XVI International Conference on Durability of Building Materials and Components
DBMC 2023, China
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Analytical and Experimental Service Life Assessment of Ningbo-Zhoushan Port Main Channel Sea Link Project

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Abstract. *The Ningbo-Zhoushan Port Main Channel (NZPMC) sea link is one of the most important projects undertaken by the People's Republic of China. The main factors that determine the service life of these marine structures, exposed to chloride-induced corrosion, are the "penetrability" and thickness of the concrete cover that protects the steel reinforcement. In an initial design phase, these factors are defined by modeling the penetration of chlorides with analytical tools (based on the Duracrete approach). In the construction phase, data are collected from the in-site laboratory for concrete chloride diffusivity, and from non-destructive tests for the concrete cover thickness and air permeability for the prefabricated bridge piers. On the basis of these data, two model-based approaches are used to predict the service life of the bridge. The first model is an analytical one based on the solution of Fick's 2nd diffusion law, for chloride ingress into concrete using the corrosion initiation as durability limit state. The second model uses the "Exp-Ref" model, using the concrete cover thickness and air permeability as input parameters and calibrated by the EuroCode specifications on structural concretes in marine environments. Both approaches use Monte-Carlo simulations and consider the statistical properties of the input parameters. A comparison of the analytical and experimental predictions is made, showing compatibility with 100 years of service life. The convenience of verifying the analytical predictions with those obtained from site experimental data is discussed.*

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

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 working life 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 within 10,700-17,020 mg/L, a sulfate (SO_4^{2-}) concentration within 1,140-2,260 mg/L, and total salinity between 23,632 and 26,845 mg/L (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 work presented refers specifically to the service life design of the precast concrete piers of sea bridges. The shape and size of the piers can be appreciated in Fig. 1.

Figure 1. Shape and size of the prefabricated bridge piers.

A verification of the service life was performed after construction, based on the data collected in the field, including test results on concrete specimens and non-destructive measurements. The objective of the paper is to present the estimates of the service life from different approaches, comparing their results and drawing conclusions from the analysis.

2 Durability Requirement and Data

2.1 Durability Requirements

During the preliminary design phase, the durability requirements for the piers include the requirements on the raw materials of structural concrete, durability properties of concrete, depth of concrete cover to reinforcement, and control of crack width (Sarja, 2000; Li et al., 2020).

The requirements on the raw materials include the limitation on the C_3A content and SO_3 content in cement to control the risk of the delayed ettringite formation (DEF) and the internal sulfate reaction in concrete, the chloride content to control the corrosion risk of reinforcement steel, and the binder content to control the thermal cracking at early age.

The durability properties refer to the minimum concrete strength, maximum water to binder ratio and the corresponding chloride diffusion coefficient (Li, 2016). Moreover, a maximum allowable cracking width is prescribed to control the risk of penetration of external aggressive agents in atmospheric environment into the concrete inside. Table 1 summarizes the requirements on the durability properties and crack width for the prefabricated bridge piers.

Table 1. Durability requirements.

Requirements	Values
Design service life (year)	100
Durability limit state (DLS)	Corrosion Initiation
Minimum Concrete cover x_d^{min} (mm)	70
Concrete grade	C40
Water to binder ratio	0.36
Chloride diffusion coefficient ($10^{-12}m^2/s$) at 28d	⩽6.0
Chloride diffusion coefficient ($10^{-12}m^2/s$) at 84d	⩽2.0
Allowable crack width (mm)	0.15

During the construction, in-field laboratories were set up to check and control the quality and properties of the structural concretes used in the prefabricated piers. Also, non-destructive tests (NDT) were performed on the hardened concrete. These data provide the basis for the assessment of the achieved durability of the bridge piers.

2.2 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).

A total of 33 concrete piers were investigated and 3840 concrete cover depths were measured. Statistical analysis showed that the cover depth can be described by a normal distribution with a mean of 74.2 mm and a standard deviation of 3.0 mm. Figure 2 shows the distribution of cover depth results, measured on the piers. It can be seen that only ~ 5% of the actual values of cover depth fall below the minimum value of x_d^{min} = 70 mm, stipulated in the Durability Requirements (Table 1).

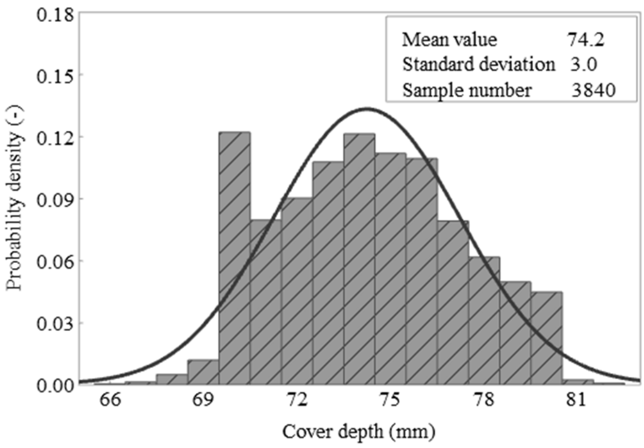

Figure 2. Cover depth measured on the bridge piers.

2.3 Air-Permeability and Electrical Resistivity on Piers

A total of 116 on site NDT measurements of the coefficient of air-permeability *kT* [1] (complemented by surface moisture *m*), following Swiss Standard [SIA 262/1, 2019], were performed on five piers of the bridge. In addition, the electrical resistivity (Wenner method) ρ was also measured. As these piers are used in the bridge segments on land, near the coast, they are exposed to marine atmospheric exposure (XS1 according to EN standards). The test results are summarized in Table 2, where the arithmetic means and standard deviations are shown for *m* and ρ whereas for *kT* (which is log-normally distributed) the geometric mean kT_{gm} of the values and the standard deviation s_{LOG} of the $\log_{10}$ of the values are reported. The reported values of ρ where obtained with the more typical electrodes' separation of 38 mm; not shown in Table 2, values were obtained also with 50 mm electrodes' separation which were, in average, 14% lower (the scatter was 17% lower as well).

Table 2. Results of on site NDT measurements on five piers of the bridge.

Pier	N° of Areas Investigated	*m* (%)		*kT* (10^{-16} m²)		ρ (kΩ.cm)	
		Mean	St. Dev	kT_{gm}	s_{LOG}	Mean	St. Dev.
1	12	5.7	0.5	0.011	0.16	26.0	4.0
2a	12	6.0	0.4	0.042	0.18	14.2	4.0
2b	12	6.0	0.3	0.079	0.37	10.9	1.2
3a	12	5.4	0.1	0.018	0.29	21.4	2.4
3b	12	5.1	0.1	0.036	0.27	19.3	3.2
4	24	5.3	0.2	0.022	0.31	25.4	4.4
5	32	5.6	0.3	0.020	0.14	21.2	4.0

The measurements were performed at the relatively early age of 14 days, where concrete is still immature and moist. With age, *kT* will drop due to continued hydration and grow due to evaporation of water to the environment; based on experimental data from [Brühwiler et al, 2005], see also [Torrent et al, 2022], it is assumed that both phenomena would cancel out and that the *kT* values reported in Table 2 are representative of the concrete's quality at 28 days.

In Piers 2 and 3, two series of tests were conducted at different periods of construction. A t-test showed a significant difference in *kT* results, reason why they are differentiated in Table 2.

Fig. 3 presents a $\log(kT_{gm} \pm s_{LOG})$ plot of the results, showing that all the piers present *kT* values corresponding to the 'Low Permeability' class.

Fig. 4 shows that there is a reasonable coherence between the central values of ρ and kT_{gm}, with both techniques agreeing in that Pier 1 is of best quality and Pier 2b of worst quality.

[1] More information on *kT* test method can be found in (Torrent and Ebensperger 2012) and in (Torrent et al. 2022).

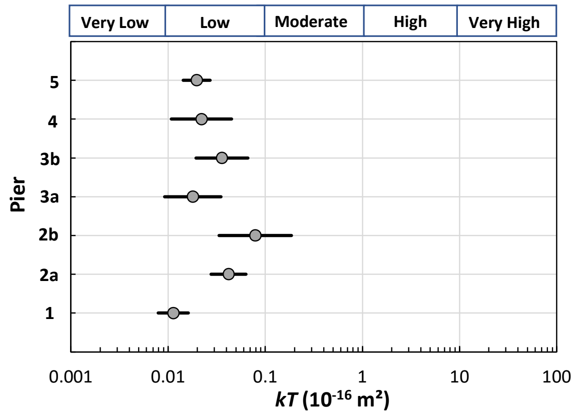

Figure 3. Mean and scatter plot of the kT test results

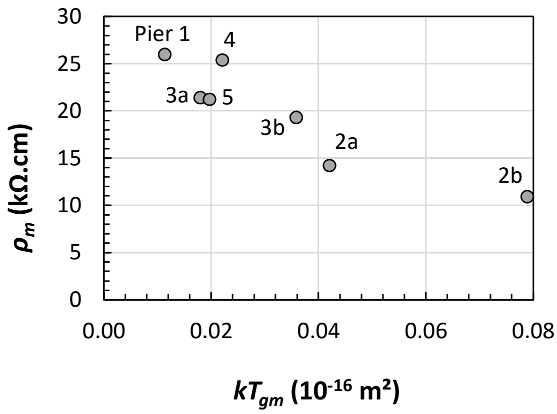

Figure 4. Correlation between ρ and kT mean values

3 Service Life Assessment through Chloride Ingress Modeling

3.1 Chloride Ingress Analytical Model

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

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

with C_{cr} the critical chloride concentration for corrosion initiation (%); C_s and C_0 standing for the cover surface and initial chloride concentration in concrete (%), respectively; 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 function η,

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

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. $\eta\left(t_0, t, n\right)\big|_{t>30\text{years}} = \eta\left(t_0, t = 30\text{years}, n\right)$.

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_{cr}, C_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 $C_{cr,s}$ 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. For the concrete cover depth x_d, the collected data in Fig. 2 is used to update the statistical properties. The statistical properties of all parameters are given in Table 3.

Table 3. Statistical properties for chloride ingress.

Parameter	Statistical properties	Values
Initial chloride content C_0	Uniform (%)	0.03
Surface concentration C_s (Lognormal)	Average (%)	5.4
	Deviation (%)	0.82
Critical concentration C_{cr} (beta)	Lower bound L (%)	0.45
	Upper bound U (%)	1.25
	Coefficient α (-)	0.22
	Coefficient β (-)	0.36
Diffusion coefficient D_{Cl}^0 (Lognormal)/28d	Average (10^{-12} m^2/s)	1.96
	Coef. of Variation	0.20
Exponent coefficient n (Normal)	Average (-)	0.47
	Deviation (-)	0.029
Concrete cover x_d (Normal)	Average (mm)	74.2
	Deviation (mm)	3.0

3.2 Full probabilistic assessment

On the basis of the statistical properties in Table 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 prefabricated bridge piers is illustrated (black broken line) in Fig. 5, giving a failure probability p_f = 0.0354% at 100 years.

4 Service Life Assessment with NDT

The initiation time t of corrosion can be assessed through site NDT measurements of cover thickness x_d and air permeability measurements kT, applying the 'Exp-Ref' method [Torrent, 2015; Torrent et al., 2022]:

$$t = \alpha \frac{x_d^2}{\sqrt[3]{kT}} \tag{3}$$

where α is a coefficient that depends on the exposure class, resulting α = 0.0156 for EN class XS1. In Eq. (3), x_d is expressed in mm, the coefficient of air-permeability kT in 10^{-16} m² and t in years.

Eq. (3) was solved by the Monte Carlo method running 10,000 instances, assuming that x_d followed the normal distribution shown in the last two rows of Table 3 and kT a log-normal distribution with the parameters shown in Table 2 for the seven cases considered. Fig. 5 shows (full lines) the predicted probability of initiation of corrosion as function of age for the extreme cases of Pier 1 (lowest values of kT_{gm} and s_{LOG}) and of Pier 2b (highest values of same parameters).

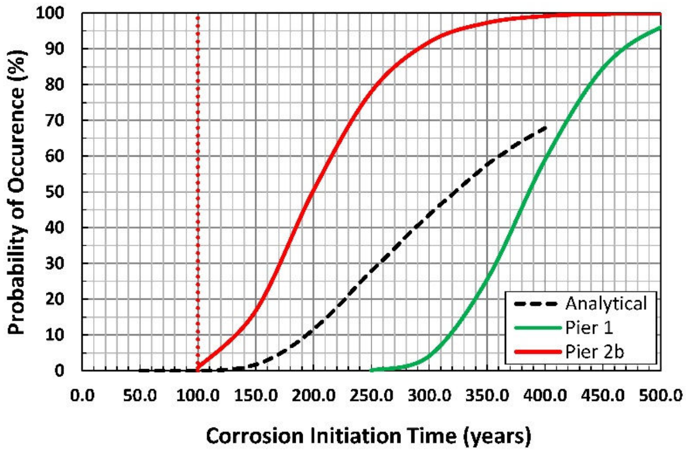

Figure 5. Failure probability (corrosion initiation) estimated by Analytical and Exp-Ref modeling

5 Analysis of the Results

The paper presents two instances of the service life design of the NZPMC sea link's prefabricated bridge piers.

The first instance happened applying a probabilistic analytical simulation based on the Duracrete model, using materials data obtained on cast specimens during the quality control. The outcome of this approach is strongly dependent on the selection of the parameters introduced in the model. A preliminary design had been made for 100-year service life with a minimum cover depth of x_d^{min}= 70 mm and a chloride diffusion of D_{Cl}^0= 6.0 and 2.0×10^{-12} m^2/s (Table 1) at 28 and 84 days, respectively. The quality control exercised during construction and the non-destructive measurement of cover depth showed that only 5% of the data fell below x_d^{min}, meaning that a high quality was achieved for the structural concrete in piers. The analytical service life modelling, based on those experimental data yielded a failure probability p_f= 0.0354% at 100 years (reliability index β=3.39).

The Exp-Ref model provides an individual estimate of service life for each investigated pier. Although still of good quality in terms of permeability, Pier 2b presents the highest values of kT_{gm} and s_{LOG}, yet yielding a probability of failure as low as 0.9% at 100 years which, given the different approaches followed, can be considered consistent with the Analytical solution. For the best quality Pier 1, a probability of failure of 0.3% is expected only after 250 years of service.

6 Conclusions

The information presented in this paper allows the following conclusions to be drawn:

- The NZPMC sea link project has a design working life of 100 years. The concrete piers for sea bridges are selected as one of the key concrete elements to study their expected working life after the design and construction process. To this aim, the main design parameters are reviewed and the concrete cover to reinforcement were collected during construction.
- NDT measurements were performed on the surface of prefabricated piers at the curing age of 14 days for gas permeability and electrical resistivity. The NDT results show a consistent correlation between the gas permeability and the electrical resistivity

considering the moisture content was varying from pier to pier at measurement. Globally, the concrete cover satisfies the design requirement of 70 mm and the surface tightness is judged as of good quality from the gas permeability values, generally in the order of 10^{-18} m^2.

- The durability of concrete pier of NZPMC sea link project is analysed using two parallel approaches: the full probabilistic approach integrating the chloride ingress modelling with the corrosion initiation as the durability limit state, and the NDT-based approach considering the in-situ NDT test results. Though different in values, both approaches predict a rather large safety margin for the corrosion initiation for a design working life of 100 years. The advantage of using NDT-based approach is its direct consideration of the in-situ results from the specific element. Certainly, more measurements and engineering cases are needed to improve the correlation of the two approaches and the reliability of NDT-based approach.

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