a tensile strength of 2.65 MPa. Portland cement, sand and gravel with a maximum aggregate size of 25mm were used and the cement: sand: gravel proportion by weight was determined as 1: 1.34: 3.28 with a water-to-cement (W/C) ratio of 0.37 in the concrete mix design. To improve the experimental efficiency, sodium chloride (NaCl) solution with chloride concentration of 2% was added into the concrete during the mixing. The material parameters of the rebar are provided in Table 1.

2.2 Deterioration Testing of the Segmental Specimen

A loading jack and electrical corrosion technique were applied in the experiments to realize the combined effects of loads and aggressive agents on the segmental specimens. As shown in Fig. 3, loads were placed on both end sides of the segmental specimens using the loading jack, which caused the specimen to be under the combined effect of an axial force and a bearing moment. Next, a NaCl solution pool with a chloride content of 20% was placed on the top surface to corrode the tensile rebar shown in Fig. 3 (a). The steel corrosion process was initiated using the electrolytic technique and had a duration of 22 days.

Three stages were considered in the experiment to study the deterioration process of segmental linings under different load levels and determine how the mechanical performance of segmental lining deteriorates, as shown in Fig. 4. During the testing process, loading occurred during the first stage (Step 1), which enabled the specimens to be under different load levels. In the second stage, the load level of the specimens remained constant, and an accelerated corrosion test was conducted (Step 2). Finally, in the third stage, the ultimate limit load was provided to cause the deteriorating specimens to fail (Step 3). Five groups of segmental specimens, named F1, F2, F3, F4 and F0, were used in the experiments. F1, F2 and F3 were the groups of accelerated corrosion without cracking, accelerated corrosion with a small number of cracks and accelerated corrosion with severe cracking, respectively. F4 was a contrast group of accelerated corrosion without loading. F0 was also a contrast group to determine the ultimate bearing capacity without corrosion.

2.3 Failure Mode of the Segmental Specimens under Different Deterioration States

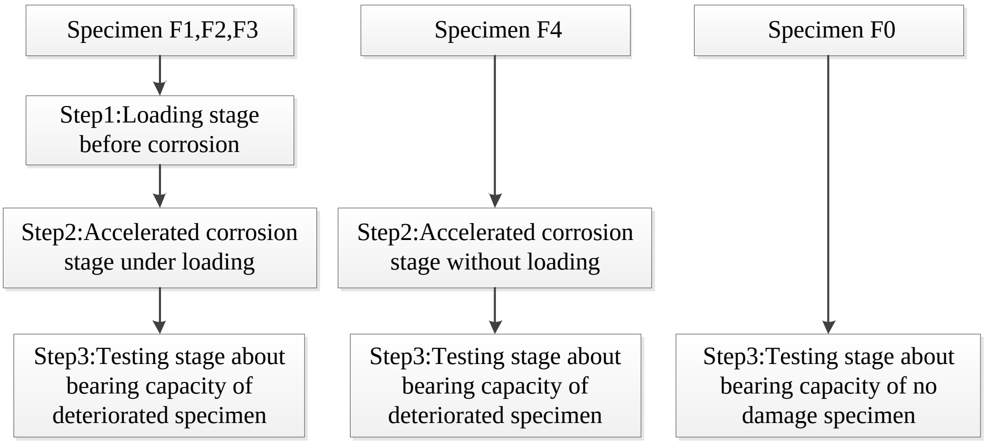


Fig.4 Experimental process of the specimens in each group

The corrosion products are expansive and induce corrosion cracking when the resulting tensile stress in the surrounding concrete reaches its tensile strength limit. Moreover, the corrosion-induced cracking patterns of segmental specimens in each group are different due to the effect of the load level. For the unloading specimen F4, corrosion-induced cracks along the direction of the rebar occurred at the cover concrete, and as the corrosion developed, the longitudinal cracks became interconnected and grew wider. Finally, the maximum crack width of specimen F4 measured by the crack scale was approximately 2.2mm.

For bearing specimens F1, F2 and F3, segmented corrosion-induced cracks along the direction of rebar occurred primarily between the tensile cracks in the cover concrete, and as the steel weight loss increased, the corrosion-induced cracks became interconnected with tensile cracks and propagated together. For example, the tensile crack widths on the bottom surface of specimen F3 at near the location of maximum bending moment ranged from 2.1mm to 2.6mm.

Because cracking propagation induces further degradation of the steel-concrete interface and exposes more of the steel surface to aggressive agents, a higher loading level led to greater steel weight loss and more severe cracking. Considering that different deteriorated states of specimens might lead to different failure modes, after the corrosion testing of the segmental specimens, the loading acting on the specimens increased and the failure modes of segmental specimens under differently deteriorated states were identified, as shown in Fig. 5.

For the non-corrosion specimen F0, Fig. 5(a) shows that the tensile cracks propagated a substantial distance in the tensile zone of each specimen, and the largest crack occurred at the mid-span; moreover, the concrete was crushed in the compressive zone of each specimen. As shown in Fig. 5(b), specimens F1 and F4, which did not exhibit a significant degree of corrosion, exhibited larger tensile cracks than specimen F0, and the two largest failure cracks appeared at the mid-span. Finally, Fig. 5(c) shows that specimens F2 and F3, which had greater steel weight loss, exhibited interconnected failure cracks and spalling of the cover concrete.

(a) Specimen without corrosion (F0)

(b) Specimen of corrosion without cracks (F1)

(c) Specimen of corrosion with cracks (F3)

Fig.5 Failure modes of specimens under differently deteriorated states

3. DAMAGE PROCESS ANALYSIS OF A BEARING SEGMENTAL SPECIMEN SUBJECTED TO ATTACK FROM CHLORIDE

3.1 Definition of Damage for the Segmental Specimen

The life-cycle structural performance of an underwater tunnel is influenced by three aspects: environmental stressors, time after construction (t) and the provided load level (f). Because the RC segmental linings are subjected to chemical-physical damage, the

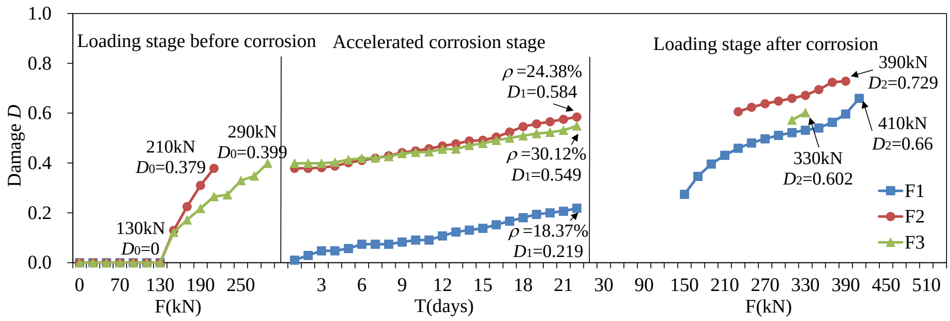


Fig.6 Damage curves of specimens under different load levels

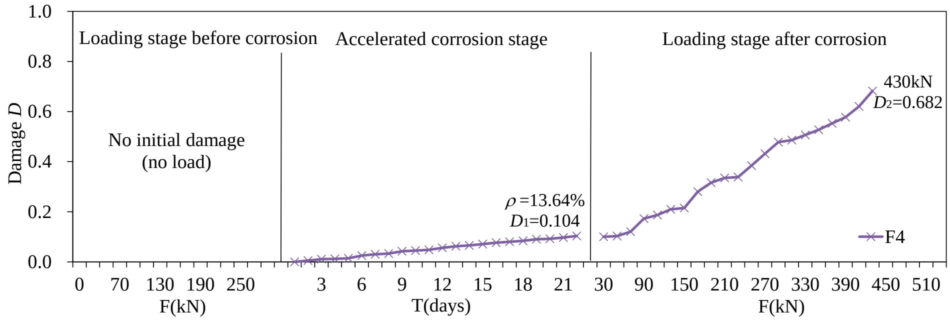


Fig.7 Damage curve of the specimen without initial damage

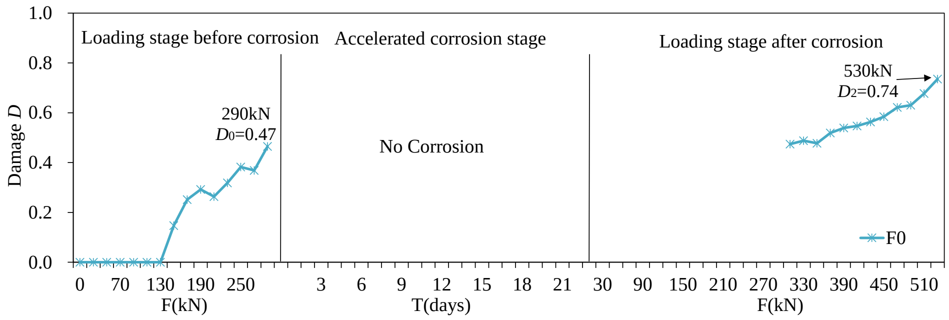


Fig.8 Damage curve of the specimen without corrosion

structural and material performance will deteriorate and the structural stiffness will decrease with time after construction. As the structural stiffness decreases, the deformation of the segmental linings would increase significantly, which can be regarded as a macroscopic phenomenon of structural deterioration. Moreover, structural deformation is an important part of the on-site monitoring of a tunnel structure. Therefore, a damage index denoted by deformation facilitates assessments of the deterioration level of a tunnel structure.

Based on stiffness damage theory reported in [7], a damage index of segmental specimen can be defined as:

$$D = 1 - \frac{E'I'}{E_0 I_0} \tag{1}$$

where $E'I'$ and E_0I_0 are the residual stiffness and initial stiffness of specimen, respectively.

Thus, according to the relationship between the displacement at the mid-span and the stiffness of the beam shown in Eq.2, Eq.1 can also be expressed as Eq.3:

$$u = \frac{Ml^2}{8EI} \tag{2}$$

$$D = 1 - \frac{M'u_e}{M_e u'} \tag{3}$$

where M' is the moment of the specimen and u' is the displacement of the damaged specimen, which can be measured experimentally. M_e and u_e are the moment at the elastic limit of the specimen and its corresponding displacement, respectively. D is the damage value of the segmental specimen.

Furthermore, for the specimens in the experiment, the specimen damage is expressed by D_0, D_1 and D_2 according to the testing stage. D_0 is the initial damage induced by loading during the first stage (i.e. loading stage before corrosion), and D_1 and D_2 are the total damage of the specimens during the second stage (i.e. accelerated corrosion stage) and third stage (i.e. loading stage after corrosion), respectively. In particular, for the second stage, D_1 contains the initial damage D_0 and deteriorating damage Δd, thus, D_1 is expressed as:

$$D_1 = D_0 + \Delta d \tag{4}$$

where Δd is the damage increment of the specimen induced by the combined effects of loading and corrosion during the accelerated corrosion stage.

3.2 Damage Evolution of the Segmental Specimens

Based on the damage equation for the segmental specimens (Eq. 3), the damage value D of the specimens in each group can be derived from the measured

Table 2 Deteriorating damage Δd and steel weight loss ρ (%) of the segmental specimens

Experimental Time/days		0	3	6	9	12	15	18	21	22
F1	Deteriorating Damage Δd	0	0.048	0.074	0.083	0.107	0.138	0.180	0.206	0.219
	Steel Weight Loss ρ	0	6.42	9.42	13.74	15.67	16.54	17.54	18.3	18.37
F2	Deteriorating Damage Δd	0	0.004	0.033	0.064	0.090	0.113	0.168	0.198	0.206
	Steel Weight Loss ρ	0	8.87	12.73	16.11	19.36	20.9	22.74	24.32	24.38
F3	Deteriorating Damage Δd	0	0.001	0.020	0.040	0.058	0.081	0.111	0.133	0.151
	Steel Weight Loss ρ	0	11.21	16.85	20.11	23.18	25.94	27.53	29.94	30.12
F4	Deteriorating Damage Δd	0	0.012	0.030	0.045	0.062	0.077	0.090	0.104	0.111
	Steel Weight Loss ρ	0	3.61	7.49	9.97	10.99	11.78	12.5	13.17	13.64

displacement value u' of the specimens. The damage curves for the five groups of specimens at all loading stages are shown in Figs. 6-8.

Figs. 6-8 show that for the specimens with higher load levels (e.g., specimens F2 and F3), the initial damage occurred before the corrosion began. However, specimens F1 and F4 remained in the undamaged state, and no cracking occurred before the corrosion began. Thus, with the development of steel corrosion, the damage of specimens increased linearly with time. Meanwhile, the ingress of chloride was accelerated because of the effect of the load, causing the corrosion rate to be higher with increases in the load level during the corrosion testing. Finally, at the end of the corrosion test, the measured ultimate steel weight loss was 18%, 24% 30% and 14% for specimens F1, F2, F3, and F4, respectively.

With respect to the ultimate bearing capacity of the deteriorating specimens, the ultimate bearing capacity of the specimens decreased more when the steel weight loss was larger. As shown in Figs. 6-8, the ultimate bearing capacity of specimens F1, F2, F3 and F4 decreased by 23%, 26%, 38% and 18%, respectively.

Finally, in terms of the ultimate damage value of specimens, flexural failure occurred when the loading reached the ultimate load of the deteriorating specimen. However, because the failure specimen still had a slight residual stiffness, $E'I'$ was greater than zero, and the ultimate damage value from Eq. 1 was less than one.

3.3 Deteriorating Damage Analysis of the Segmental Specimens

The deteriorating deformation u_t is regarded as a macroscopic phenomenon for the damage of the segmental lining's stiffness and is typically determined by the load level f of the segmental linings and the steel weight loss. Therefore, the function of displacement u_t can be expressed as $u_t=u_t(f, \rho)$. Immediately after tunnel construction, the rebar is not corroded and $\rho=0$; thus, the structure only has the loading damage D_0. Then, because the aggressive agents and high water-soil pressure affect the segmental linings, the deteriorating damage Δd accumulates gradually. As a result, the deteriorating damage Δd is a function of the load level f and steel weight loss ρ is given as:

$$\Delta d = D_1 - D_0 = g(f, \rho) \tag{5}$$

$$f = \frac{\sigma}{\sigma_t} = \frac{E_0 \varepsilon}{\sigma_t} = \left(\frac{M \cdot y_s}{I} - \frac{F}{A_c} \right) \Big/ \sigma_t \tag{6}$$

where σ and ε are the average stress and average strain in the position of rebar of the RC, respectively, E_0 is the elastic modulus of the RC, σ_t is the equivalent cracking stress of the RC, y_s is the distance from the position of rebar to neutral axis of the specimen, I is the moment of inertia of the specimen, A_c is the cross sectional area of the specimen.

According to the previous research results [8], which considered the relationship between steel weight loss and accelerated corrosion time based on this experiment, the details of deteriorating damage and steel weight loss are shown in Table 2.

Based on Table 2, a deteriorating damage formula of a segmental specimen denoted by the steel weight loss and load level can be expressed as:

$$\Delta d = (A\rho^2 + B\rho + C)\rho \tag{7}$$

where A, B and C are the influence coefficients of the load.

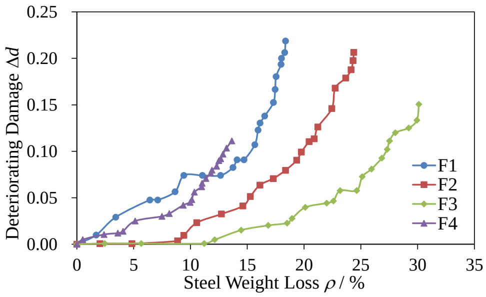
For the specimens with corrosion but without initial cracks, the value of f ranges from 0 to 0.94; A, B and C can be expressed as:

$$\begin{aligned} A &= (4f + 8) \times 10^{-5} \\ B &= -(1.7f + 9) \times 10^{-5} \\ C &= (13.7f + 6.3) \times 10^{-3} \end{aligned} \tag{8}$$

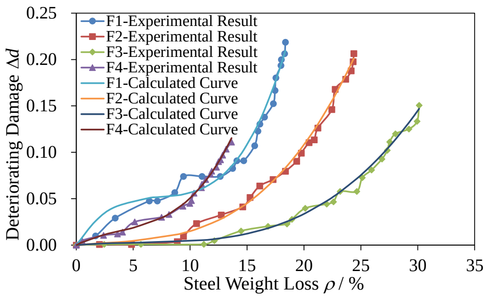
For the specimens with corrosion and with initial cracks, the value of f ranges from 0.94 to 2.07; A, B and C can be expressed as:

$$\begin{aligned} A &= (f^2 - 5f + 4) \times 10^{-4} \\ B &= -(3.5f^2 - 12.5f + 11.1) \times 10^{-3} \\ C &= (2.65f^2 - 9.6f + 8.6) \times 10^{-2} \end{aligned} \tag{9}$$

The relationship between the deteriorating damage and steel weight loss of the segmental specimen under



(a) Experimental results



(b) Calculated results versus experimental results

Fig.9 Deteriorating damage associated with steel weight loss under different load levels

different load levels are shown in Fig. 9 based on the experimental results.

Fig. 9 (a) reveals that a higher loading level led to greater steel weight loss because the severe cracks accelerate the rebar corrosion process. However, the effect of rebar corrosion on deteriorating damage of bearing specimens decreases with increases in the loading crack width. The reason for this phenomenon might be the following process: corrosion rust first fills the initial cracks, and after the rust fills the cracks, the deteriorating damage begins to increase. Finally, as shown in Fig. 9 (b), the calculated value matches the experimental results well and can accurately reflect the deteriorating damage process.

In terms of the life-cycle structural performance of an underwater shield tunnel, the use of Eqs. 7-9 represents a new approach for assessing the life-cycle structural performance of an underwater tunnel in an aggressive environment. By considering the load level and steel weight loss at different sections of the segmental linings, the deteriorating damage level of tunnel structure can be estimated using Eqs. 7-9. Based on the deteriorating damage value of segmental lining, the stiffness of aging tunnel structure can be obtained and applied to the mechanical performance estimation.

4 CONCLUSIONS

(1) This paper described a proposed method for calculating the deteriorating damage of segmental linings based on the linings' load level and steel weight loss; this proposed method can be regarded as a bridge between the mechanical performance analysis and life-cycle performance assessment of deteriorating tunnel structures.

(2) The deterioration process of segmental specimens under different load levels was studied based on experiments of corrosion-accelerated specimens of a tunnel segment. Under an aggressive environment, the level of applied tensile load has a substantial effect on the steel corrosion of specimens, accounting for the significant reduction of the ultimate loads. As a result, some sections of the tunnel lining with higher tensile stress should be regarded as hazard zones and be maintained in a timely manner when the deterioration is initiated.

(3) Further research is required to conduct time-dependent structural analysis of an underwater tunnel in connection with deteriorating damage.

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