Application of Air-Permeability Measurements to Hong Kong-Zhuhai-Macao Link

Taken from Section 11.3.2 of [Torrent et al, 2022]

The Hong Kong–Zhuhai–Macau (HZM) sea link project involves 28.8 km of sea bridges (four navigable spans), two offshore artificial islands and a submerged tunnel of 6.8 km, with a total investment of nearly 12 billion US dollars. The project is situated on the south-eastern coast of China and links three important cities (Hong Kong, Zhuhai and Macau) with six lanes in dual directions with a design speed of 100 km/h.

The reinforced concrete structures in the project include piers, bearing platforms and piles for sea bridges, the segments for the submerged tunnel and also retaining walls and breakwaters for the artificial islands. One of the technical challenges of the HZM project was to achieve a design service life of 120 years for the concrete structures in an aggressive marine environment.

An analytical service life design was performed applying a probabilistic model, based on the DuraCrete approach [DuraCrete, 2000], but defining the input parameters from a thorough analysis of 30 years of experimental data of an exposure station located in a similar environment to that of the project and from tests performed during construction. The model was applied to structures under the following marine environment exposures: Submerged, Tidal, Splash and Atmospheric Zones. For a detailed description of the applied analytical model, see [Li et al, 2015].

This real case refers to non-destructive measurements of air-permeability *kT* and cover thickness *d* (also of electrical resistivity ρ, not discussed here) on the monumental precast sections of the submerged tunnel (see Fig. 1). These segments were built on land and later floated to be towed and sunk at their precise positions. The durability requirements for the construction of the segments are described in Table 1.

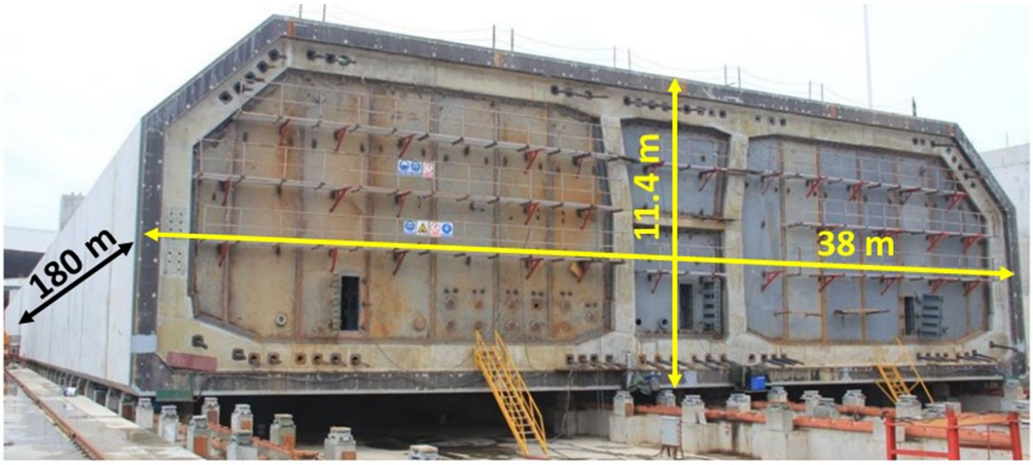

Fig. 1 – View and dimensions of tunnel precast segments of Hong Kong – Zhuhai – Macao link

Table 1 – Durability requirements for the construction of submerged precast tunnel elements

Requirements			Intrados	Extrados
Design Service Life		years	120	
Durability Limit State		---	Corrosion Initiation	
Minimum Cover Thickness		mm	50	70
Concrete Grade	@ 28 d.	MPa	C45	
Chloride diffusion coefficient	@ 28 d.	10^{-12} m²/s	6.5	6.5
	@ 56 d.		4.5	4.5
Allowable crack width		mm	0.2	0.2

Once the construction was started, samples of the placed concrete were taken, on which the coefficient of diffusion was measured at 28 and 56 of age, following the migration test [EN 12390-18, 2021. At each age, 148 samples were tested with mean values of 4.68 and 2.95 (10^{-12} m²/s) at 28 and 56 days, respectively and coefficients of variation of 9.9% and 8.7% for same ages, respectively; i.e. in conformity with the requirements in Table 1.

An analytical assessment of the service life, regarded equal to the corrosion initiation time, was made assuming the probability distributions and parameters indicated in Table 2. A Monte Carlo simulation of Eqs. 1 and 2, making the variables adopt at random the probability functions indicated in Table 2, was run for different times *t*. For each *t*, the proportion of 'failure' cases, i.e. cases where $C(x,t) > C_{cr}$, was computed, providing the 'Analytical' probability distribution of the initiation time illustrated in Fig. 2 (green line). Consequent with its design criterion, it yields 5% probability of corrosion initiation at 120 years.

$$C(x,t) = C_0 + (C_s - C_0) . \left\{1 - \text{erf}\left[\frac{x}{2\sqrt{D_o . (t_0/t)^n . t}}\right]\right\} \quad (1)$$

The chloride-induced corrosion initiation time t_i is reached when the chloride content at the location of the steel ($x = d$) is:

$$C(d, t_i) = C_{cr}, \quad (2)$$

Table 2 – Variables and probability distributions used for the Analytical service life prediction

Variable	Distribution	Parameters	Extrados values
Initial Chloride Content C_0	Rectangle (Uniform)	Lower Limit (%)	0.02
		Upper Limit (%)	0.04
Surface Chloride Content C_s	Log-Normal	Average (%)	5.76
		Std. Dev. (%)	0.86
Critical Chloride Content C_{cr}	Beta	Lower Bound L (%)	0.45
		Upper Bound U (%)	1.25
		Coefficient α (-)	0.22
		Coefficient β (-)	0.36
Chloride Diffusion Coefficient D_0 (at 28 d.)	Log-Normal	Average (10^{-12} m²)	4.71
		C.o.V. (%)	9.8
Diffusion Decay Exponent n	Normal	Average (-)	0.47
		Std. Dev. (-)	0.029
Cover Thickness d	Normal	Average (mm)	73.4
		Std. Dev. (mm)	3.9

In addition, during construction, the cover thickness was measured non-destructively applying the common midpoint (CMP) technique, based on transmitting an electromagnetic wave pulse and receiving the reflected waves from the steel bars by two adjacent antennas [Halabe et al. 1993]. The cover thickness was measured on 24 segments with a mean value of 73.4 mm and a standard deviation of 3.9 mm (used in the Analytical service life prediction), showing that ≈ 80% of the values exceeded the minimum cover of 70 mm, stipulated in Table 1 [Li & Torrent, 2016].

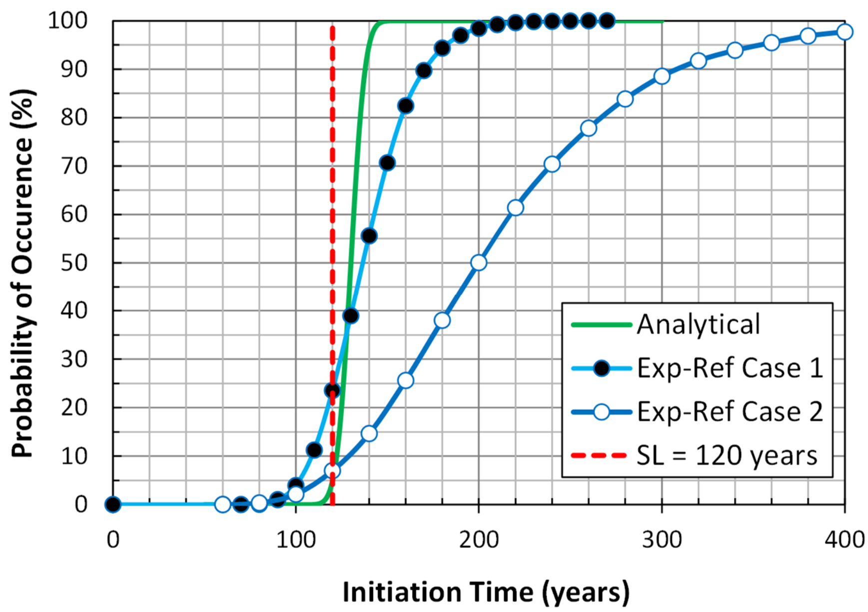

Fig. 2 – Probability of occurrence of corrosion initiation time (Analytical and Exp-Ref predictions)

The air-permeability kT of some segments (Case 1) was measured on 14 points at the age of 56 days, with a $kT_{gm} = 0.069\times10^{-16}$ m² and $s_{LOG} = 0.18$ [Li & Torrent, 2016]. Another set of 15 kT results (Case 2) was reported in table 2 of [Wang et al, 2014] with $kT_{gm} = 0.022\times10^{-16}$ m² and $s_{LOG} = 0.42$. This set has a much lower central value kT_{gm} and larger scatter s_{LOG} than for Case 1. s_{LOG} is the standard deviation of the decimal logarithms of kT.

The 'Exp-Ref' model for chloride-induced corrosion [Torrent, 2013, 2015], expressed by Eq. 3, was applied to estimate the corrosion initiation time, using the Monte Carlo simulation method, assuming that d and kT have the distributions and parameters shown in Table 3. A value of 0.0104 was assigned to parameter α, corresponding to exposure class XS2 (submerged elements).

$$t_{SL} = \propto \frac{d^2}{\sqrt[3]{kT}} \qquad d\ (\text{mm});\ kT\ (10^{-16}\ \text{m}^2) \qquad (3)$$

Table 3 - Variables and probability distributions used for the 'Exp-Ref' service life prediction

Variable		Distribution	Central value	Scatter
Cover Thickness d		Normal	Mean = 73.4 mm	Std. Dev. = 3.9 mm
Air-Permeability kT	Case 1	Log-Normal	$kT_{gm} = 0.069\ 10^{-16}$ m²	$s_{LOG} = 0.18$
	Case 2		$kT_{gm} = 0.022\ 10^{-16}$ m²	$s_{LOG} = 0.42$

The Monte Carlo simulation was run through 8000 instances, generating for each of them independent random values of d and kT according to the distributions and parameters shown in Table 3 which, by applying Eq. 3, yielded 8000 values of the corrosion initiation time. The resulting probability of occurrence for both cases is plotted in Fig. 2 (black dots for Case 1, white dots for Case 2).

Fig. 2 shows that the 'Exp-Ref' prediction for Case 1 yields a median service life (50% Probability) very similar to the Analytical prediction (≈ 135 years), but the probability of occurrence at 120 years is much higher for the 'Exp-Ref' Case 1 (24%) than for the Analytical prediction (5%). The 'Exp-Ref' Case 2 predicts at 120 years a probability of 7% (closer to the Analytical prediction) but a much longer median service life (≈ 200 years), reflecting the very low central value but high scatter of kT values, compared to Case 1.

It is difficult to compare the Analytical with the Exp-Ref predictions, because the principles of the models are quite different. Yet, since all three predictions are based on the same probability distribution of the cover thickness (squared), the differences can be attributed mostly to the penetrability (by diffusion or permeability) of the concrete cover. In this respect, the higher scatter of the Exp-Ref predictions probably reflects the higher variability of the quality (*kT*), measured on site, compared to that obtained on cast specimens (D_0).

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