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The effect of chloride binding on the predicted service life of RC pipe piles exposed to marine environments

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ABSTRACT

Chloride binding capacity has a significant effect on the service life of reinforced concrete (RC) pipe piles exposed to marine environments. Four typical chloride binding isotherms (i.e., null, linear, Langmuir and Freundlich binding isotherms) were reviewed in this paper. The effect of chloride binding on service life predictions of RC pipe piles, in terms of these different binding isotherms, was investigated. An experimental program was conducted to verify the theoretical predictions developed in the present study. The free and total chloride concentration profiles were presented for RC pipe piles exposed to submerged and splash zones for 5, 10 and 30 years. Furthermore, the predicted service life of RC pipe piles exposed to submerged and splash zones, using different binding isotherms, was also presented in this paper. The results of the present study indicated that the chloride binding has a more significant effect on the service life of RC pipe piles in submerged zone than in splash zone, and RC pipe piles in submerged zone display longer service life than those in splash zone.

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1. Introduction

Chloride-induced steel corrosion in RC pipe piles exposed to marine environments is a significant deterioration mechanism in ocean engineering, such as piers, bridges, off-shore platforms, port terminals, wharves, and harbors. In general, the hydration products of cement in fresh RC pipe piles form a high alkaline pore solution environment, which results in the formation of a passive film of iron oxides at the steel–concrete interface. This passive film covering the steel surface remains sufficiently chemically stable to protect the reinforcing steel from corrosion (Reale and O'Connor, 2012). In marine environments, however, the chloride ions in the seawater gradually diffuse from the surfaces of the RC pipe pile, through the concrete cover, toward the reinforcing steel. Chloride diffusion may result in the accumulation of chloride content at the reinforcing steel to the chloride threshold level; the high alkaline environment is destroyed, and the passive film on the reinforcing steel surface is disrupted. If sufficient oxygen and moisture are available, steel corrosion is initiated (Melchers and Li, 2009). As corrosion progresses, the expansion volume of the corrosion products, which is approximately two to six times the volume of the original steel, produces increasing

expansive pressure to the concrete cover around the reinforcing steel. Eventually, the damage to the RC pipe piles results in the cracking, spalling and delaminating of the concrete cover, reduction of the cross-section area of reinforcement and loss of the bond between the concrete and reinforcement (Chen and Mahadevan, 2008; Lu et al., 2011; Bazant, 1979; Liu and Weyers, 1998; El Maaddawy and Soudki, 2007).

Chloride-induced steel corrosion is an important criterion for analyzing and evaluating the service life of RC pipe piles. Once steel corrosion begins, cracks in the concrete cover appear. These cracks can provide preferential pathways for the ingress of aggressive agents, such as moisture, oxygen, and chloride ions; they dramatically facilitate the build-up of aggressive species at the depth of the embedded steel, thereby accelerating the corrosion of the steel (Djerbi et al., 2008; Jaffer and Hansson, 2008). Therefore, the initiation of steel corrosion is a key indicator of the end of the service life of an RC pipe pile. It is widely accepted that the state of steel corrosion initiation induced by chloride ions is identified as the serviceability limit state of RC pipe piles.

However, when chloride ions penetrate into the concrete, and some are captured by the hydration products, which is called chloride binding. The chloride binding may reduce both the rate of chloride ionic diffusion and the amount of chlorides accumulating at the reinforcing steel layer because of the reduced amount of available free chlorides, thus retarding the corrosion of the steel (Martin-Perez et al., 2000; Tuutti, 1982; Xi and Bazant, 1999; Lu et al., 2002; Yuan et al., 2009; Cheewaket et al., 2010). Therefore, it becomes necessary to

determine the effect of chloride binding on the diffusion process and to reasonably predict the service life of RC pipe piles.

Many studies have been conducted to assess the effect of chloride binding on the service life predictions of RC structures. Martin-Perez et al. (2000) investigated the effect of the different binding relations on the time-dependent chloride penetration profiles by solving the chloride mass conservation statement with a finite difference approach, and they discussed the implications of accounting for chloride binding in service life estimations. Glass and Buenfeld (2000) presented a theoretical assessment of the influence of chloride binding on the chloride induced corrosion risk in reinforced concrete. The results revealed that the time to corrosion initiation of embedded steel is dependent on the corrosion risk presented by the bound chlorides. In some circumstances, the time to corrosion initiation may be reduced by an increase in chloride binding because of the possible corrosion risk presented by the bound chlorides. Liang et al. (2011) obtained the analytical solution of the modified Fick's second law of nonlinear diffusion equation with initial and boundary conditions using Kirchhoff's transformation associated with Laplace's transformation methods. They discussed the implications of considering chloride binding in the service life predictions of concrete structures. Shazali et al. (2012) examined the effect of chloride binding resulting from the transport of chloride ions in concrete on service life using different isotherm formulations. However, most of these studies are focused on chloride diffusion in RC structures with single surface exposed to chloride environments. To our knowledge, there have been few papers that report the effect of chloride binding on the service life of RC pipe piles when the inner and outer cover surfaces are both exposed to chloride environments. The analytical solution of chloride diffusion equation with a single boundary condition is not suitable for RC pipe pile subject to double boundary conditions.

The main objective of this study was to investigate the effect on service life of chloride binding resulting from chloride diffusion in RC pipe piles exposed to marine environments. The four different published chloride binding isotherms were employed to quantify the effect of chloride binding on service life. An experimental program was conducted to verify the theoretical predictions developed in the present study. The free and total chloride concentration profiles in RC pipe piles exposed to two different exposure conditions, using the different binding isotherms, were presented in this paper. In addition, by determining the chloride threshold level, the service life of RC pipe piles exposed to two different exposure conditions was also presented for the different binding isotherms in this paper. The results of the present study may offer an important reference on the maintenance, strengthening or demolition of existing RC pipe piles in marine environments.

2. Chloride diffusion equation

Assume that the RC pipe pile exposed to marine environments is in a saturated state and is initially chloride-free, the inner and outer radii of the RC pipe pile are a (m) and b (m) respectively, and the surface chloride ion concentrations on the outside inner and outer cover surfaces of the pipe pile are C_{fa} (kg/m³) and C_{fb} (kg/m³), respectively. In addition, to simplify the mathematical treatment of the problem, it is assumed that the hoop and axial diffusions of the chloride ions can be ignored, and the chloride ions in marine environments penetrate into the concrete cover mainly by radial diffusion because of the existing concentration gradient between the exposed surface and the pore solution of the cement matrix. Based on Fick's first law of diffusion, the rate of diffusion of chloride ions (J_c) through a plane perpendicular to the direction of diffusion is proportional to the concentration gradient, which can be written as follows (Martin-Perez et al., 2000; Crank, 1975):

$$J_c = -D_c w_e \frac{\partial C_f}{\partial r} \tag{1}$$

where J_c is the flux of chloride ions resulting from diffusion [kg/(m² s)], D_c is the effective diffusion coefficient (m²/s), w_e is the evaporable water content (%), and C_f is the free chloride concentration (kg/m³ of pore solution) at depth r (m). The negative sign in Eq. (1) indicates that diffusion occurs in the direction opposite to that of increasing chloride concentration.

Based on mass balance, the equation governing the chloride diffusion mechanism in the RC pipe pile can be expressed as

$$r \frac{\partial C_t}{\partial t} + J_c + r \frac{\partial J_c}{\partial r} = 0 \tag{2}$$

where C_t is the total chloride concentration (kg/m³ of concrete) at time t (s).

Substituting Eq. (2) into Eq. (1), equation governing the chloride diffusion mechanism in the RC pipe pile can be rewritten as (Crank, 1975; Arora et al., 1997; Hwang and Huang, 2012)

$$\frac{\partial C_t}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r}\left(r D_c w_e \frac{\partial C_f}{\partial r}\right) \tag{3}$$

The relationship among the total (C_t), bound (C_b); and free (C_f) chloride concentrations in the concrete medium can be expressed as (Martin-Perez et al. 2000; Shazali et al., 2012; Sergi et al., 1992; Nilsson et al., 1994)

$$C_t = C_b + w_e C_f \tag{4}$$

Substituting Eq. (4) into Eq. (3), the following equation can be derived:

$$\left(\frac{\partial C_b}{\partial C_f} + w_e\right)\frac{\partial C_f}{\partial t} = D_c w_e \frac{1}{r} \frac{\partial C_f}{\partial r} + \frac{\partial}{\partial r}\left(D_c w_e \frac{\partial C_f}{\partial r}\right) \tag{5}$$

Eq. (5) can be rewritten as

$$\frac{\partial C_f}{\partial t} = D_c^* \frac{1}{r} \frac{\partial C_f}{\partial r} + \frac{\partial}{\partial r}\left(D_c^* \frac{\partial C_f}{\partial r}\right) \tag{6}$$

with

$$D_c^* = \frac{D_c}{1 + (1/w_e)(\partial C_b/\partial C_f)} \tag{7}$$

where D_c^* is the apparent diffusion coefficient (m²/s), and $\partial C_b/\partial C_f$ is the specific binding capacity, defined as the slope of the corresponding chloride binding isotherm, representing the equilibrium relations between free chlorides and bound chlorides specific to a given concrete medium. Once the binding relation characterizing the specific concrete binder is known and the free chloride concentration is determined (by solving Eq. (6)), the total amount of chloride concentration in the concrete cover of the RC pipe pile is calculated from Eq. (4).

According to the previous assumption, the associated initial and boundary conditions of Eq. (6) can be expressed as

$$\begin{cases} C_f(r,0) = 0, & (t = 0, \ a \le r \le b) \\ C_f(a,t) = C_{fa}, & (t > 0, \ r = a) \\ C_f(b,t) = C_{fb}, & (t > 0, \ r = b) \end{cases} \tag{8}$$

3. Chloride binding isotherms

3.1. Mathematical models

Consequently, chloride binding, in view of chloride diffusion in concrete, is significantly critical and cannot be ignored (Shazali et al., 2012). To quantify the effect of chloride binding on service life, the four typical isotherms used in the literature (Martin-Perez et al., 2000; Liang et al., 2011; Shazali et al., 2012; Liang et al., 2012;