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Marine corrosion behavior of a novel pipe pile based on the principle of convection

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ABSTRACT

In order to slow down the diffusion of chloride ions, a novel concrete pipe pile is proposed based on the principle of convection. Pressurized water can be pumped into the hollow space of pipe pile, which results in a hydraulic head difference compared with the seawater pressure, leading to an outward radial flow in the concrete pipe pile. Hence, the rate of chloride diffusion in concrete is reduced due to the convection of water. The mechanism of chloride ion transport in the pipe pile is analyzed, and a mathematical model is established. The developed model is then implemented into a finite element software to study the influence of water head difference on the diffusion of chloride ions.

Keywords: pipe pile; chloride diffusion; anti-corrosion; mathematical model; numerical simulation

1 INTRODUCTION

Reinforced concrete structures are widely used in marine environments, and the performance of marine structures can often be deteriorated by chloride-induced corrosion. Chloride ions can be transmitted from the seawater into concrete through macropores or cracks, and eventually accumulate on the surface of steel rebars. When the concentration of chloride ions reaches a critical value, corrosion of steel rebars (e.g., rust) occurs. Nowadays, the service life of concrete marine structures is generally less than the design requirement, where rehabilitation or replacement is needed. Unsatisfactory structural durability of marine structures becomes an important issue for engineers (Dong 2001).

All current protective measures can be mainly divided into two categories, including improving the material properties of concrete, and adding protective coating for concrete and steel rebars. It should be emphasized that all these techniques are passive protective measures. Once the improvement of concrete properties reduces with time, or the protective coating fails, corrosion of concrete will be accelerated easily.

A novel concept of permeable pipe pile has been proposed by Mei et al. (2018), where drainage holes are opened around a pipe pile to provide drainage paths to accelerate soil consolidation after pile driving. This conceptual design has been proved to be effective through numerical simulations (Ni et al. 2017b), and laboratory tests (Ni et al. 2017a; Ni et al. 2018a). Ni et al. (2018b) demonstrates that the flow of groundwater can also facilitate antiflotation design for water tank. The idea of introducing hydraulic head difference inside and outside the pipe pile inspires a new design of pipe pile, where an active protective measure is proposed based on the convection of water to slow down the rate of chloride diffusion.

2 MATHEMATICAL MODEL

A new corrosion resistant pipe pile is proposed to minimize the diffusion of chloride ions in marine environments as schematically shown in Fig. 1. Pressurized water is pumped into the hollow space of pipe pile, which causes an outward radial flow in the concrete pipe pile due to the pressure difference, hindering the inward diffusion of chloride ions.

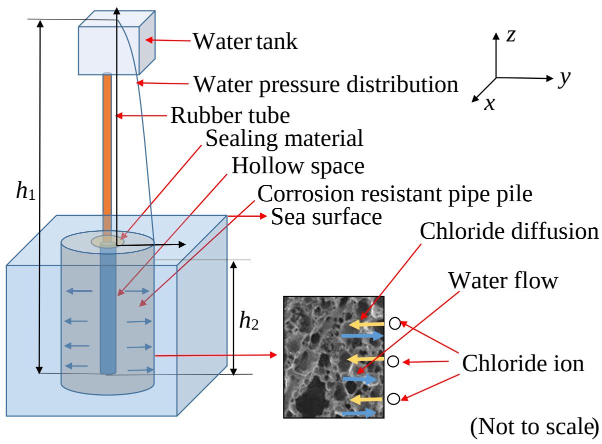

Fig. 1. Schematics of corrosion resistant pipe pile.

2.1 Chloride ion transport model

The chloride flux, J, transported from the outside surface to the inside of the concrete contains two parts:

$$J = J_d + J_c \tag{1}$$

where J_d is the diffusion flux (mol/m^2·s), and J_c represents the convection flux.

The term is controlled by Fick's first law:

$$J_{\mathrm{d}} = -D\frac{\mathrm{d}C}{\mathrm{d}y} \tag{2}$$

where D is the diffusion coefficient of chloride ion (mm^2/s), and dC/dy is the gradient of chloride ion concentration.

The convection flux J_c is controlled by:

$$J_{\mathrm{c}} = uC \tag{3}$$

where u is the flow rate of water (m/s).

During the chloride ion transport process, the mass equilibrium in the system should be maintained, based on which a transport model for chloride ion in concrete is derived without considering the adsorption and hydration of concrete:

$$\begin{aligned}\frac{\partial C(x,y,z,t)}{\partial t} &= \nabla(D\nabla C(x,y,z,t)) \\ &-\nabla uC(x,y,z,t)\end{aligned} \tag{4}$$

where x, y, and z denote the coordinates (m), and t corresponds to the time (s).

2.2 Water flow rate in concrete pipe piles

The seepage mechanism of water in porous media can be used to calculate the seepage of pore fluids in concrete (Zhang 2008). The radial head distribution in the pile satisfies the Laplace equation:

$$\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} + \frac{\partial^2 H}{\partial z^2} = 0 \tag{5}$$

where H indicates the water head height (m).

The governing equation is then expressed in polar coordinates as follows:

$$\frac{\partial^2 H}{\partial r^2} + \frac{1}{r}\frac{\partial H}{\partial r} + \frac{1}{r^2}\frac{\partial^2 H}{\partial \theta^2} + \frac{\partial^2 H}{\partial z^2} = 0 \tag{6}$$

Since the water flow is symmetrical about the z axis in the horizontal plane, the velocity of water flow in the z direction is assumed to be 0. Due to the symmetry, the hydraulic head becomes independent of the angle, where both terms of $\partial^2 H/\partial\theta^2$ and $\partial^2 H/\partial z^2$ are eliminated.

$$\frac{\partial}{\partial r}\left(r\frac{\partial H}{\partial r}\right) = 0 \tag{7}$$

At the inner surface of the pipe pile, the radius is r_1, and the water head is h_1; whereas the outer radius of the pipe pile is defined as r_2 with a water head of h_2. Considering the length of the seepage path is r, the water head height is determined as H which is written as follows:

$$H = h_1 + (h_2 - h_1)\frac{\ln rr_1^{-1}}{\ln r_2 r_1^{-1}} \tag{8}$$

The seepage of pore fluids in concrete is resulted from external pressure, and the process of liquid flow in porous medium can be qualitatively described by Darcy's law. The non-Darcy flow due to small water flow rate is neglected.

$$Q = -\frac{k}{\eta}\frac{dp}{dx} \tag{9}$$

where Q is the volume flow rate of the pores (m/s), k is the medium permeability (m/s), η is the viscosity coefficient of the liquid (Pa·s), and p is the pressure head (m).

The concrete is assumed to be a homogeneous and isotropic medium. The radial water flow rate obtained by Darcy's law is then derived as:

$$u = K\frac{\Delta h}{\ln r_2 r_1^{-1}} r^{-1} \tag{10}$$

where K is the permeability coefficient of water in concrete (m/s), Δh is the difference between the internal water head and the external water head, which is positive (m).

The velocity of water flow in the x and y directions can be calculated through the projection of radial water velocity in respective directions:

$$\begin{aligned} u_x &= u\cos\theta \\ u_y &= u\sin\theta \end{aligned} \tag{11}$$

2.3 Boundary and initial conditions

The problem is defined to follow a boundary condition that the concentration of chloride ions on the concrete surface is the same as the seawater due to direct contact.

The flux should be essentially continuous, given that the molecular diffusion of chloride ions in water is neglected.

$$J = uC\,|_{r=r_1} \tag{12}$$

where J is the flux of chloride ions on the inner boundary of the concrete (mol/m^2·s), u is the seepage velocity of water on the inner boundary (m/s), and $C\,|_{r=r_1}$ is the corresponding concentration of chloride ions (mol/m^3).

The initial condition is defined that the concentration of chloride ions inside the concrete is assumed to be zero initially (Shi and Wang 2004).

3 MUMERCIAL CALCULATION

3.1 Model evaluation

The proposed mathematical model cannot find an explicit solution, which is hence implemented into a finite element software Comsol Muitiphysics. All pores in the concrete are fully saturated during the diffusion process. The two-phase model of water and chloride irons is implemented in Comsol through the Transport of Diluted Species interface following three steps: (a) the water pressure head and the concentration of chloride irons are set as two variables to be solved, (b) the equations describing the water flow and the diffusion of chloride irons are specified in Comsol by replacing the corresponding coefficients of partial differential equations, and (c) the boundary and initial conditions are directly applied in Comsol. Three-noded triangular elements with an element size of 5 mm are used to discretize the model.

On the site of a pile supported wharf after 10 years' service, Zhu et al. (2003) drilled concrete cores to different cover depths in selected piles, which were further ground into powders. Mixing concrete powders with water enabled to measure the concentration of chloride irons. Similarly, Wu and Gu (2010) measured the concentration of chloride irons for concrete piles in the marine environment after 18 years' service. Results from these two field tests are used in this investigation to assess the effectiveness of the proposed analytical solution.

Fig. 2 shows the concentration of chloride ions calculated using the proposed numerical approach, the experimental data and the analytical solutions reported in the literature. The diameter of the concrete pile is 400 mm. At the outside boundary of the pile, the concentration of chloride ions is taken as 1%, and the diffusion coefficient D is 80 mm^2/s. Comparisons are conducted for the analyses after 10 years (Zhu et al. 2003) and 18 years (Wu and Gu 2010) as illustrated in Fig. 2a and Fig. 2b, respectively. In general, the proposed diffusion model can provide satisfactory simulations for the diffusion process of chloride ions in concrete.

3.2 Parametric analysis

A short parametric study is performed to investigate the influence of water head difference on the corrosion behavior of pipe piles. Two cases are considered: no water head difference and 2.5 m water head difference. All parameters used in the calculation are summarized in Table 1. Following the study of Yan (1993), the concrete class is defined as S12, which has a permeability coefficient of 0.104×10^{-8} cm/s.

For two values of water head difference outside the pipe pile, the distribution of radial concentration of chloride ions is calculated as depicted in Fig. 3. It is clear that when a water head difference of 2.5 m is introduced, the radial concentration of chloride ions reduces significantly. It is noteworthy that the concentration remains basically unchanged after 40 years for the pipe pile with the application of 2.5 m water head difference, indicating that the transport of chloride ions on the concrete surface has reached an equilibrium. The chloride ions that are diffused inward by the concentration gradient will be resisted by the outward flow of water due to the hydraulic head difference based on the principle of convection. The analyses demonstrate that the proposed corrosion resistant pipe pile is effective to reduce the concentration of chloride ions in concrete in marine environments.

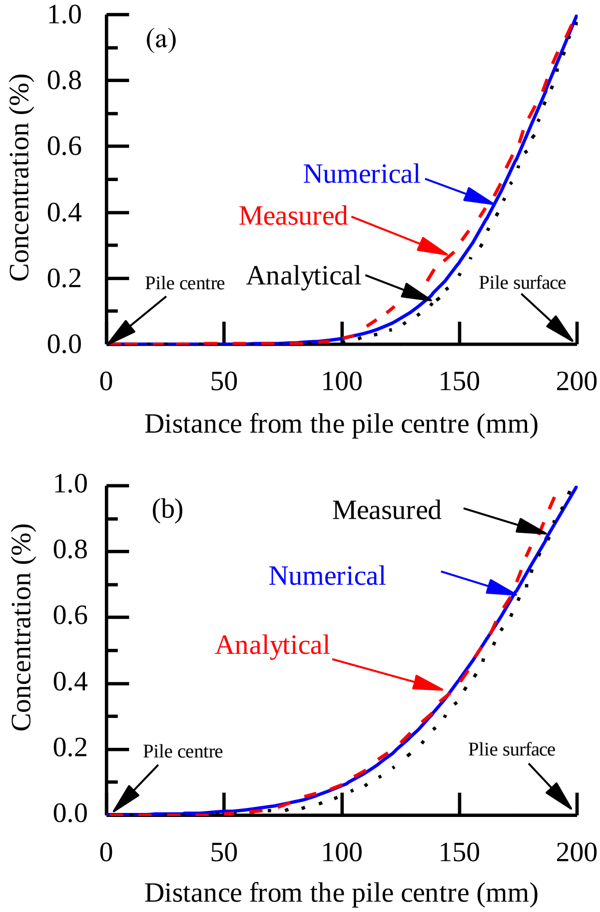

Fig. 2. Comparison of numerical and experimental data: (a) 10 years, and (b) 18 years.

Table 1. Parameters used in parametric analysis.

Parameter	Value
Inner radius r_1 (mm)	50
Outer radius r_2 (mm)	250
Destiny (kg/m^3)	2300
Young's modulus (GPa)	25
Poisson's ratio	0.2
Porosity	0.03

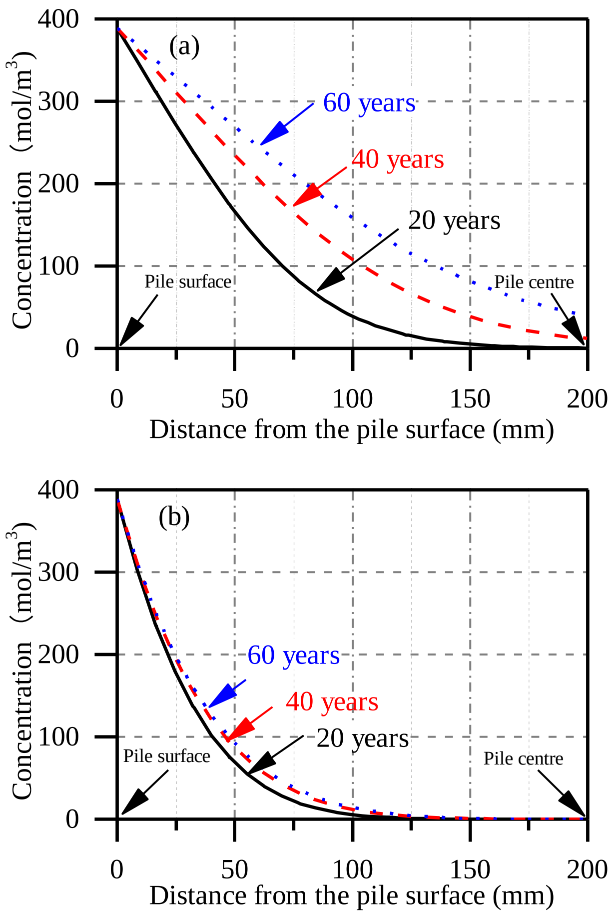

Fig. 3. Radial distribution of chloride ions: (a) no water head difference, and (b) 2.5 m water head difference.

4 CONCLUSIONS

This paper proposes a novel concept to introduce a water pressure difference inside and outside a pipe pile to minimize the potential of corrosion in concrete. From the analyses, it has been found that with the increase of water head difference, the rate of inward diffusion of chloride ions can be effectively reduced. The principle of convection can also hinder the intrusion of other harmful ions into concrete.

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