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Service Life Prediction of Reinforced Concrete Coastal Structures in Vietnam Subjected to Chloride Ingress

Quynh Chau Truong, Chinh Van Nguyen, Charbel-Pierre El Soueidy,
and Emilio Bastidas-Arteaga

Abstract Chloride-induced corrosion on reinforcing steel is one of the main causes that may shorten the service life of concrete structures. Recent studies have found that the deterioration process of these structures is highly influenced by material properties, environmental factors (exposure conditions) and climatic conditions (such as temperature, humidity, seasonal variations, etc.). For infrastructure in coastal areas of Vietnam, it has been observed that corrosion occurs within 10 to 30 years of service. The purpose of this paper is to carry out the service life prediction of reinforced concrete (RC) structures in coastal areas in Vietnam. A model simulation of chloride penetration into concrete before and after repair and under various climatic conditions is developed in FreeFEM++ software to assess the effects on structure service life. A case study is conducted in three coastal cities in Vietnam where the annual temperature and humidity vary. The results show that chloride ingress into concrete is highly influenced by weather conditions. In addition, some maintenance strategies, that are appropriate with the practical conditions in each area in Vietnam, are recommended to prolong the service life of corroding RC structures.

Keywords Chloride penetration · Climatic conditions · Durability · Vietnam · Modelling

1 Introduction

Steel corrosion in concrete is the primary cause of deterioration of RC structures and eventual reduction of service life. The high alkalinity of the cement paste surrounding the reinforcing steel induces a reactively passive state, but chloride ingress breaks down the passive film on steel reinforcing bars and initiates corrosion. Previous studies indicate that the structural deterioration process subject to chloride ingress is highly affected by material properties, concrete cover thickness, exposure environment and climatic conditions including humidity and temperature [1].

Many models have been developed to simulate the chloride ingress in RC for service life prediction. A simple and general model based on Fick's second law has been commonly adopted, in which the diffusion coefficient and surface chloride content are constant in a saturated environment [18]. However, experimental work has proved that those parameters are time dependent [9, 11] and so a time dependent chloride diffusion model has been proposed [8]. Moreover, the chloride ingress is even more complex in an unsaturated environment, that involves the interaction of diffusion, convection, and chemical phenomena. In response more comprehensive models of chloride ingress have been established [1, 10] that consider coupled heat transfer and moisture transport relationships and chloride binding capacity among those parameters mentioned above.

Vietnam is a tropical country where the climate is hot and humid. The RC structures located along the more than 3,200 km of coastline are vulnerable to corrosion attack due to a high content of chloride ions. The corrosive environments of RC structures can be classified in 3 zones as described in TCVN 12,041: 2017 [17], including the atmospheric zone (XS_1), submerged zone (XS_2), tidal zone and splash zone (XS_3). The deterioration of RC structures in the coastal areas of Vietnam is recognised as a serious problem for building and infrastructure maintenance. It has been reported that steel corrosion in RC structures begins after 10 to 30 years of service, depending on concrete strength, concrete permeability, chloride resistance, cement type, cement content, construction method and maintenance history. Over their service life, the repair cost of these structures is estimated to be 70% of the initial construction cost.

The aim of this study is to investigate the effect of varying environmental conditions in Vietnam on chloride ingress into concrete which leads to service life reduction for RC structures. This paper uses the chloride ingress model developed by Emilio Bastidas et al. [1] to predict the corrosion initiation time and service life of repaired RC structures in coastal areas in Vietnam with the support of FreeFEM++ software. Three coastal cities in the Northern area (Hai Phong), Central area (Danang) and Southern area (Ho Chi Minh) of Vietnam are selected. Based on the results, a proper maintenance strategy for RC structures in each coastal area is recommended.

2 Model of Chloride Ingress and Model of Maintenance

The modelling approach proposed by Bastidas-Arteaga et al. [1] was applied to simulate chloride penetration in concrete. In this method chloride ion transfer is treated using a convection–diffusion coupling. However, this study considers constant surface chloride concentration, temperature, and humidity. When humidity is constant, only the diffusion phenomenon occurs. In this case, the one-dimensional chloride ingress process, considering temperature, humidity and time, is presented in Eq. (1):

$$\frac{\partial C_{fc}}{\partial t} = D_c^* \left(\frac{\partial^2 C_{fc}}{\partial x^2} \right) \quad (1)$$

where D_c^* represents the apparent chloride diffusion coefficients:

$$D_c^* = \frac{D_c}{1 + \left(\frac{1}{w_e} \right) \left(\frac{\partial C_{bc}}{\partial C_{fc}} \right)} \quad (2)$$

where w_e is the amount of free water and $\frac{\partial C_{bc}}{\partial C_{fc}}$ is the chloride binding capacity of cement [12]. The isotherm used to estimate the binding capacity in this study is Langmuir isotherm [7]:

$$C_{bc} = \frac{\alpha C_{fc}}{1 + \beta C_{fc}} \quad (3)$$

where C_{bc} is the bound chloride concentration, C_{fc} is the free chloride concentration, $\alpha = 0.1185$ and $\beta = 0,09$ are material coefficients for a C_3A content of 8% [7].

D_c in Eq. 2 is the effective chloride diffusion coefficient depending on the temperature, concrete age and humidity [10, 16].

$$D_c = D_{c,ref} \cdot k_1(T) \cdot k_2(t) \cdot k_3(h) \quad (4)$$

$D_{c,ref}$ is a reference diffusion coefficient which has been measured in standard conditions.

$k_1(T)$ is the factor accounting for temperature effect:

$$k_1 = \exp \left[\frac{U_c}{R} \left(\frac{1}{T_{ref}} - \frac{1}{T} \right) \right] \quad (5)$$

$k_2(t)$ is the time effect factor:

$$k_2(t) = \left(\frac{t_{ref}}{t} \right)^{m_c} \quad (6)$$

$k_3(h)$ is the factor of relative humidity effect:

$$k_3(h) = \left[1 + \frac{(1-h)^4}{(1-hc)^4} \right]^{-1} \quad (7)$$

For repairing corrosive concrete, “cover rebuilding” repair is chosen, and this method is implemented by reconstructing the chloride-contaminated concrete cover by several techniques (formed concrete, dry shotcrete, wet shotcrete, and manual repair). In this case, chloride penetration should be modelled before and after repair to evaluate the effectiveness of repair strategy on the durability of RC structures. The interaction of the physical and chemical mechanisms of chloride penetration before repair can be modelled with Eq. 1. However, after repair chloride penetration requires consideration of the interaction of two sources of chloride ions, i) the chloride content on the concrete surface exposed to the environment that penetrates the whole concrete and ii) the distribution of residual chloride ions in the original, aged concrete. These residual chlorides will diffuse into the new concrete layer as well as being redistributed in the remaining concrete layer. In the end, the resulting diffusion of chloride ions in the original and repaired concrete is a combination of chloride ingress from the exposed concrete surface and the chloride redistribution inside the concrete [4, 14].

3 Case Study

3.1 Problem Description and Basic Assumptions

The software FreeFEM++ is used to calculate the simplified one-dimensional model of chloride ingress under varying weather conditions as described above. The maintenance model is then developed to observe the response of RC structures to a chosen repair strategy. Other analysis assumptions are also considered in this study:

- The chloride content in the concrete is zero at the start.
- The structure is exposed to a marine atmospheric zone and located 0.1 km from the shoreline. Chlorides are carried by salt spray from seawater and mixed in the humid air.
- The surface chloride content is assumed to be constant during the lifetime of structures, $C_s = 2.95 \text{ kg/m}^3$ concrete [15].
- The concrete is modelled as 8% C₃A Ordinary Portland Cement (OPC), the cement content of 400 kg/m^3 and water/cement ratio of 0.5 meet Vietnamese standards for RC structures in a marine atmospheric zone [17].
- Concrete used in structure repair is the same quality as the original concrete.

Table 1 The model parameters of the chloride penetration and maintenance models

Parameter	Symbol	Units	Value
Activation energy of the chloride diffusion process	U_c	kJ/mol	41.8
Gas constant	R	J/ (mol K)	8.314
Reference temperature in K	T_{ref}	K	296
Aging factor	m_c		0.15
Humidity at which D_c drops halfway	h_c		0.75
Reference time of exposure	t_{ref}	day	28
Reference chloride diffusion coefficient	$D_{c,ref}$	m ² /s	3×10^{-11}

Table 2 Annual temperature and humidity in three cities in Vietnam

Locations	Annual Temperature (°C)	Annual humidity (%)
Haiphong [5]	23.3	85
Danang [2]	25.8	81.6
Ho Chi Minh City [6]	27.4	78

- Service life is 50 years, and the corrosion initiation starts when the chloride content at the position of rebar exceeds a critical value $C_{rit} = 0.5\%$ by weight of cement (about 2.0 kg/m³ concrete) [3].
- Concrete cover is 50 mm ($X_c = 50$ mm).

The model parameters and their values used for chloride ingress model and maintenance model are presented in Table 1.

Climatic conditions are based on three coastal cities in Vietnam with varying temperature and humidity data: Haiphong (Northern Vietnam where the climate is in the subtropical zone, high temperature and humidity), Danang (Central Vietnam, located in the tropical monsoon climate, high temperature with less fluctuation), Ho Chi Minh City (Southern Vietnam, sub-equatorial climate, high and quite stable temperature during the year). The data of annual temperature and humidity in three mentioned-above cities is presented in Table 2.

3.2 Results and Discussion

Service Life Prediction of Unrepaired Concrete Structures

Chloride concentration at rebar depth ($X_c = 50$ mm) in unrepaired concrete structures over a 50-year service life was modelled and is shown in Fig. 1 for the three coastal cities. The surface chloride concentration for all study locations was assumed to be the same and constant. It is observed that the relative humidity and temperature have a significant effect on the progression of free chloride concentration over 50 years. Considering a critical chloride content of 2 kg/m³, the estimated time to corrosion

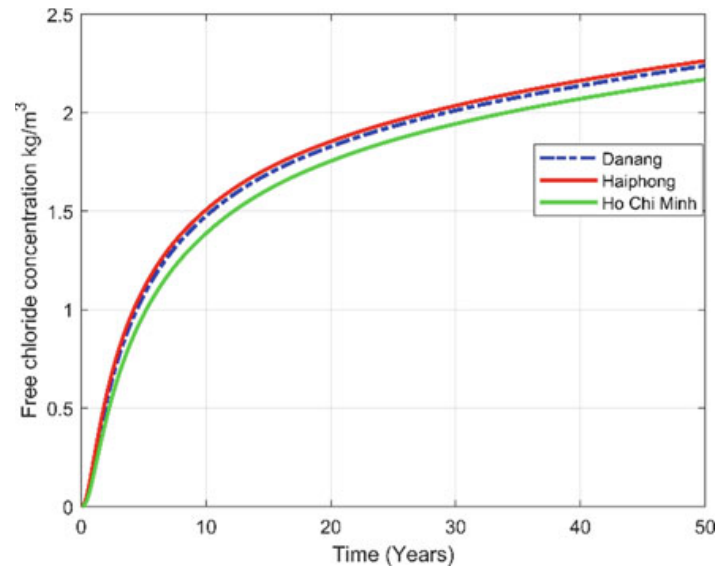


Fig. 1 Chloride profiles at the cover depth of 50 mm in three coastal cities

initiation in Haiphong and Danang are 27.6 years and 29.2 years respectively, while it is 34 years for RC structures in Ho Chi Minh City. Although the average annual temperature in Ho Chi Minh City is recorded as the highest, the time to initiate corrosion on RC infrastructure in this area is the longest. This may be attributed to the lower annual humidity in Ho Chi Minh City compared to the two remaining cities.

Service Life Prediction of Repaired Concrete Structures

Chloride ingress is now modelled considering concrete repair occurs during structure service life. The parameters in Table 1 were used and chloride concentration is again assessed at a depth of 50 mm. A maintenance plan may consider several repair factors including the number of repair cycles, the replacement concrete depth and repair interval (time between two repairs). The first repair strategy considered is the removal and replacement of 50 mm of surface concrete at 15 and 18-year intervals.

Figures 2a, b present 50-year chloride concentration with repair intervals of 15 years and 18 years and a 50-mm repair depth. By taking a threshold chloride content of 2 kg/m^3 at a cover thickness of 50 mm, it is observed that the chloride profiles of Ho Chi Minh satisfy the requirement of reducing the risk of corrosion initiation for multiple repairs. Hence the 50-mm replacement depth and the 18-year maintenance interval are well-adapted for marine structures in Ho Chi Minh City. Meanwhile, in Haiphong, those above repair strategies are not suitable in preventing the risk of corrosion initiation, the repair interval for Haiphong should be shorter, approximately 10 to 13 years. For Danang, it is necessary to address the maintenance issue in the last years of service life when the corrosion rate is faster, and the repair should be conducted at an earlier age than planned.

According to previous studies [13], replacement depth is one of the main factors influencing the effectiveness of maintenance and repairing with a deeper depth is

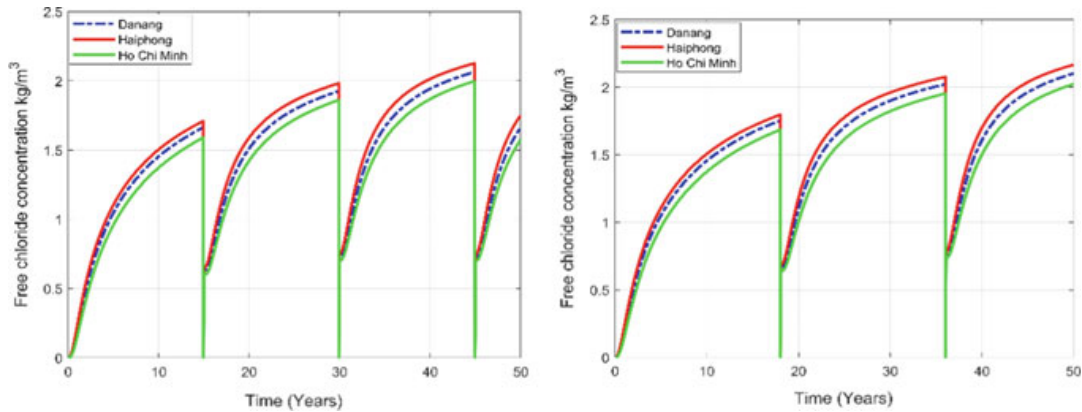


Fig. 2 Chloride profiles at $X_c = 50$ mm with repair interval of **a** 15 years, **b** 18 years ($X_p = 50$ mm)

proved by previous studies to be more effective. Hence, a 60-mm deeper repair depth is considered in this section, with repair intervals of 15- and 18-years. Figures 3a, b show that when considering the threshold chloride level of 2 kg/m^3 at the rebar depth, both repair strategies are appropriate for RC structures in Danang and Ho Chi Minh City. In which case the less frequent repair interval of 18 years may be preferred from both economic and environmental aspects as it has less expected number of repairs. For Haiphong, the 18-year interval appears to be a better solution compared to the 50-mm replacement depth. However, a comprehensive maintenance plan should evaluate additional repair intervals and replacement depths to achieve the optimization of protecting structures from corrosion and the maintenance cost.

In summary, temperature and humidity have a significant effect on the service life of RC structures exposed to chloride-heavy environments. The conditions of high temperature and high humidity in most of cities in Vietnam would accelerate the chloride penetration into concrete and shorten the service life of structures before and after repair. Particularly in coastal areas of Northern and Central Vietnam, where

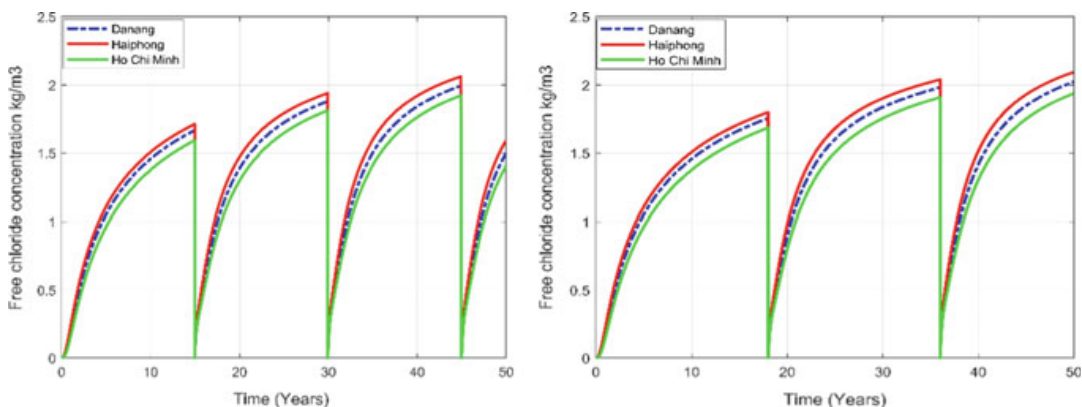


Fig. 3 Chloride profiles at $X_c = 50$ mm with repair interval of **a** 15 years, **b** 18 years ($X_p = 60$ mm)

the average annual humidity and temperature are quite high compared to other locations, maintenance policy and repair strategy should be well planned to ensure the serviceability and durability of chloride contaminated RC structures. Besides cover rebuilding method, it is recommended to include additional corrosion protection methods such as water concrete coating, anti-corrosion coating for reinforcement, or application of supplementary cementitious materials to optimize the effectiveness of maintenance and enhance the durability of structures. Moreover, the current standards for concrete quality and concrete cover depth to prolong the operational life of RC structures subjected to chloride ingress must be complied with.

4 Conclusions

This paper presents the influence of different weather conditions in the three coastal cities of Haiphong, Danang and Ho Chi Minh City on the durability of RC structures exposed to a chloride environment. It is shown that chloride penetration is highly affected by climate conditions through temperature and humidity, in which chloride ingress is more sensitive with humidity rather than temperature. Accordingly, Haiphong with highest humidity have highest risk of corrosion initiation after 27.6 years, followed by Danang with 29.2 years and Ho Chi Minh City with 34 years. Climate conditions also affect the response behaviour of RC structures in each location when applying one repair strategy for structures exposed to chloride attack. Particularly, for 50 mm concrete replacement depth of corroding concrete structures, the 18-year maintenance interval are well-adapted for marine structures in Ho Chi Minh City. Meanwhile, in Haiphong, those above repair strategies are not suitable in preventing the risk of corrosion initiation. For Danang, it is necessary to consider the maintenance issue in the last years of service life and the repair should be conducted at an earlier age than planned. Therefore, it is necessary to consider the local environmental conditions in developing a maintenance and repair strategy for RC structures.

Further improvements are in progress and to be considered:

- Implementing sensitivity analysis and stochastic modelling of chloride penetration to estimate the probability of corrosion initiation.
- Modelling of chloride ingress under real weather conditions in Vietnam with hourly or daily temperature and humidity as input
- Surveying the evolution in time of chloride penetration into RC structures located in submerged zone or tidal zone in coastal areas in Vietnam.

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