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Durability Assessment and Maintenance Planning of Concrete Structures in Ningbo-Zhoushan Port Main Channel Sea Link Project

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Abstract. *This paper performs the durability assessment and maintenance planning of concrete structures during construction phase in the ongoing Ningbo-Zhoushan Port Main Channel (NZPMC) sea link project with a service life of 100 years. The background of this project is first introduced and the durability design at preliminary study phase is recalled; the chloride-induced corrosion of reinforcement steel was considered as the most critical process that controls the design. Then, the durability model for assessment is established for this durability limit state and the statistical properties of the model parameters are given. From the collected data on the concrete cover thickness and modified chloride diffusion coefficients, the statistical properties of these parameters are updated. With the design options adopted in design phase and the updated parameter properties, taking one non-navigable bridge as an example, the achieved reliability levels and failure probabilities are calculated for structural elements under different exposure conditions by using full probabilistic approach. On the basis of the achieved reliability level of durability, a preliminary maintenance planning is performed for the concrete elements in the concrete structures, and the corresponding recommendations are given.*

Keywords: *NZPMC project; Durability assessment; Service life; Failure probability; Reliability; Maintenance planning*

1 Introduction

1.1 The Ningbo-Zhoushan Port Main Channel Sea Link

The Ningbo-Zhoushan Port Main Chanel (NZPMC) sea link project situates in the East China Sea area and links the islands across the water region of Hui'bie Ocean. The NZPMC project includes sea bridges of 17.8 km (three navigable bridges and four non-navigable bridges) and land bridges of 14.0 km, with a total investment of nearly 2.3 billion US dollars. The design service life (DSL) of the whole project is 100 years. The preliminary study phase of the project started in 2015, and the construction works finished at the end of 2021.

1.2 Environment and Design Service Life

One of the technical challenges of NZPMC project was to achieve the service life of 100 years for the concrete structures in an aggressive marine environment. The concrete structures in the project include the piers, bearing platforms and piles for sea and land bridges.

The analysis of the sea water chemistry shows a chloride (Cl^-) concentration within10,700-17,020 mg/L, a sulfate (SO_4^{2-}) concentration within 1,140-2,260 mg/L, and total salinity between 23.632 and 26.845 (at the sea bottom).

From a criticality analysis of the possible deterioration processes, the chloride-induced steel corrosion of RC/PC elements was identified as the controlling process of durability design.

1.3 Scope and Objective

The durability assessment is of utmost importance for concrete structures in NZPMC project due to the complexity of quality control, the expected service life of 100 years and the required high durability performance level in service. Using durability models, the assessment aims to determine the accomplished durability levels of concrete elements in structures, and further to provide a realistic basis for maintenance planning. Accordingly, this paper collects the chloride diffusion coefficients of structural concretes and the thickness of concrete cover measured on the concrete elements. The accomplished durability level is evaluated through models, and a preliminary analysis is performed for the maintenance planning on the basis of the assessment results.

2 Durability Assessment: Requirements and Models

2.1 Durability Requirements

During the preliminary design phase, the durability requirements for the concrete structures include the requirements on the raw materials of structural concrete, durability properties of concrete, depth of concrete cover to reinforcement (x_d^{min}), and control of crack width (Sarja, 2000; Li et al., 2020). The durability properties refer to the minimum concrete strength, maximum water to binder ratio (w/b) and the corresponding chloride diffusion coefficient D_{Cl}^0 (Li, 2016). Moreover, a maximum allowable cracking width is prescribed to control the risk of penetration of external aggressive agents in marine environment into the concrete inside. Table 1 summarizes the requirements on the durability properties and crack width for the concrete elements.

Table 1. Durability requirements for RC elements of sea bridges in NZPMC project

Construction	Element	DSL (year)	Exposure	Concrete	w/b	x_d^{min} (mm)	D_{Cl}^0 (10^{-12}m²/s) at 56d	Allowable crack width (mm)
Prefabricated	Box girder (exterior)	100	Salt fog	C50	0.33	45	≤ 2.0	0.15
	Box girder (interior)	100	Salt fog	C50	0.33	40	≤ 2.0	0.15
Cast-in-place	Pier	100	Salt fog	C40	0.36	70	≤ 3.0	0.15
			Splashing	C40	0.36	70	≤ 2.5	0.15
Cast-in-place	Bearing platforms	100	Splashing	C35	0.38	75	≤ 3.0	0.15
Cast-in-place	Bored hole pile	100	Immerged	C35	0.38	75	≤ 3.5	0.15

During the construction, the properties of structural concretes are tested in on-site laboratory. In parallel, the constructed concrete elements, prefabricated or cast-in-place, are inspected for the achieved quality, and particularly for the thickness of concrete over. These data provide the information on the realistic construction quality of concrete elements, thus help to update the statistical properties of parameters in the durability assessment models. These data sources in Table 1 form the essential basis for predicting the durability performance of concrete elements during service life. In this paper, the durability assessment of concrete elements is performed through fully probabilistic approach for the chloride ingress

2.2 Chloride Ingress Model

The assessment model for chloride-induced corrosion is also adapted from the analytical model of Fick's second law. With the corrosion initiation specified as durability limit state, the assessment equation writes,

$$G = (C_{\mathrm{cr}} - C_0) - (C_{\mathrm{s}} - C_0)\left[1 - \mathrm{erf}\left(\frac{x_{\mathrm{d}}}{2\sqrt{D_{\mathrm{Cl}} \cdot t_{\mathrm{SL}}}}\right)\right] \geq 0 \tag{1}$$

with C_{cr} the critical chloride concentration for corrosion initiation (%); $C_{\mathrm{s},0}$ standing for the cover surface and initial chloride concentration in concrete (%); t_{SL} denoting the design service life; x_{d} the concrete cover depth (m). The gradual decrease of concrete chloride diffusivity D_{Cl} (m^2/s) with time can be described by the ageing factor η,

$$D_{\mathrm{Cl}}(t) = D_{\mathrm{Cl}}^0 \left(\frac{t_0}{t}\right)^n = D_{\mathrm{Cl}}^0 \eta(t_0, t, n) \tag{2}$$

The term n is the exponential coefficient for the ageing law and D_{Cl}^0 the concrete diffusivity at age t_0. Since it is not rational to assume the chloride diffusivity to decrease infinitively, this decrease law is truncated at t = 30 years to ensure a conservative design, i.e. $\eta(t_0, t, n)\big|_{t>30\,\mathrm{years}} = \eta(t_0, t = 30\,\mathrm{years}, n)$.

In total, the assessment model contains six parameters: C_{cr}, C_{s}, C_0, x_{d}, D_{Cl}^0 and $\eta(n)$. The statistical properties of the parameters $C_{\mathrm{cr,s}}$ and ageing exponent n need to be obtained on the basis of long-term exposure tests. Since the long-term exposure data of concrete samples is still being collected, the values of the parameters $C_{\mathrm{cr,s}}$ and n refer to that investigated in the Hong Kong–Zhuhai–Macau (HZM) sea link project (Li et al. 2015). For the initial concentration C_0, a uniform distribution is adopted for the structural concretes from the chemical analysis of raw materials. The statistical properties of all parameters are given in Table 2.

3 Statistical Analysis on Collected Data

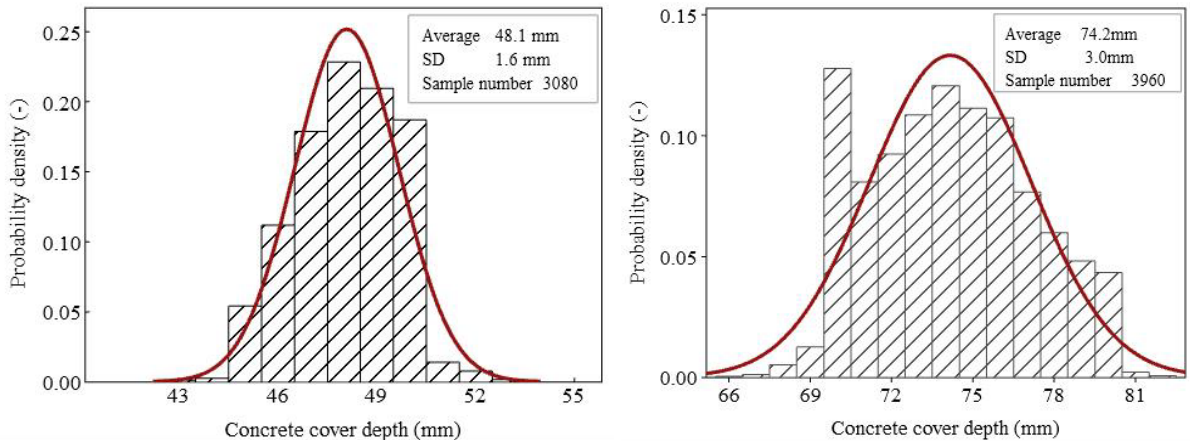
3.1 Concrete Cover Depth

The concrete cover was measured through the common midpoint (CMP) method. The principle of CMP method is to detect the depth of reinforcement bars through transmitting an electromagnetic wave pulse and receiving the reflected waves from the steel bars by two adjacent antennas (Halabe et al. 1993).

Figure 1 illustrates the statistical analysis on the cover thickness measured on the prefabricated (e.g. box girder) and cast-in-place (e.g. piers) elements. The design value for concrete cover thickness for box girder (exterior) is 45 mm, cf. Table 1, and the measured mean value attains 48.1 mm with only 1.6 mm as SD value, providing a safety margin for the design value; the design thickness for piers is 70 mm and the measured values have 74.2 mm as mean value and 3.0mm as SD value in Figure 1. This probably relates to the fact that the quality control on cover thickness was more difficult for cast-in-place elements than prefabricated elements.

Table 2. Statistical properties for model parameters of chloride ingress

Parameter	Statistical properties	Atmospheric	Splashing	Tidal	Immerged
Initial chloride content C_0	Uniform (%)	0.03	0.03	0.03	0.03
Surface concentration C_s (Lognormal)	Average (%)	2.0	5.4	3.8	4.5
	Deviation (%)	0.31	0.82	0.58	0.68
Critical concentration C_{cr} (Lognormal)	Average (%)	0.85	-	-	-
	Deviation (%)	0.13	-	-	-
Critical concentration C_{cr} (beta)	Lower bound L (%)	-	0.45	0.45	1.0
	Upper bound U (%)	-	1.25	1.25	3.5
	Coefficient α (-)	-	0.22	0.22	0.23
	Coefficient β (-)	-	0.36	0.36	0.33
Diffusion coefficient D_{Cl}^0 (Lognormal)/28d	Average (10^{-12} m^2/s)	Design values			
	Coef. of Variation	0.2			
Exponent coefficient n (Normal)	Average (-)	0.53	0.47	0.46	0.44
	Deviation (-)	0.079	0.029	0.029	0.028
Concrete cover x_d (Normal)	Average (mm)	Design values			
	Deviation (mm)	1.6 (prefabricated)/3.0 (cast-in-place)			



(a) Prefabricated elements (b) Cast-in-place elements

Figure 1. Statistical properties for concrete cover thickness.

3.2 Chloride Diffusion Coefficient

Another issue concerns the diffusion coefficient D_{Cl}^0. In the preliminary design and the durability assessment, the chloride diffusion coefficients are measured from the rapid chloride migration (RCM) method. The chloride diffusion coefficient from RCM method is by nature a non-steady state migration coefficient D_{Cl}^{NSSM}, while the original significance of D_{Cl}^0 in the model corresponds to the long term non-steady state diffusion coefficient D_{Cl}^{NSSD}. During the preliminary study, the correlation between the two coefficients was subject to extensive experimental research and a conservative relationship is adopted as $D_{Cl}^{NSSD} = 0.5D_{Cl}^{NSSM}$. Through this correlation, the collected data on D_{Cl}^{NSSM} in Table 3 can be converted into D_{Cl}^{NSSD} and used in the model. The detailed correlation study can be referred to Li et al.

Table 3. Concrete cover thickness and quality of RC elements of one non-navigable bridge

Construction	Element	Exposure	Concrete	x_d (mm)		D_{Cl}^0 (10^{-12}m^2/s)	
				Average	SD	Average	SD
Prefabricated	Box girder (exterior)	Salt fog	C55	48.1	1.6	3.81	0.27
	Box girder (interior)	Salt fog	C55	43.1	1.6	3.81	0.27
Cast-in-place	Pier	Salt fog	C40	74.2	3.0	4.03	0.20
		Splashing	C40	74.2	3.0	4.03	0.20
Cast-in-place	Bearing platform	Splashing	C35	79.2	3.0	4.36	0.20
Cast-in-place	Bored hole pile	Immerged	C35	79.2	3.0	4.70	0.20

4 Durability Assessment of Concrete Structures

4.1 Full Probabilistic Assessment

On the basis of the statistical properties in Tables 2 and 3, a full probabilistic assessment is performed via Monte-Carlo simulations. A computer-based program is developed specially to perform the probabilistic assessment.

In the simulation, six parameters are considered as joint occurrence random variables: C_{cr}, C_s, C_0, x_d, D_{Cl}^0 and n. For a given exposure age t, the Monte-Carlo simulations are performed to calculate the failure probability of Eq.(1), and 1,000,000 samplings are used to ensure the solution of “real” probability. Accordingly, the failure probability is solved with time from t=0 to t=100 years. The analytical evolution of failure probability for the different elements is illustrated in Figures 2 and 3.

4.2 Bridge Elements in Atmospheric Zone

The bridge elements in atmospheric zone include box girders and piers. The box girders are prefabricated using C55 concrete. The failure probability at 100 years is 0.06% and β = 3.24 for external side and 0.68% and β = 2.47 for internal side, cf. Figure 2.

The piers are constructed by cast-in-place method. The failure probability is inferior to 10^{-6} at 100 years, and the corresponding reliability index β>5.0. From the above results of assessment, it can be seen that the bridge elements in atmospheric zone have very low failure probability, i.e. $p_f \leq 0.68\%$ at 100 years and the corresponding reliability index $\beta \geq 2.47$. The failure probability and the corresponding reliability index serve as a basis for maintenance planning in service life of concrete structures.

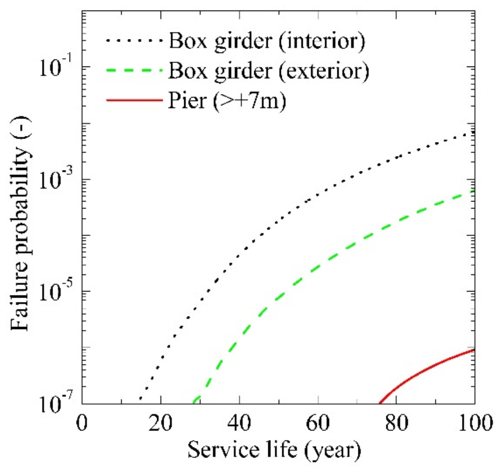


Figure 2. Failure probability of bridge elements in atmospheric zone

4.3 Bridge Elements in Splashing and Tidal Zones

The bridge elements in splashing and tidal zones include piers and the bearing platforms. For the reason aforementioned, the tidal zone is conservatively considered as splashing zone in this assessment. The piers are cast-in-place using C40 concrete and the silane impregnation on the external surface in addition to 70 mm concrete cover. The assessment gives $p_f<10^{-4}$ and $\beta>3.83$ for the cast-in-place piers, cf. Figure 3. The bearing platforms are exposed to splashing/tidal actions. These platforms are cast-in-place with C35 concrete, using epoxy-coated bars and surface silane impregnation as additional measures in addition to 75 mm concrete cover. The failure probability is calculated as $p_f<10^{-4}$ and $\beta>3.83$.

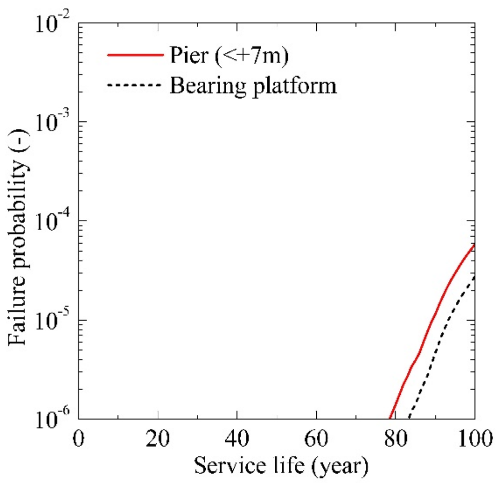


Figure 3. Failure probability of bridge elements in splashing and tidal zones

4.4 Bridge Elements in Immerged Zone

The bridge elements in immerged zone include bore-hole piles. The bore-hole piles use C35 concrete and concrete cover of 75 mm is prescribed without other additional measures. The assessment gives $p_f < 10^{-6}$ and $\beta > 5.0$ at 100 years.

5 Preliminary Maintenance Planning

The maintenance planning is to establish maintenance schemes, including the techniques and intervention periods, on the basis of the durability state of concrete elements. The maintenance strategies can be classified as preventive, necessary and mandatory. The preventive maintenance refers to the intervention at early stage of deterioration, normally at low maintenance costs. For the concrete elements in NZPMC project, the maintenance planning adopts a preventive strategy. During the service life, the deterioration processes will be monitored via periodical inspection and on-line sensors. The maintenance actions are to be taken at early stage of deterioration for elements with the help of these inspections and monitoring.

From the assessment results in the previous section, all concrete elements have failure probability $p_f < 1$ % ($\beta > 2.33$), i.e. within the suggested p_f value for preventive maintenance of chloride-induced corrosion and corrosion initiation. So, theoretically all elements can be exempted from maintenance during service life. However, given the uncertainty associated with the concrete construction, e.g. early-age cracking, and the unexpected environmental actions during service life, e.g. the global warming and long-term change of hydrology, a basic maintenance planning is necessary for concrete elements. The basic maintenance planning considers mainly two aspects: the durability performance level of elements, denoted by p_f at 100 years, and the structural importance of elements. The basic maintenance scheme consists in performing the surface chloride extraction by electrochemical method and applying silane impregnation on the surface of elements periodically. The maintenance period is recommended to be 40 years due to the much lower failure probability (<0.68%). Note that the basic maintenance scheme applies only to the elements in atmospheric and splashing/tidal zones. The immerged elements are not included in this scheme. It should be noted that this basic maintenance scheme is to interact with the durability inspection/monitoring data and the real-time durability assessment during the service life.

6 Conclusions

- This paper investigates the acquired durability of concrete elements of the NZPMC project through model-based assessment. A full probabilistic approach is used in the assessment and the statistical properties of the parameters are from exposure tests and the laboratory characterization for in situ structural concretes in construction. The assessment results serve as the basis for the check of acquired durability after construction phase and the preliminary maintenance planning.
- The Monte-Carlo simulations are performed to calculate the failure probability of chloride ingress process with respect to chloride initiation state. The assessment results are presented for bridge elements in atmospheric, splashing and tidal, and immerged zones. The results show that all elements have low failure probability $p_f < 1\%$ ($\beta > 2.33$)

at 100 years.

- On the basis of the durability assessment, the failure probability of all elements is within the limit value of preventive maintenance, and a basic maintenance planning is installed to counteract the uncertainty associated with the concrete construction and the environmental actions in service life.

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