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Reliability-Based Durability Design of Shield Tunnels in Coastal Regions

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ABSTRACT: In this paper, a reliability-based durability design method for shield tunnels in a marine environment is introduced. In this context, a method for integration of the coupling effects of chlorides and hydrostatic pressure into reliability-based durability design of shield tunnels in a marine environment is proposed. By using the proposed method, material parameters of RC segmental linings can be determined. The target reliability-based durability design level shall be satisfied during structural lifetime.

1. INTRODUCTION

The reliable and durable performance of underwater shield tunnels is essential to support the stable development of cities located in the coastland or regions with numerous lake and rivers. Due to aggressive chemical attacks, reinforced concrete (RC) segment linings are at risk from deterioration processes. Especially for the undersea shield tunnels, the detrimental effects, such as high concentration of aggressive chemicals and great hydrostatic pressure, lead to unsatisfactory structural performance of these tunnels soon after their construction. Therefore, a reliable design method for new underwater shield tunnels is needed (i.e. durability design).

In recent decades, significant attention (Kudo and Guo 1994; Lei et al. 2015) has been addressed for the durability of tunnel structures based on corrosion testing of the RC component and on-site monitoring. Meanwhile, several attempts (Song et al. 2009; Bagnoli et al. 2015) to evaluate the deterioration performance of underwater tunnels have been proposed using probabilistic methods. However, in term of durability design of undersea tunnels, the research is very limited (Sun 2011; Li et al. 2015). In addition, there has been a lack of research considering the coupling effects of marine environmental hazard and hydrostatic pressure on the durability design of undersea tunnels.

In this paper, considering the influence of structural location and its surroundings, the coupling effects of chloride and hydrostatic pressure are integrated into the reliability-based durability design of tunnel structures in a marine environment. Next, based on the proposed durability design criterion for RC segment linings, the durability design factors are discussed, so that the target durability reliability level of tunnel structures during their lifetime will be satisfied.

2. HAZARD ASSESSMENT DUE TO MARINE CHLORIDE

Since the long-term performance of RC structures is strongly influenced by their environmental conditions, environmental hazards should be quantitatively assessed and considered in the durability design of RC shield tunnels in a marine environment. In previous research (He et al. 2018), a probabilistic model of hazard associated with underground chloride for tunnels at different regions was presented, and a brief summary of this model is described as follows.

Observed values in the city of Xiamen, China are used to obtain the attenuation relationship between the chloride content in the underground, C_{soil} (ppm, i.e., 1 mg/L), and the distance d (km) from the coastline (Guo et al. 2004). Considering the influence of chloride content in the coastal waters, C_{sea} (ppm), the attenuation of C_{soil} (ppm) in horizontal direction can be expressed as:

$$C_{soil} = 0.62 \cdot C_{sea} \cdot 0.63^{d} \tag{1}$$

Due to the uncertainties involved in the prediction of underground chlorides around tunnels, parameters associated with model error are included in the attenuation equations. Thus, the attenuation with model uncertainty can be expressed as:

$$C_{Soil} = X_R \cdot \left[0.62 \cdot \left(X_S \cdot C_{Sea} \right) \cdot 0.63^{d} \right] \tag{2}$$

where X_R is a lognormal random variable related to estimation of chloride content in soil; and X_S is a normal random variable associated with the marine chloride content at different coastal regions.

Finally, the probability that C_{soil} at a specific site exceeds an assigned value c_{soil} is described as:

$$\begin{aligned} q(c_{Soil}) &= P(C_{Soil} > c_{Soil}) \\ &= \int_0^{\infty} P\left(X_R > \frac{c_{Soil}}{0.62 \cdot X_S C_{Sea} \cdot 0.63^{d}}\right) \times f(X_S) dX_S \end{aligned} \tag{3}$$

where $f(X_S)$ is the probability density function of X_S.

Figure 1 shows the hazard curves for two coastal cities in China using Eq. (3). Based on this approach for estimating hazard associated with underground chloride, the influence of marine environment on tunnel can be quantified.

3. BASIC FUNCTIONS FOR ESTIMATING STRUCTURAL PERFORMANCE DUE TO CORROSION

In terms of the underground environment in coastal regions, surface chloride content of the shield tunnel, C_s (kg/m^3), is assumed to be approximately equal to the chloride content of the soil, C_{soil}, and it may not change with time due to the chemical equilibrium for the concrete exposed to infinite seawater (Ann et al. 2009). Therefore, C_s can be described as:

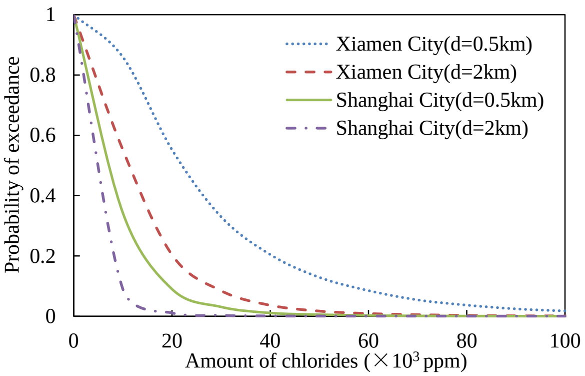

Figure 1. Hazard curves for content of underground chlorides at two coastal cities with the distance of 0.5 km and 2 km from coastline

$$C_S = X_1 \cdot 0.001 C_{Soil} \tag{4}$$

where X_1 is a lognormal random variable representing model uncertainty.

Due to the effect of high hydrostatic pressure on tunnels, structures withstand a large water pressure gradient between the inside and outside walls, and the chloride motion in the linings is associated with external water pressure as proved by experimental results. Considering the action of hydrostatic pressure and the water environment, as the total amount of chloride around rebar accumulates and reaches critical threshold of chloride content C_{cr} (kg/m^3), the corrosion of rebar begins. Thus, the time t_1 to corrosion initiation can be obtained using the following event:

$$g_1 = X_2 C_{cr} - C(c,t) < 0 \tag{5}$$

where

$$C(c,t) = X_3 \frac{C_s}{2} \left[erf\left(\frac{c-ut}{\sqrt{4Dt}} \right) + e^{\frac{uc}{D}} erfc\left(\frac{c+ut}{\sqrt{4Dt}} \right) \right] \tag{6}$$

$$D = 10^{-6.77(W/C)^2 + 10.10(W/C) - 1.14} \tag{7}$$

Table1 Parameters of random variables

Variables	Distribution	Mean	COV
Chloride content in soil (X_R)	Lognormal	1.00	0.73
Marine chloride content (X_S)	Normal	1.00	0.043
C_s-C_{soil} equation (X_1)	Lognormal	1.43	1.08
Critical threshold chloride content at occurrence of steel corrosion (X_2)	Normal	1.00	0.375
Estimation of chloride transport (X_3)	Lognormal	1.24	0.906
Critical threshold of corrosion amount at crack initiation (X_4)	Lognormal	1.00	0.352
Corrosion rate (X_5)	Lognormal	1.00	0.58

c is the concrete cover specified in design, mm; t is the time after construction, year; W/C is the ratio of water to cement; D is the chloride ion transportation coefficient in concrete, mm^2/year; u is the average velocity of chloride motion, mm/year; C_{cr} is assumed to be 2.8 kg/m^3, X_2 is a normal variable associated with the evaluation of C_{cr}; and X_3 is a lognormal variable representing the model uncertainty associated with estimation of $C(c, t)$.

As the passive film is broken by chloride ions, a large volume expansion of rust formation causes internal stress and induces cover concrete segment cracks when the total amount of steel corrosion product Q_b exceeds the critical threshold of corrosion associated with crack initiation Q_{cr}. According to Akiyama et al. (2010), the probability associated with the corrosion crack occurrence can be estimated by the occurrence of the event:

$$g_2 = X_4 Q_{cr}(c) - Q_b(V_1, t_{co}, t) < 0 \tag{8}$$

where

$$Q_{cr}(c) = \eta(W_{c1} + W_{c2}) \tag{9}$$

$$Q_b(V_1, t_{co}, t) = X_5 \rho_s V_1 (t - t_{co}) \tag{10}$$

ρ_s is the steel density, 7.85 mg/mm^3; V_1 is the corrosion rate of the steel bar before the occurrence of a corrosion crack, mm/year, assumed as the corrosion rate is 7.7 μm/year; η is the correction factor; X_4 is a lognormal random variable representing the model uncertainty associated with the estimation of Q_{cr}; and X_5 is a lognormal random variable related to the corrosion rate.

In this study, the corrosion-induced cracking is regarded as the structural serviceability limit state. All parameters of the random variable X_i ($i = S, R$, 1, 2, 3, 4, and 5) involved in the calculation of reliability using Monte Carlo simulation (MCS) are summarized in Table 1. The probability that the cracking occurs before the time t_c is defined as:

$$P_f(t) = P\left(t_1 + t_2 \le t_c\right) \tag{11}$$

and this probability is transformed into a reliability index β, as follows:

$$\beta(t) = \Phi^{-1}(P_f(t)) \tag{12}$$

where Φ is the cumulative distribution function of the standard normal variable.

4. RELIABILITY-BASED DESIGN CRITERION

4.1 Proposed design criterion

To ensure the serviceability of a structure during its life-cycle, its reliability index, β, is required to satisfy a target value, β_{target}, during its lifetime. However, due to the coupling effects of aggressive agents and high hydrostatic pressure, premature steel corrosion of segment occurs easily. As a result, durability design, especially for a new shield tunnel in a marine environment, is necessary. Herein, a design criterion is proposed, so that the reliability index for the occurrence of corrosion cracking will be very close to the target value without complex reliability computations. After confirming that the time to occurrence, $T_{crack,d}$, is larger than the lifetime of structure, T_d, the designers can determine the concrete cover and concrete quality. The design formulation proposed is:

$$T_d \le T_{crack,d} = \varphi\left(T_1 + T_2\right) \tag{13}$$

$$C_{S,d} = C_{Sea} \cdot 0.8^d \tag{14}$$

$$C_{\lim,d} = \frac{C_{S,d}}{2}\left[erfc\left(\frac{c_d - uT_1}{\sqrt{4DT_1}}\right) + e^{\frac{uc_d}{D}} erfc\left(\frac{c_d + uT_1}{\sqrt{4DT_1}}\right)\right] \tag{15}$$

$$T_2 = \frac{Q_{cr,d}}{V_d} \tag{16}$$

where φ is durability design factor taking into account the uncertainties in the computation of $T_{crack,d}$; T_1 and T_2 are the time of steel corrosion initiation and the time from steel corrosion initiation to occurrence of cracks, respectively; c_d is the design concrete cover; $C_{lim,d}$ is equal to C_t as the mean value; V_d is equal to V_1 as the media value; and $Q_{cr,d}$ is equal to Q_{cr} multiplied by X_4 as the median value.

To determine the durability design factor for tunnels in a marine environment, the procedure based on code calibration has the following steps:

(a) Set the target reliability index β_{target} and the life time of tunnel T_d.

(b) Set the calculation group under different marine environments (i.e. the design value of surface chloride content of tunnel using Eq. (2) and design value of hydraulic pressure). In this study, 100 locations from 12 coastal cities of China are chosen to represent different marine environmental conditions.

(c) Assume the initial durability design factor φ.

(d) Determine the design concrete cover using Eq. (15).

(e) Calculate β_i (i = 1, 2, …, 100) of tunnels under all cases that have the design concrete cover determined in step (d).

(f) Repeat steps (c) to (e) until

$$U = \sum_{i=1}^{100} (\beta_{\text{target}} - \beta_i(\varphi))^2 \tag{17}$$

is minimum, and the durability design factor is found.

4.2 Durability design factor

Specifications, like JSCE Standard Specifications (2002) and RILEM (1998), proposed the reliability indices ranging from 1.5 to 2.5 for serviceability limit state of RC structures. However, since the target lifetime of tunnels is generally almost 100 years or longer, it is very difficult to design using too high reliability indices. Thus, a target reliability index of Hong Kong-Zhuhai-Macau project for a working life of 120 years was suggested to be 1.3 (Li et al. 2015). Meanwhile, the Code for Durability Design of Concrete Structure of China (2008) suggests that failure probability of RC structures should range from 5% to 10% to ensure structural serviceability during its lifetime (i.e. β_{target} ranges from 1.282 to 1.645). In this study, β_{target} is set to be 1.1, 1.3 and 1.5, and the lifetime of tunnel is set to be 80 years, 100 years and 120 years. Minimum concrete cover is assumed 30 mm.

The calculated durability design factors for each target reliability index and lifetime are shown in Figure 2. This figure indicates that φ is more sensitive to β_{target} than to T_d. The reliability indices for structures under different requirements (i.e. prescribed lifetime, T_d, and target reliability value, β_{target}) and conditions (i.e. different cities, distance from coastline, d, hydrostatic pressure, P_w, and water to cement ratio, W/C) are listed in Table 2. As shown in Table 2, the reliability indices are very close to the target values. Therefore, based on the proposed design criterion and durability design factor, shield tunnels in a marine environment requiring target durability reliability indices for prescribed lifetime can be designed.

5. CONCLUSIONS

A computational procedure for integration of the coupling effects of underground chloride and hydrostatic pressure into reliability-based durability design of RC shield tunnels in a marine environment was proposed. In this proposed procedure, the probability associated with the corrosion-induced cracking occurrence of RC segment could be determined based on structural

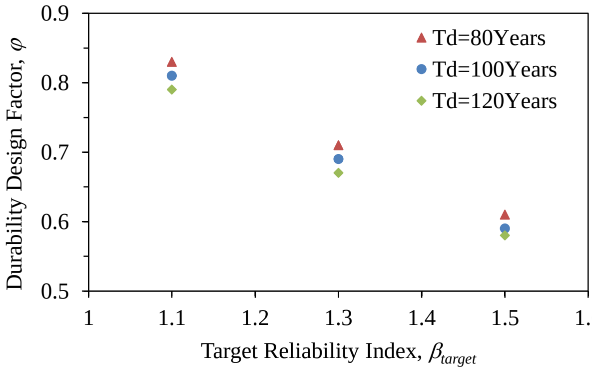

Figure 2. Relationship between lifetime of structures T_d, target reliability index β_{target}, and durability design factor φ

Table 2 Reliability indices of RC tunnels using durability design factor

Coastal City in China	***Case Considered***			
	T_d=100Year β_{target}=1.3		*T_d=80Year β_{target}=1.5*	
	P_w=0.2MPa d=0.3km		*P_w=0.08MPa d=0.5km*	
	W/C = 0.35	*W/C = 0.4*	*W/C = 0.35*	*W/C = 0.4*
Dandong	*1.32*	*1.33*	*1.57*	*1.58*
Tianjin	*1.32*	*1.35*	*1.55*	*1.58*
Yantai	*1.31*	*1.34*	*1.55*	*1.58*
Ningbo	*1.24*	*1.26*	*1.49*	*1.49*
Xiamen	*1.28*	*1.31*	*1.52*	*1.55*
Shenzhen	*1.28*	*1.30*	*1.51*	*1.51*
Beihai	*1.32*	*1.35*	*1.56*	*1.58*
Zhanjiang	*1.27*	*1.29*	*1.49*	*1.50*
Mean	*1.29*	*1.32*	*1.53*	*1.55*
Standard Deviation	*0.03*	*0.03*	*0.03*	*0.03*
Coefficient of Variation	*0.02*	*0.02*	*0.02*	*0.02*

location and its surrounding environments. Also, a discussion of durability design factors and on the criterion for designing RC segmental linings satisfying the target reliability-based durability design level was presented.

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