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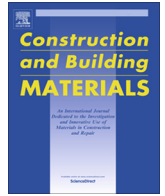
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# Service life of prestressed high-strength concrete pile in marine environment considering effects of concrete stratification and temperature

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## HIGHLIGHTS

- PHC piles show concrete stratification phenomenon due to centrifugal process.
- Fick's second law is used to derive diffusion equation for two-layer annulus.
- Increase of mortar layer thickness leads to rapid decrease of service life.
- Sealing pile ends is an effective method to extend service life of PHC piles.

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## ABSTRACT

Prestressed high-strength concrete (PHC) piles have advantages of light weight and high load carrying capacity, which have been widely applied in coastal and offshore engineering. However, PHC piles serving in the coastal or offshore regions have already undergone severe durability problem. This paper presents a comprehensive method for predicting the service life of PHC piles in the marine environment, which reasonably takes the temperature effects and the concrete stratification caused by centrifugation of PHC piles into account. The pile service life is divided into the diffusion and corrosion periods. The service life of the diffusion period is predicted by solving the diffusion equation formulated for chloride ion diffusion in a two-layer ring medium, the results of which are compared with the data obtained from the elaborate experimental tests to examine the validity. The service life of the corrosion period is determined based on the ultimate corrosion expansion pressure produced by the accumulated corrosion products of steel bar. Various possible key factors, like protective cover thickness, initial chloride ion concentration, mortar layer thickness, etc., are considered to investigate how these parameters critically affect the pile service life. The results suggest that increasing mortar layer thickness can lead to a significant decrease of the service life in both diffusion and corrosion periods; and increasing protective cover thickness and sealing pile end are two effective ways to extend the service life of PHC piles.

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## 1. Introduction

Since the invention of PHC piles, they have attracted widespread attention from both academia and industry due to high load carrying capacity, reliable quality, short construction time as well as good ability of saving concrete consumption compared with solid piles. The present applications of PHC piles can be found almost everywhere in civil engineering, such as the housing build-

ing, the highway, bridge and pier construction, the offshore wind power foundation and the like. However, the durability of PHC piles must be paid attention to when they serve in the coastal or offshore regions (i.e., the marine environment). The chloride ions in the marine environment can penetrate into the concrete cover of the PHC pile and accumulate at the surface of steel bar. When the chloride ion concentration at the surface of steel bar arrives at the critical value, the hydrated film will be destroyed and the steel bar begins to rust. Since the volume of the rusts are much larger than the volume of the original steel bar, the corrosion-induced expansive pressure will be generated with accumulation of the rust, which will lead to the cracking of concrete cover and finally

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result in the failure of PHC piles as the expansive pressure increases to the critical pressure [1].

Compared with the common concrete structures, the PHC piles own some unique features, which specifically include (1) PHC piles are hollow and thus the chloride ions can penetrate from both the inner and outer surfaces; (2) the centrifugation, one essential process of producing PHC piles, can lead to the stratification of the concrete: the inner mortar layer and the outer concrete layer; the diffusion coefficients of the two layers are different from each other; (3) PHC piles belong to the prestressed concrete structures and hence the corrosion of steel bar will result in the loss of prestress and hence accelerate the concrete cracking. All the above-mentioned characteristics will result in different chloride diffusion and failure mechanisms of PHC piles compared with common concrete structures. Besides, it has been only about 50 years since the birth of PHC piles and the service time of PHC piles in the marine environment is relatively short. Therefore, the durability of PHC piles temporarily has not been brought to the forefront yet. However, in fact, the durability of PHC piles in some coastal or offshore areas has already become as a severe problem [2]. Therefore, for the sake of better employing PHC piles in the marine environment and offering suggestions on maintaining PHC piles that have already suffered from the durability problem, it is of great interest and necessity to explore the diffusion mechanism of chloride ions in PHC piles and then reasonably predict the service life of PHC piles in the marine environment.

At present, numerous research efforts (e.g. [3–6]) have been devoted to the chloride ion diffusion in common concrete structures. However, for structures that have hollow shapes, the corresponding research on the chloride ion diffusion is still heavily lacking. To the best of authors' knowledge, only the following researchers have devoted to exploring the chloride diffusion in pipe piles. Huang et al. [7] and Lau et al. [8] have relatively early explored the chloride ion diffusion in pipe piles, but the simultaneous chloride diffusion from both the inner and outer surfaces of pipe piles has not been taken into account. In addition, the concrete stratification of PHC piles can occur due to the centrifugation, which is beyond the scopes of their research. Therefore, their results are still far away from reasonably modelling the chloride ion diffusion in PHC piles. Later, Shao and Li [9] and Li and Shao [10] proposed methods for predicting the service life of pipe piles in the marine environment, where the effects of chloride binding and cracks were considered, respectively, however again the effects of concrete stratification and the chloride diffusion from both the pile inner and outer surfaces have been neglected. It is worth noting that the experiments conducted by Yue et al. [11] reveal the concrete stratification phenomenon of PHC piles for the first time. Up to now, no analytical solution that incorporates the effects of the concrete stratification caused by centrifugation on the chloride diffusion in PHC piles has been proposed and the corrosion of steel bars in PHC piles has not been explored either. In another word, the approach for predicting the service life of PHC piles in the marine environment is currently unavailable.

In this paper, the whole service life of PHC piles is divided into two periods: the chloride ion diffusion period and the steel bar corrosion period. The chloride ion diffusion in PHC piles is modelled by chloride ion diffusion in a two-layer ring medium, which is formulated as differential equations based on the Fick's second law and takes the effects of temperature into consideration. The length of the service life in this period is taken as the time from the start of chloride penetration into PHC piles to the chloride ion concentration around steel bar reaching the critical concentration. The service life in the steel bar corrosion period is defined as the time from the start of steel bar corrosion to the cracking occurrence in concrete protective cover, which is predicted based on the ultimate corrosion expansion pressure derived based on the cavity expansion

theory. The validity of the proposed method is examined by comparing with the elaborate experimental tests prepared and conducted by the authors. Various possible important factors are considered to explore how these factors critically affect the service life of PHC piles, based on which some important suggestions are proposed so as to help civil engineers better utilize PHC piles in the marine environment. It is expected that the proposed method will serve as a feasible guidance for the service life prediction of PHC piles in the marine environment.

## 2. Analytical analysis of service life of PHC piles

### 2.1. Service life in diffusion period considering concrete stratification and temperature

The diffusion of chloride ions in the concrete is usually described by Fick's second law, the validity of which has been solidly verified by many researchers (e.g., [9,12–14]). In the Cartesian coordinate system, the diffusion equation of Fick's second law is a two-dimensional problem and its expression can be written as

$$\frac{\partial C}{\partial t} = -D \left( \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right), 0 < x, y < +\infty, t > 0 \quad (1)$$

where  $C$  is the chloride ion concentration;  $D$  is the diffusion coefficient;  $t$  is the diffusion time;  $x$  and  $y$  are the Cartesian coordinates; and the minus sign indicates that the diffusion occurs from the high concentration region to the low concentration region.

The cross section of PHC piles is a circular ring, hence the diffusion equation in the Cartesian coordinate system requires to be converted into the diffusion equation in the polar coordinate system to better simulate the chloride diffusion in PHC piles. The relationship between the Cartesian and polar coordinates, as shown in Fig. 1, can be written as

$$\begin{cases} x = r \cos \theta \\ y = r \sin \theta \end{cases} \quad (2)$$

where  $r$  and  $\theta$  are the polar coordinates.

From the above equation, it is found that the Cartesian coordinates  $x$  and  $y$  are the functions with regard to the polar coordinates  $r$  and  $\theta$ . Therefore, the total differential equations of  $x$  and  $y$  can be derived as

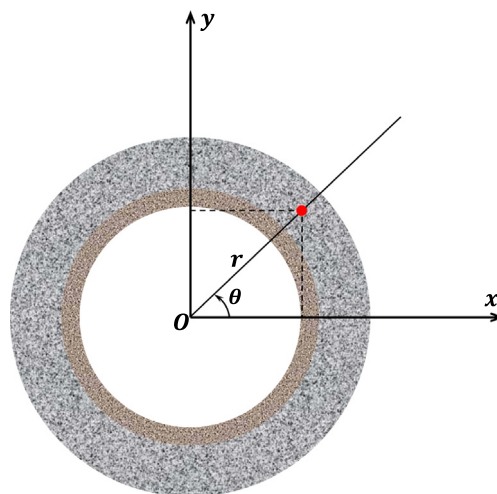


Fig. 1. Coordinate systems for building diffusion equations of chloride ions in PHC piles.

$$\frac{\partial}{\partial x} = \frac{\partial r}{\partial x} \frac{\partial}{\partial r} + \frac{\partial \theta}{\partial x} \frac{\partial}{\partial \theta} = \cos \theta \frac{\partial}{\partial r} - \frac{1}{r} \sin \theta \frac{\partial}{\partial \theta} \quad (3)$$

$$\frac{\partial}{\partial y} = \frac{\partial r}{\partial y} \frac{\partial}{\partial r} + \frac{\partial \theta}{\partial y} \frac{\partial}{\partial \theta} = \sin \theta \frac{\partial}{\partial r} + \frac{1}{r} \cos \theta \frac{\partial}{\partial \theta} \quad (4)$$

Taking the derivatives of Eqs. (3) and (4) with respect to  $r$  and  $\theta$  again yields

$$\begin{aligned} \frac{\partial^2}{\partial x^2} &= \cos^2 \theta \frac{\partial^2}{\partial r^2} - \frac{2 \sin \theta \cos \theta}{r} \frac{\partial^2}{\partial r \partial \theta} + \frac{\sin^2 \theta}{r} \frac{\partial}{\partial r} + \frac{2 \sin \theta \cos \theta}{r^2} \\ &\times \frac{\partial}{\partial \theta} + \frac{\sin^2 \theta}{r^2} \frac{\partial^2}{\partial \theta^2} \end{aligned} \quad (5)$$

$$\begin{aligned} \frac{\partial^2}{\partial y^2} &= \sin^2 \theta \frac{\partial^2}{\partial r^2} + \frac{2 \sin \theta \cos \theta}{r} \frac{\partial^2}{\partial r \partial \theta} + \frac{\cos^2 \theta}{r} \frac{\partial}{\partial r} - \frac{2 \sin \theta \cos \theta}{r^2} \\ &\times \frac{\partial}{\partial \theta} + \frac{\cos^2 \theta}{r^2} \frac{\partial^2}{\partial \theta^2} \end{aligned} \quad (6)$$

Substituting Eqs. (5) and (6) into Eq. (1) gives the diffusion equation in the polar coordinate system as

$$\frac{\partial C}{\partial t} = -D \left( \frac{\partial^2 C}{\partial r^2} + \frac{1}{r} \frac{\partial C}{\partial r} + \frac{1}{r^2} \frac{\partial C^2}{\partial \theta^2} \right) \quad (7)$$

Since the chloride diffusion in PHC piles is a symmetry problem along the radial direction, the diffusion in the circumferential direction can be ignored and then the diffusion equation, Eq. (7), can be further written as

$$\frac{\partial C}{\partial t} = -D \left( \frac{\partial^2 C}{\partial r^2} + \frac{1}{r} \frac{\partial C}{\partial r} \right) \quad (8)$$

When the PHC pile suffers from the attack of chloride ions from both the inner and outer surfaces, the initial condition as well as the boundary conditions for the diffusion equation can be given as

$$C(0, r) = C_0, a < r < b \quad (9)$$

$$C(t, a) = C_a, C(t, b) = C_b, t > 0 \quad (10)$$

where  $a$  and  $b$  are the inner and outer radii of the PHC pile, respectively;  $C_0$  is the initial chloride ion concentration; and  $C_a$  and  $C_b$  represent the chloride ion concentrations at the inner and outer surfaces of the PHC pile, respectively.

To convert the nonhomogeneity of the boundary condition into the homogeneity, two functions, i.e.  $V(t, r)$  and  $v(r)$ , are introduced to express  $C(t, r)$  as

$$C(t, r) = V(t, r) + v(r) \quad (11)$$

Substituting Eq. (11) into Eq. (8) gives

$$\frac{\partial V}{\partial t} = -D \left( \frac{\partial^2 V}{\partial r^2} + \frac{1}{r} \frac{\partial V}{\partial r} \right) - D \left( \frac{\partial^2 v}{\partial r^2} + \frac{1}{r} \frac{\partial v}{\partial r} \right) \quad (12)$$

The corresponding initial and boundary conditions of the above equation can be given as

$$V(0, r) = C_0 - v(r), a < r < b \quad (13)$$

$$V(t, a) = C_a - v(a), V(t, b) = C_b - v(b), t > 0 \quad (14)$$

Converting the nonhomogeneity of Eq. (14) into the homogeneity and making the items including  $v(r)$  in Eqs. (12) equal 0, i.e.,

$$\begin{cases} D \left( \frac{\partial^2 v}{\partial r^2} + \frac{1}{r} \frac{\partial v}{\partial r} \right) = 0 \\ C_a - v(a) = 0, C_b - v(b) = 0 \end{cases} \quad (15)$$

The function,  $v(r)$ , can be obtained as

$$v(r) = \frac{C_a \ln(b/r) + C_b \ln(r/a)}{\ln(b/a)} \quad (16)$$

With the substitution of Eq. (15) into Eqs. (12) and (14), the diffusion equation with regard to the function,  $V(t, r)$ , can be given by

$$\frac{\partial V}{\partial t} = -D \left( \frac{\partial^2 V}{\partial r^2} + \frac{1}{r} \frac{\partial V}{\partial r} \right) \quad (17)$$

The corresponding boundary condition is determined as

$$V(t, a) = 0, V(t, b) = 0, t > 0 \quad (18)$$

To derive the solution of Eq. (17), the separation of variables method is adopted by assuming  $V(t, r) = R(r)T(t)$ . Substituting it into the equation yields

$$\frac{T'(t)}{DT(t)} = \frac{R''(r) + \frac{1}{r}R'(r)}{R(r)} \quad (19)$$

The left item of the above equation is a function with regard to the time,  $t$ , while the right item is with respect to the radial distance,  $r$ . Because the two items require to be equal to each other, they must equal a certain constant. Here, the certain constant is denoted as the notation,  $\lambda$ . Then, the above equation can be rewritten as the two equations, i.e.,

$$T'(t) + \lambda DT(t) = 0 \quad (20)$$

$$r^2 R''(r) + rR'(r) + \lambda r^2 R(r) = 0 \quad (21)$$

Due to the boundedness of the chloride diffusion equation, the constant,  $\lambda$ , should be greater than 0 and thus it can be assumed as  $\lambda = \beta^2$  ( $\beta > 0$ ). Note that Eq. (20) is a linear first-order differential equation and thus its solution can be easily obtained as

$$T(t) = A_1 \exp(-\beta^2 Dt) \quad (22)$$

where  $A_1$  is an undetermined coefficient.

Eq. (21) is a zero-order Bessel function and its general solution can be written as

$$R(r) = A_2 J_0(\beta r) + A_3 Y_0(\beta r) \quad (23)$$

where  $J_0$  and  $Y_0$  are the first-kind and second-kind Bessel functions with zero order, respectively; and  $A_2$  and  $A_3$  are two undetermined coefficients.

With the initial condition, Eq. (13), and the homogenous boundary condition, Eq. (18), the boundary equation for Bessel function can be obtained based on Eq. (23) as

$$\begin{cases} R(a) = A_2 J_0(\beta a) + A_3 Y_0(\beta a) = 0 \\ R(b) = A_2 J_0(\beta b) + A_3 Y_0(\beta b) = 0 \end{cases} \quad (24)$$

Assuming  $U_0(\beta r) = J_0(\beta r)Y_0(\beta b) - J_0(\beta b)Y_0(\beta r)$ , it can be found that  $U_0(\beta r)$  is always equal to 0 when  $r = b$ . Provided that  $U_0(\beta r)$  is also always equal to 0 when  $r = a$ , the function  $U_0(\beta r)$  satisfies the boundary condition, Eq. (24). Based on the characteristic of Bessel function, infinite values of  $\beta$  are available for satisfying  $U_0(\beta a) = 0$ , which is denoted as  $\beta_n$ . Therefore, the solution of  $R(r)$  can be determined as

$$R(r) = U_0(\beta_n r) = J_0(\beta_n r)Y_0(\beta_n b) - J_0(\beta_n b)Y_0(\beta_n r) \quad (25)$$

According to the principle of superposition, the solution of  $V(t, r)$  can be then calculated as

$$V(r, t) = \sum_{n=1}^{\infty} V_n(r, t) = \sum_{n=1}^{\infty} A_n \exp(-\beta_n Dt) U_0(\beta_n r) \quad (26)$$

To determine the undetermined coefficient,  $A_n$ , Eq. (26) can be written with the initial condition, Eq. (13), as

$$\sum_{n=1}^{\infty} A_n U_0(\beta_n r) = C_0 - v(r) \tag{27}$$

Making use of the orthogonality of the Bessel function and timing both sides of the above equation with the radial distance,  $r$ , as well as integrating both sides from the inner radius,  $a$ , to the outer radius,  $b$ , give the expression of the undetermined coefficient,  $A_n$ , as

$$A_n = \frac{\int_a^b r U_0(\beta_n r) [C_0 - v(r)] dr}{\int_a^b r U_0^2(\beta_n r) dr} \tag{28}$$

After calculating the integral, the final form of Eq. (28) can be written as

$$A_n = \pi C_0 \frac{J_0(a\beta_n)}{J_0(a\beta_n) + J_0(b\beta_n)} - \pi \frac{[C_b J_0(a\beta_n) - C_a J_0(b\beta_n)] J_0(a\beta_n)}{J_0^2(a\beta_n) - J_0^2(b\beta_n)} \tag{29}$$

Substituting Eq. (29) into Eq. (26), with combination of Eqs. (11) and (16), yields the distribution of chloride ion concentration in PHC piles, which suffer from the attack of chloride ions from both pile inner and outer surfaces, as follows

$$C(t, r) = \pi C_0 \sum_{n=1}^{\infty} \frac{J_0(a\beta_n) U_0(\beta_n r)}{J_0(a\beta_n) + J_0(b\beta_n)} e^{-D\beta_n^2 t} - \pi \sum_{n=1}^{\infty} \frac{[C_b J_0(a\beta_n) - C_a J_0(b\beta_n)] J_0(a\beta_n) U_0(\beta_n r)}{J_0^2(a\beta_n) - J_0^2(b\beta_n)} e^{-D\beta_n^2 t} + \frac{C_a \ln(b/r) + C_b \ln(r/a)}{\ln(b/a)} \tag{30}$$

After trials and analysis, it is found that the above equation converges very fast and the first 10 items of the parameter,  $\beta_n$ , already satisfy the calculation requirement.

Fig. 2 shows the distribution of mortar and aggregate in a PHC300 pile (a kind of PHC piles with the wall thickness of 70 mm and the outer radius of 300 mm). It can be seen that after centrifugal process the mortar accumulates around the pile inner surface due to its light weight and the thickness of mortar layer ranges from 5 mm to 20 mm; on the contrary, the aggregate is uniformly distributed. Because the mortar layer generally has a large chloride diffusion coefficient, the existence of mortar layer is certain to have significant effects on the service life of PHC piles in the diffusion period. In another word, when predicting the service life of PHC piles, the effect of concrete stratification should be taken into account rather than the concrete made into PHC piles is simply assumed to be isotropic.

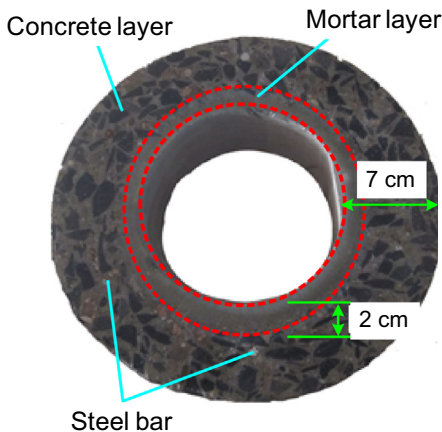


Fig. 2. Cross section of an actual PHC300 pile.

Using the notation,  $m$ , to denote the radial distance of the interface that the materials around are different (i.e. one side is the mortar layer, and the other is the concrete layer), Eq. (8) can be written as

$$\frac{\partial C_1}{\partial t} = -D_1 \left( \frac{\partial^2 C_1}{\partial r^2} + \frac{1}{r} \frac{\partial C_1}{\partial r} \right), a < r < m \tag{31}$$

$$\frac{\partial C_2}{\partial t} = -D_2 \left( \frac{\partial^2 C_2}{\partial r^2} + \frac{1}{r} \frac{\partial C_2}{\partial r} \right), m < r < b \tag{32}$$

where  $D_1$  and  $D_2$  are the diffusion coefficients of the mortar and concrete layers, respectively; and  $C_1$  and  $C_2$  are the chloride ion concentrations of the mortar and concrete layers, respectively.

As for the diffusion problem with different diffusion coefficients in the polar coordinate system, Carslaw et al. [15] has presented the Laplace solution of the diffusion in a solid circle. However, it will become very complex to derive a Laplace solution of the diffusion in a ring, making it almost impossible to be adopted by practicing engineers. Therefore, the difference method is employed here to derive the numerical solution for the present diffusion equation.

When  $a < r < m$ , the difference scheme of Eq. (31) can be expressed as

$$\frac{C_1(i+1, j) - C_1(i, j)}{\tau} = D_1 \left[ \frac{C_1(i, j+1) - 2C_1(i, j) + C_1(i, j-1)}{h^2} + \frac{1}{a + (j-1)h} \frac{C_1(i, j+1) - C_1(i, j)}{h} \right] \tag{33}$$

where  $\tau$  is the time increment; and  $h$  is the radial distance increment.

With Eq. (33), the explicit solution of the diffusion equation can be given by

$$C_1(i+1, j) = C_1(i, j) + \frac{\tau D_1}{h^2} \left\{ C_1(i, j+1) - 2C_1(i, j) + C_1(i, j-1) + \frac{\tau D_1}{h[a + (j-1)h]} [C_1(i, j+1) - C_1(i, j)] \right\} \tag{34}$$

The difference scheme of the initial and boundary conditions can be written as

$$C_1(1, j) = C_0, C_1(i, 1) = C_a, C_1(i, N) = C_b \tag{35}$$

where  $N$  is the number of meshes along the radial axis.

For  $m < r < b$ , the same transformation can be conducted. Then, the diffusion of chloride ions in the PHC pile is explored through Eq. (34), just as shown in Fig. 3. It can be observed that the results

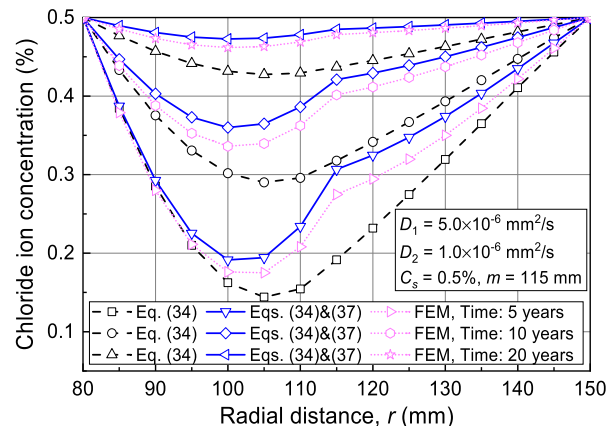


Fig. 3. Diffusion of chloride ions in PHC pile considering stratification due to centrifugal process.

calculated from Eq. (34) are in bad agreement with the results obtained from the finite element simulation. At the position where the diffusion coefficient changes, the concentration gradients at each side of this position shows an inconspicuous change and the variation curve is too smooth. The two phenomena indicate that the results obtained from Eq. (34) are lack of accuracy. Therefore, the chloride ion concentration at the position, where the diffusion coefficient changes, should be redefined so as to improve the computing accuracy. Based on the law of conservation of mass, one can obtain [16]

$$D_1 \frac{\partial C_1}{\partial r} \Big|_{r \rightarrow m^-} = D_2 \frac{\partial C_2}{\partial r} \Big|_{r \rightarrow m^-} \tag{36}$$

The difference scheme of Eq. (36) can be expressed as

$$C(i+1, j^*) = \frac{D_2 C(i, j^* + 1)}{D_1} + \frac{C(i, j^* - 1)}{1 + D_2/D_1} \tag{37}$$

where  $j^*$  is the sequence of mesh at the position where the diffusion coefficient changes.

The results calculated by Eq. (34) along with the incorporation of Eq. (37), are also illustrated in Fig. 3. It can be found that after incorporating Eq. (37), the chloride ion concentrations obtained from Eq. (34) show good agreements with the results obtained from the finite element simulation; in particular, the concentration gradient at the position where the diffusion coefficient changes shows a sudden change. In addition, the difference between the results obtained from Eq. (34) along with Eq. (37) and the results obtained from the finite element simulation becomes smaller, which indicates that the calculation tends to be stable. Therefore, when adopting the difference method to derive the solution of chloride diffusion equation for PHC piles, the position where the diffusion coefficient changes (i.e. stratification happens) should be tackled individually.

Due to the ring structure of PHC piles, the pile inner surface is always in the dark environment, while the pile outer surface may be exposed to strong sunlight and thus has a relatively high temperature. This can give rise to the temperature difference between the pile inner and outer surfaces. The temperature difference can bring about different chloride diffusion coefficients and further results in different chloride diffusion rates at the inner and outer surfaces. The literature [17] shows that the chloride diffusion coefficient can be doubled when the temperature increases from 20 °C to 30 °C and is also able to decrease to half as the temperature decreases from 20 °C to 10 °C. This indicates that the chloride diffusion coefficient is very sensitive to the temperature. Thus, the temperature effects should also be taken into account when exploring the chloride diffusion in PHC piles.

To quantitatively determine the effects of temperature on the diffusion coefficient of chloride ions in PHC piles, the temperature correction factor is introduced. At present, four main methods for calculating the temperature correction factor are available. Three of them are equations, which are proposed by Amey et al. [18], Gehlen [19] and Ehlen et al. [20], respectively. The specific forms of the equations are as follows

$$k_T = \frac{T}{T_0} e^{q \left( \frac{1}{T_0} - \frac{1}{T} \right)} \tag{38}$$

$$k_T = \exp \left[ b_T \left( \frac{1}{T_0} - \frac{1}{T} \right) \right] \tag{39}$$

$$k_T = \exp \left[ \frac{U}{R} \left( \frac{1}{T_0} - \frac{1}{T} \right) \right] \tag{40}$$

where  $q$  is the activation constant, related to the water-cement ratio and equal to 6550 when the water-cement ratio equals 0.3;  $b_T$  is a fitting parameter, obeying the normal distribution of mean,  $\mu$ , equal to 4800 and standard derivation,  $\sigma$ , equal to 700;  $U$  is the activation energy in the diffusion process, equal to 35,000 J/mol;  $R$  is the gas constant, equal to 8.314 J/(mol · K); and  $T_0$  and  $T$  are the Kelvin temperatures and the value of  $T_0$  is generally taken as 293 K (i.e., 20 °C).

The other one is the table (i.e. Table 1) given by Thoft-Christensen [21], which not only considers the temperature effect, but also includes the effect of water-cement ratio on the chloride diffusion coefficient. Fig. 4 shows the variation of correction coefficient with temperature obtained from all the above-mentioned methods. It can be found that the curves plotted based on the method proposed by Thoft-Christensen [21] show poor continuity, while the curves presented by Amey et al. [18], Gehlen [19], and Ehlen et al. [20] are smoother and show similar variation trends. When the temperature is between -10 °C and 20 °C, the variation of correction coefficient is small; in contrast, as the temperature ranges from 20 °C to 60 °C, the correction coefficient shows an apparent increase trend. The correction coefficient obtained from the method proposed by Amey et al. [18] is relatively large among three methods and shows the smooth trend. The correction coefficient determined from the method proposed by Gehlen [19] is between the correction coefficients presented by Amey et al. [18] and Ehlen et al. [20]. As a consequence, Eq. (39) is adopted to determine the temperature effects on the chloride ion diffusion in PHC piles.

The temperature correction difference coefficient,  $\delta$ , is defined to consider the temperature difference between the pile inner and outer surfaces, the expression of which is

$$\delta = \frac{k_{T_0} - k_T}{k_T} \tag{41}$$

where  $k_T$  and  $k_{T_0}$  are the temperature correction coefficients at the pile inner and outer surfaces, respectively.

Assuming that the temperature at the pile outer surface is always larger than that at the inner surface, Fig. 5 shows the variation of temperature correction difference coefficient with regard to the temperature difference. It can be observed that when the temperature at the pile outer surface is a constant, the correction difference coefficient increases with the increase of temperature difference and shows an exponential increase trend. When the temperature difference is between 0 °C and 15 °C, the temperature correction difference coefficient is small and within 2. However, as the temperature difference exceeds 15 °C, the temperature correction difference coefficient changes dramatically. In addition, with a lower temperature at the pile outer surface, the temperature correction difference coefficient shows a more apparent increase trend, which illustrates that the difference between the chloride diffusion coefficients at the pile inner and outer surfaces increases due to the low temperature at the outer surface.

Since the corrected diffusion coefficient, which incorporates the temperature effect, is only related to the temperature and has no connection with the time and the radial distance, it can be directly substituted into Eq. (30) to conduct further calculations. If the tem-

**Table 1**  
Temperature effect on chloride diffusion coefficient.

	Low temperature	Average temperature	High temperature
Loww/c	0.1D <sub>0</sub>	0.2D <sub>0</sub>	0.1D <sub>0</sub>
Averagew/c	0.5D <sub>0</sub>	D <sub>0</sub>	2D <sub>0</sub>
Highw/c	D <sub>0</sub>	2D <sub>0</sub>	10D <sub>0</sub>

Note that w/c denotes the water-cement ratio and D<sub>0</sub> is a characteristic diffusion coefficient in terms of average yearly temperature and an average w/c value.

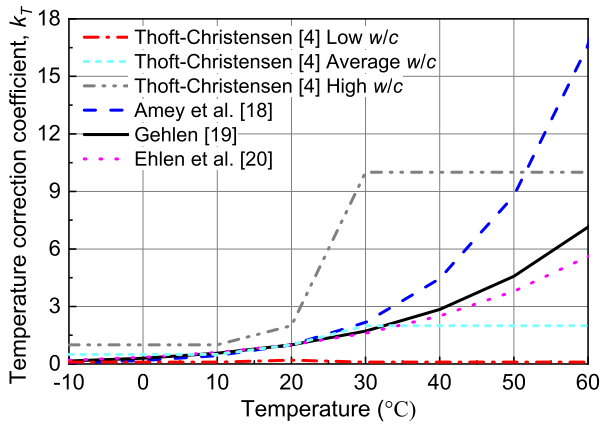


Fig. 4. Variation of temperature correction coefficient with temperature.

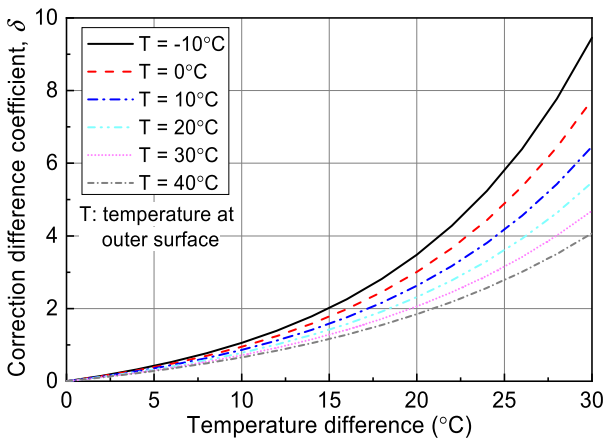


Fig. 5. Variation of temperature correction difference coefficient with temperature difference.

perature difference at the pile inner and outer surfaces is taken into account, Eq. (34) should be adopted for prediction on the service life of PHC piles in the diffusion period.

While the chloride ion concentration around the steel bar gradually increases as a consequence of the diffusion, it will finally arrive at the critical chloride ion concentration. As such, the strong alkaline environment at the surface of steel bar will be destroyed and the steel bar will begin to rust. Therefore, the time between the start of chloride penetration into PHC piles and the rust occurrence of steel bars is defined as the service life of PHC piles in the diffusion period.

## 2.2. Service life of PHC piles in corrosion period

Corrosion products will be generated as soon as the chloride ion concentration around the steel bar reaches the critical value. In general, the volume of corrosion products is in the order of 2~6 times as that of its initial volume. Therefore, the corrosion products will quickly fill in the voids around the interface between the steel bar and concrete. Correspondingly, the concrete will be subjected to the corrosion expansion pressure. As the corrosion expansion pressure increases with the further rust of the steel bar, the PHC pile will expand with a tiny change in size, the mechanism of which can be well modeled by cavity expansion theory. To develop the analytical solution for the cylindrical cavity expansion and further determine the stress state in PHC piles when the corrosion of steel bars occurs, the following assumptions need to be made:

- (1) The PHC pile is isotropic and the initial stress in the concrete is denoted as  $\sigma_0$ . The steel bar rusts homogeneously and the corrosion products expand evenly;
- (2) The concrete made into PHC piles belongs to the typical elasto-brittle material, the strength criterion of which is the maximum tensile-stress criterion;
- (3) The PHC pile is in the plane strain state. Hence, the elastic modulus,  $E$ , and the Poisson's ratio,  $\nu$ , can be defined as the values in the plane strain state;
- (4) The distance between the center of steel bar and the margin of concrete protective cover and the radius of steel bar are denoted as  $c$  and  $a_0$ , respectively. Then, the expansion region of corrosion products can be regarded as a cavity with the inner radius of  $a_0$  and the outer radius of  $c$ ;
- (5) With the increase of corrosion expansion pressure, resulting from the rust of steel bar, the assumed cavity around steel bar will be expanded.

During the rust of steel bar, the boundary of corrosion products is denoted as  $a$ . As a result, the corrosion expansion pressure at the boundary can be denoted as  $\sigma_a$ . Then, the boundary conditions of cavity expansion can be expressed as

$$\sigma_r = \sigma_a, r = a_0 \quad (42)$$

$$\sigma_r = \sigma_0, r \rightarrow l \quad (43)$$

where  $\sigma_r$  is the radius stress; and  $l$  is a sufficient distance from the center of steel bar.

Fig. 6 illustrates a schematic of the PHC pile in the corrosion period, which is strictly defined by means of the above assumptions. Based on the theory of elasticity, in combination of the boundary conditions, the circumferential stress,  $\sigma_\theta$ , and the radial displacement,  $u_d$ , can be obtained as

$$\sigma_\theta = \sigma_0 - \frac{a_0^2 (l^2 + r^2)}{r^2 (l^2 - a_0^2)} (\sigma_a - \sigma_0) \quad (44)$$

$$u_d = \frac{a_0^2 (\sigma_a - \sigma_0)}{Er (l^2 - a_0^2)} [(r^2 + l^2) + \nu (l^2 - r^2)] \quad (45)$$

where  $E$  and  $\nu$  are the elastic modulus and Poisson's ratio of concrete, respectively.

As the steel bar continues rusting, the corrosion expansion pressure gradually increases, resulting in the increase of circumferential (tensile) stress in the PHC pile. When the circumferential stress at the position of  $r = c$  equals the ultimate tensile stress of concrete, i.e.  $(\sigma_\theta)_{r=c} = -\sigma_{lim}$ , the concrete at the point, A, cracks and the corrosion expansion pressure reaches the ultimate value. As a consequence, the present stress at the cavity wall,  $\sigma_a$ , is equal to the ultimate corrosion expansion pressure,  $p_u$ . Then, Eq. (44) can be rewritten as

$$(\sigma_\theta)_{r=c} = -\sigma_{lim} = \sigma_0 - \frac{a_0^2 (l^2 + c^2)}{c^2 (l^2 - a_0^2)} (p_u - \sigma_0) \quad (46)$$

Solving the above equation, the ultimate corrosion expansion pressure,  $p_u$ , can be determined as

$$p_u = \sigma_0 + \frac{c^2 (l^2 - a_0^2)}{a_0^2 (l^2 + c^2)} (\sigma_{lim} + \sigma_0) \quad (47)$$

Based on Eqs. (45) and (47), the radial displacement of corrosion products when cracking occurs at the point, A,  $u_{der}$ , can be obtained as

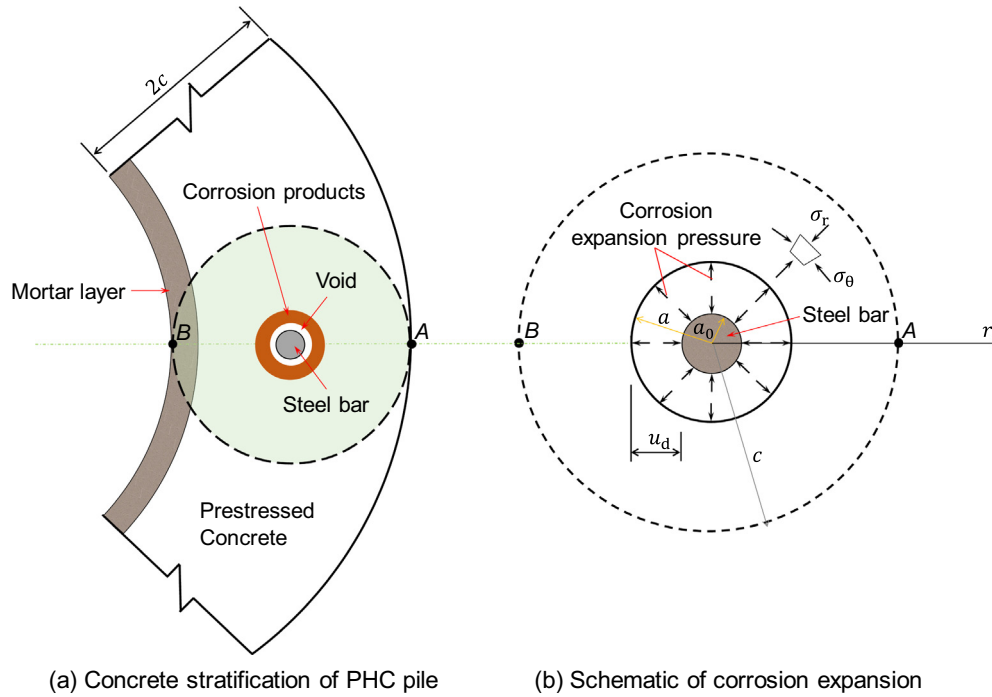


Fig. 6. Schematic of a PHC pile in corrosion period.

$$u_{dcr} = \frac{c^2(\sigma_{lim} + \sigma_0)}{Ea_0(l^2 + c^2)} \left[ (a_0^2 + l^2) + \nu(l^2 - a_0^2) \right] \quad (48)$$

The mass of corrosion products that the cracking of concrete just occurs is defined as the critical mass of corrosion products,  $M_{crit}$ , which can be determined as

$$M_{crit} = \pi \rho_{cor} \left[ (a_0 + u_{dcr})^2 - a_0^2 \right] \quad (49)$$

where  $\rho_{cor}$  is the density of corrosion products.

The literature [22] demonstrates a relationship between the mass of corrosion products and the time as

$$\frac{dM_{cor}}{dt_2} = \frac{k_p}{M_{cor}} \quad (50)$$

where  $t_2$  is the corrosion time of steel bar;  $M_{cor}$  is the mass of corrosion products; and  $k_p$  is the corrosion rate, determined as

$$k_p = 2.59 \times 10^{-6} \frac{\pi}{\alpha} D i_{cor} \quad (51)$$

where  $i_{cor}$  is the corrosion electric current density;  $D$  is the diameter of steel bar; and  $\alpha$  is the ratio of the molecular weight of iron to the molecular weight of the corrosion products, the values of which are specifically tabulated in Table 2 [23].

The experiments conducted by Vu and Stewart [24] indicate that the corrosion electric current density is related to the water-cement ratio and the thickness of concrete protective cover, the expression of which can be expressed as

$$i_{cor} = \frac{37.8(1 - w/c)^{-1.64}}{T_c} \quad (52)$$

where  $T_c$  is the protective cover thickness.

The service life of PHC piles in the corrosion period is defined as the time period between the start of steel bar corrosion and the beginning of the cracking occurrence in the protective cover induced by the expansion pressure due to the yielded corrosion products. Thus, the pile service life in this period,  $t_2$ , can be determined by means of substituting Eqs. (49), (51) and (52) into Eq. (50).

### 3. Determination of parameters and exploration on possible key factors

#### 3.1. Diffusion coefficient and chloride ion concentration

The rapid chloride migration method is generally adopted for determining the diffusion coefficient of concrete. However, this method cannot be applied for measuring the diffusion coefficient of PHC piles, since in this method standard specimens with specific dimensions are needed while PHC piles can hardly meet such a requirement. Therefore, other methods need to be discussed to find an appropriate one and then this appropriate method should be employed to estimate the diffusion coefficient of PHC piles. At present, there are two methods that may be reasonable for evaluating the diffusion coefficient of PHC piles. One is to utilize the water-cement ratio to evaluate the diffusion coefficient and the equation is written as [25]

$$D = 0.04 \times 1166^{w/c} \times 10^{-6} \quad (53)$$

The value of water-cement ratio for PHC piles usually ranges from 0.27 to 0.3 and thus the water-cement ratio here is taken as 0.3. Then, the diffusion coefficient of concrete layer can be estimated based on the above equation as  $3.33 \times 10^{-7} \text{mm}^2/\text{s}$ .

Table 2  
Ratio of molecular weight of iron to molecular weight of corrosion products.

Corrosion products	FeO	Fe <sub>3</sub> O <sub>4</sub>	Fe <sub>2</sub> O <sub>3</sub>	Fe(OH) <sub>2</sub>	Fe(OH) <sub>3</sub>	Fe(OH) <sub>3</sub> ·3H <sub>2</sub> O
$\alpha$	0.777	0.724	0.699	0.622	0.523	0.347



The other is to employ the electric flux to estimate the diffusion coefficient, the equation of which can be expressed as [26]

$$D = (2.57765 + 0.00492Q) \times 10^{-7} \quad (54)$$

where  $Q$  is the electric flux. For PHC piles in the marine environment, the value of electric flux can be taken as 1000 C. As a result, the diffusion coefficient of concrete layer calculated by Eq. (54) is evaluated as  $7.50 \times 10^{-7} \text{ mm}^2/\text{s}$ .

Although the water-cement ratio can reflect the composition of concrete materials to some degree, it cannot represent the specialty of constructing process of PHC piles. Therefore, the water-cement ratio method can still only be applied for calculating the diffusion coefficient of common concrete structures. Compared with the water-cement ratio method, the electric flux method can directly reflect the permeability and compactness of concrete and thus can better describe the chloride penetration resistance of PHC piles that undergo the special constructing process. Theoretically, the chloride penetration resistance of PHC piles should be stronger than that of common concrete members (i.e. the diffusion coefficient of PHC piles should be smaller than that of common concrete structures), since PHC piles are prestressed and undergo the high-pressure curing during construction. However, the steaming maintenance and the stratification caused by the centrifugal process can reduce the chloride penetration resistance of PHC piles. Therefore, it is reasonable that the diffusion coefficient of PHC piles estimated by electric flux method is a little greater than that obtained from the water-cement ratio method.

When exploring the diffusion of chloride ions in concrete structures, the chloride ion concentration is usually taken as a constant at the surface. However, as exposed to the real chlorinated environment, the chloride ion concentration at the surface actually increases from low concentration to high concentration and then arrives at the saturated state, instead of keeping constant in the whole diffusion period. Ehlen et al. [20] suggested that the variation process of chloride ion concentration at the concrete surface can be regarded as a linear change process and the process time can be taken as up to 10 years. Therefore, if the diffusion time is shorter than 10 years, the accumulation effect of chloride ions at concrete surfaces should be taken into consideration; however, if the diffusion time is much greater than 10 years (such as the expected service life of concrete structures), the chloride concentration at surfaces can be taken as a constant.

Engelund et al. [27] suggested that the chloride ion concentration at concrete surfaces,  $C_s$ , is related to the environment, the water-cement ratio and the concrete type. Thus, the corresponding estimation equation can be written as

$$C_s = A_c \cdot w/b \quad (55)$$

where  $A_c$  is a fitting parameter; and  $w/b$  is the water-binder ratio. For PHC piles in the water zone, the value of  $A_c$  can be taken as 10.3 [27].

With Eq. (55), the chloride ion concentration at the pile surface is evaluated as 0.54%, which is smaller than the value of 0.75% that is recommended by Bamforth [28] for the chloride ion concentration at the surface in the splash zone. Note that the diffusion rate of chloride ions is larger than that in the water zone, it is therefore more reasonable to take 0.54% as the chloride ion concentration at the surface of PHC piles in the marine environment.

The steel bar buried in the concrete will corrode, as the chloride ion concentration around it arrives at the critical value, which is exactly the minimum chloride ion concentration leading to the corrosion of steel bars. Once the steel bar begins to corrode, great damages will be caused to concrete structures in a relatively short time. Here, the method (i.e. Table 3) presented by Engelund et al. [27] is adopted to determine the critical chloride ion concentration

**Table 3**  
Critical chloride ion concentration (%).

Environment condition	Water-binder ratio		
	0.3	0.4	0.5
Water zone	2.3	2.1	1.6
Splashing zone	0.9	0.8	0.5

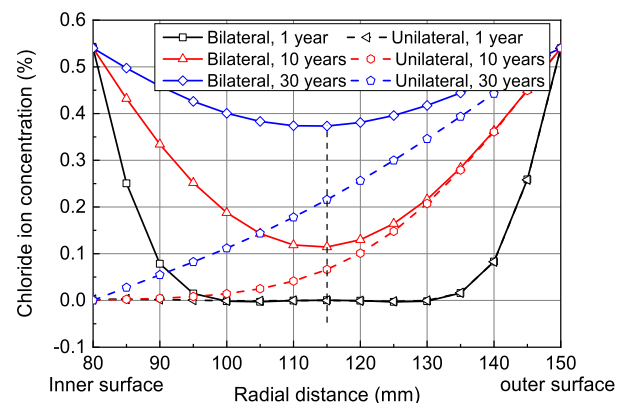
of PHC piles. The masses of cementing material and concrete of PHC piles are assumed to equal 400 kg and 2300 kg, respectively. Then, the critical chloride ion concentration of PHC piles,  $C_r$ , in the water zone can be estimated as 0.4%.

### 3.2. Selection of possible key factors

To investigate how the factors critically affect the service life of PHC piles in the chloride diffusion period, a PHC300 pile is taken as an example and the parameters used for analysis are  $D_2 = 7.50 \times 10^{-7} \text{ mm}^2/\text{s}$ ,  $C_s = 0.54\%$  and  $C_r = 0.4\%$ . The reasonability of these parameters has been specifically illustrated in the previous section.

Compared with the common concrete structures in the marine environment, PHC piles suffer from the chloride ion attack from both the pile inner and outer surfaces, instead of just the outer surface. Fig. 7 illustrates the comparison of chloride ion concentration in PHC piles from bilateral chloride penetration and unilateral chloride penetration. It is found that when the diffusion time is 1 year, the chloride ions diffusing from the inner and outer surfaces have not met in the PHC pile. The diffusion curve of bilateral chloride penetration at the unilateral penetration side agrees well with the diffusion curve of the unilateral chloride penetration. As the diffusion time increases to 10 years, the chloride ions from the inner and outer surfaces meet in the PHC pile and thus the diffusion curve of bilateral chloride penetration deviates from the curve of unilateral chloride penetration. When the diffusion time is equal to 30 years, the deviation degree increases and the chloride ion concentration of bilateral penetration is twice the concentration of unilateral penetration at the central position of PHC pile. This illustrates that with the elapse of time, the stacking effect of chloride ions diffusing from both surfaces becomes increasingly stronger. In addition, this demonstrates that under the bilateral diffusion condition, the chloride ions diffuse more rapidly, which will greatly impair the service life of PHC piles. Therefore, when predicting the service life of PHC piles in the marine environment, the bilateral chloride penetration must be taken into account.

Concrete stratification phenomenon occurs in PHC piles due to the centrifugal process. The diffusion coefficient of chloride ions



**Fig. 7.** Comparison of bilateral chloride penetration and unilateral chloride penetration.

of the concrete layer is just the value determined above. As for the chloride diffusion coefficient of mortar layer, Jensen et al. [29] suggested that when the water-cement ratio equals 0.3 and the temperature equals 20 °C, the diffusion coefficient of mortar layer can be taken as  $D_1 = 3.4 \times 10^{-6} \text{mm}^2/\text{s}$ . The position where the diffusion coefficient changes generally does not exceed the position of half thickness of the PHC pile wall. Therefore, the radial distance of the boundary between the mortar layer and the concrete layer,  $m$ , is taken as 90 mm, 100 mm, 110 mm, and 115 mm, respectively, for analysis. Note that when  $m = 80$  mm, there is no mortar layer and the effect of concrete stratification can be neglected. Fig. 8 shows the effect of concrete stratification on the diffusion of chloride ions in the PHC pile exposed to the marine environment for 10 years. It can be observed that the chloride ion concentration shows an obvious increase trend with the increase of mortar layer thickness, because the mortar layer owns a larger chloride diffusion coefficient. This phenomenon indicates that the concrete stratification due to the centrifugal process has a significant effect on the diffusion of chloride ions in PHC piles, which should be given priority to when designing PHC piles in the marine environment.

The average temperature of most regions in China varies between 10 °C and 25 °C. Therefore, assuming that the temperature at the outer surface of PHC pile is equal to 10 °C, 15 °C, 20 °C, and 25 °C, respectively, the corresponding temperature correction coefficients obtained from Eq. (39) are equal to 0.56, 0.75, 1.00 and 1.32, respectively. Here, only temperature correction is taken into account and thus Eq. (30) is adopted to estimate the chloride diffusion in the PHC pile, which is shown in Fig. 9. It can be found that as the temperature increases from 10 °C to 25 °C, the correction coefficient increases by a factor of 2.43 while the chloride ion concentration at the central position of PHC pile wall increases by a factor of 5.23 when the diffusion time equals 10 years. In addition, as the diffusion time increases to 30 years, the temperature effects become more significant. Therefore, it can prove that the temperature strongly affects the chloride diffusion in PHC piles and when estimating the service life of PHC piles in the diffusion period, the diffusion coefficient should be corrected based on the local temperature.

The building code [30] states that the chloride ion concentration in prestressed concrete structures should be less than 0.01%. Therefore, the initial chloride ion concentration in the PHC pile,  $C_0$ , can be taken as 0.01%. Fig. 10 shows the diffusion of chloride ions in the PHC pile considering the initial chloride ion concentration. It can be seen that within the range of initial chloride ion concentration suggested by the building code, the initial concentration has little effect on the chloride diffusion in the PHC pile; moreover,

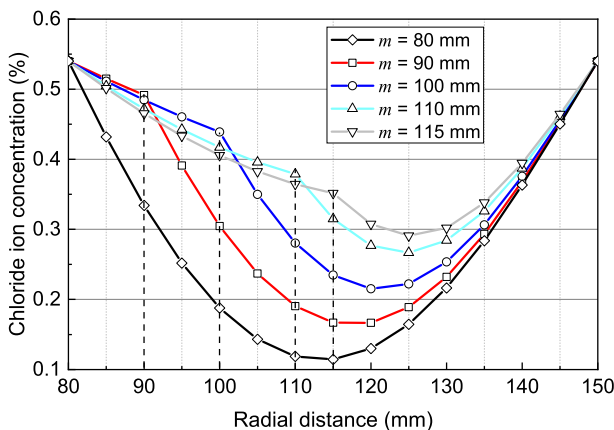


Fig. 8. Effects of mortar layer thickness on chloride diffusion in PHC pile (10 years).

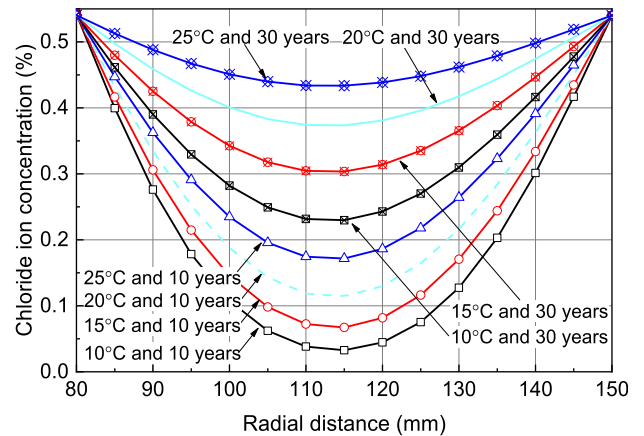


Fig. 9. Effects of temperature on chloride diffusion in PHC pile.

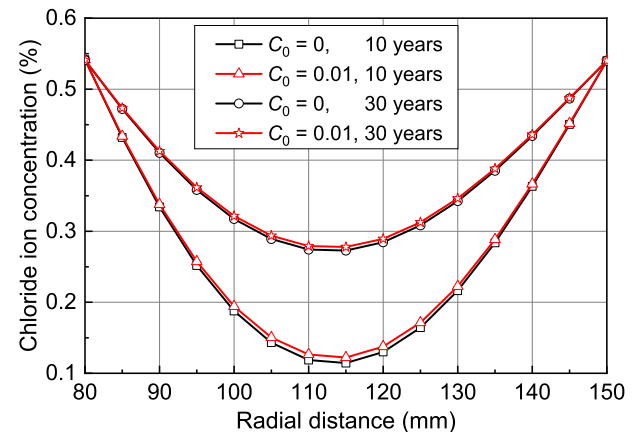


Fig. 10. Effects of initial chloride ion concentration in PHC pile on chloride diffusion.

with the increase of diffusion time, the difference between the chloride ion concentrations decreases. Therefore, when estimating the service life of PHC piles, there is no need to consider the effect of initial chloride ion concentration in PHC piles, on condition that the initial chloride ion concentration is within the range suggested by ACI [30].

#### 4. Experimental verification

The service life of PHC piles in the diffusion period predicted by the proposed method is compared with the experimental results so as to examine the validity. The type of PHC pile chosen for verification is the PHC 300 pile, the mixture proportion of which is summarized in Table 4. To simulate the PHC pile in the marine environment, the pile was completely immersed in the 5% NaCl solution for 180 days. This concentration of NaCl solution can ensure that after 180 days the chloride concentration of PHC pile specimen can be large enough for measuring. Note that the NaCl solution, instead of the simulated seawater, is employed in this study, the reason of which is that only chloride-induced corrosion is taken into consideration, while the simulated seawater consists of other corrosive ions, like sulfate ions that can also lead to concrete corrosion. After the immersion, the concrete powder samples were obtained by using the rotary impact drill that drilled perpendicular to PHC pile surface at each 1 cm along the radial direction and the weight of each powder sample was taken at least 20 g. The

**Table 4**  
Mixture proportion of PHC 300 pile.

Component	Cement	Sand	Aggregate	Water	Additive
Specification and variety	P.052.5	Medium	5 mm–25 mm	Drinking water	DN-IIIIV
Mixture ratio	1	1.748	2.852	0.28	0.018
Quantities of materials for 1 m <sup>3</sup> of concrete (kg)	420	734	1198	118	7.56

samples were then put into the distilled water for 48 h for extraction. The reason for using the distilled water is to avoid additional chloride ions from undistilled water that can increase the measured chloride content and lead to the overestimation of the chloride contents in the concrete powder samples. Then, the chloride concentrations at different radial locations of the PHC pile were measured using the rapid measuring instrument for chloride ion of concrete. The instrument model is CABR-RCTF developed by China Academy of Building Research and the working mechanism of the instrument is based on the electrode-based standard curve method. The chloride ion concentrations at the pile inner and out surfaces were determined by measuring the chloride ion concentrations of the concrete powder samples taken from 1 mm to 3 mm depth of pile surfaces (see Fig. 11), which are 0.398% and 0.114%, respectively. The concentration of inner surface is about four times of outer rates, which indicates a great difference on the accumulation rates of chloride ions at the inner and outer surfaces. The measured chloride ion concentrations are shown in Fig. 12, which illustrates that at the radial distance of  $r = 105$  mm there is a significant change. Therefore, it can be regarded as that this place ( $r = 105$  mm) is the boundary between mortar and concrete layers. The chloride ion concentrations predicted by the proposed method are also drawn in Fig. 12. It can be found that a good agreement is shown between the predicted and measured results. Hence, the proposed method can reasonably predict the service life of PHC piles in the diffusion period.

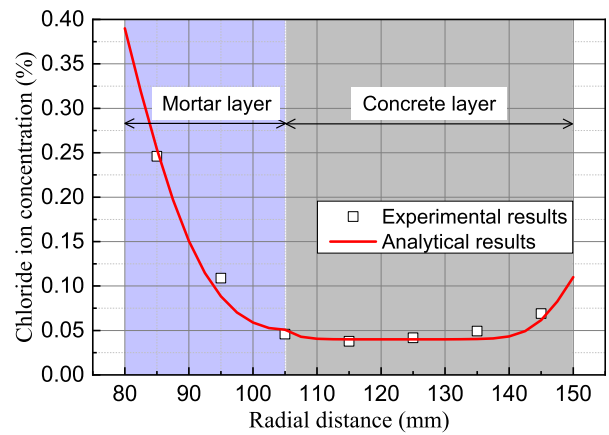
**5. Prediction on service life of PHC piles**

*5.1. Prediction on service life of PHC piles in diffusion period*

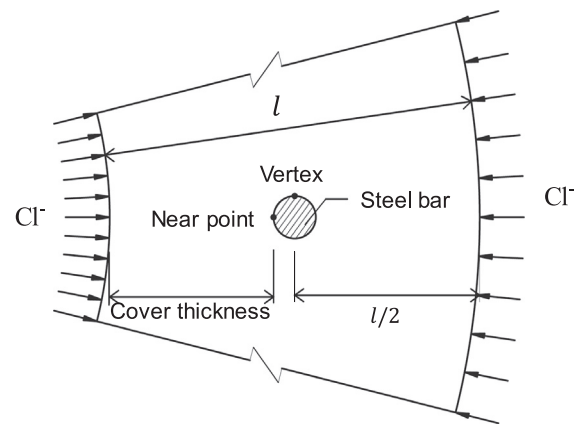
For unilateral chloride diffusion problem, the concrete protective cover is generally taken as the diffusion depth of chloride ions. However, the diffusion in PHC piles is a bilateral chloride diffusion problem and thus the corrosion location needs to be determined at first because of the blocking effect of steel bar. To determine the corrosion location, the chloride ion concentrations varying with the diffusion time are calculated at the near point and vertex of steel bar. The locations of near point and vertex are denoted in Fig. 13. It can be observed from Fig. 14 that the chloride ions accumulate more rapidly at the near point than at the vertex no matter whether there is the steel bar, because the near point is closer to



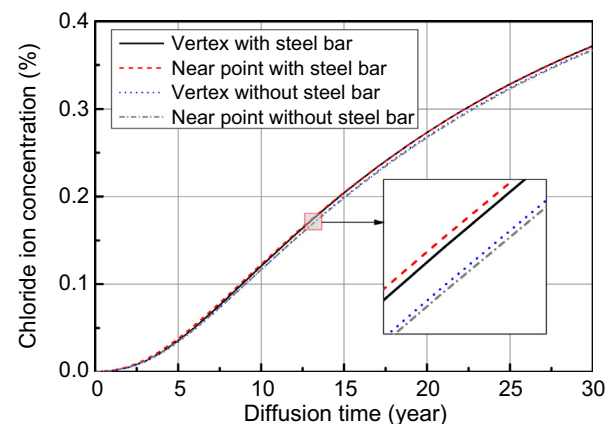
**Fig. 11.** Photo for sampling from test specimen.



**Fig. 12.** Comparison of chloride ion concentrations from proposed method and experimental measurements in diffusion period (180 days).



**Fig. 13.** Schematic of chloride penetration in PHC pile.



**Fig. 14.** Blocking effect of steel bar on chloride diffusion in PHC pile.

the penetration surface than the vertex. However, it is worth noting that the difference between them is small and the variation trends are the same. Therefore, it is more conservative and safer to adopt the vertex as the corrosion location for estimating the service life of PHC piles in the diffusion period. Moreover, given that there is no blocking effect of steel bar at the vertex and there are different types of steel bars for PHC piles, for the simplicity of calculation, the vertex is taken as the corrosion point and half of the pile wall thickness is taken as the calculation length of chloride ion diffusion.

Fig. 15 shows the variation of chloride ion concentration with the elapse of time at the central positions of seven common kinds of PHC pile walls, which are with the thickness of 70 mm, 95 mm, 100 mm, 110 mm, 125 mm, 130 mm and 150 mm, respectively. It is found that the chloride ion concentrations at the central positions increase as time goes on and with the increase of pile wall thickness, the chloride ion concentrations decrease. It is more interestingly noted that when the pile wall thicknesses are close, the corresponding curves of chloride ion concentrations versus time almost coincide with each other. This is because when the wall thickness is determined, no matter what the combination of inner and outer radii is, the eigenvalues of Bessel function are the same, which leads to the same chloride diffusion curves. Therefore, the two kinds of PHC piles, with the wall thicknesses of 110 mm ( $a = 190 \text{ mm}, b = 300 \text{ mm}$ ) and 130 mm ( $a = 170 \text{ mm}, b = 300 \text{ mm}$ ), are adopted to predict the service life of PHC piles in the diffusion period. In the previous section, it can be known that the temperature and concrete stratification greatly affect the diffusion of chloride ions in the PHC pile. Hence, with the diffusion curves of chloride ions considering these two factors, the service life of PHC piles in the diffusion period is estimated, respectively.

Fig. 16 illustrates the prediction on the service life of PHC pile in the chloride diffusion period considering the effects of concrete stratification due to centrifugal process. It can be found that for marine structures whose service life is required to be over 50 years, the wall thickness of PHC piles used for construction should be larger than 95 mm. When employing PHC piles with the wall thicknesses of 95 mm and 100 mm, the thickness of mortar layer should be less than 10 mm. For structures whose service life is required to be over 100 years, PHC piles with a wall thickness larger than or equal to 150 mm and a mortar layer thickness smaller than 30 mm should be chosen. These results demonstrate that although PHC piles have larger strength and higher compactness compared with common concrete structures, but due to the bilateral chloride penetration, the durability of PHC piles is not obviously stronger than common concrete structures. Moreover,

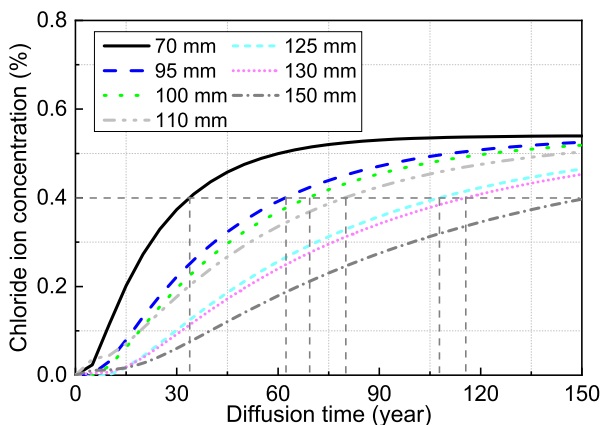


Fig. 15. Effects of pile wall thickness on chloride diffusion in PHC pile.

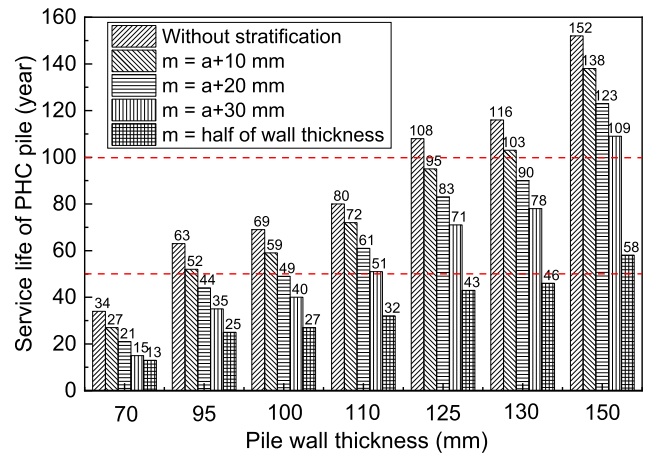


Fig. 16. Service life of PHC pile in chloride diffusion period considering concrete stratification.

when pile wall thickness exceeds 95 mm, each 10 mm increase of the mortar layer thickness gives rise to 10 years decrease of the pile service life. This indicates that the mortar layer thickness significantly affects the durability of PHC piles and thus the quality of centrifugal process should be strictly guaranteed.

Fig. 17 shows the prediction on the service life of PHC piles in the diffusion period considering the temperature correction. It can be observed that for marine structures whose service life is required to be over 50 years in regions where the temperature ranges from 15 °C to 25 °C, the wall thickness of PHC piles should exceed 100 mm; for marine structures whose service life is expected to exceed 100 years, the PHC piles with 150 mm wall thickness should be selected. In addition, it can be noticed that when the pile wall thickness is not less than 95 mm, each 5 °C increase of temperature results in 20 years decrease of pile service life. This proves that the temperature has a great effect on the service life of PHC piles, which is in accordance with the experimental findings presented by Oh and Jang [31].

### 5.2. Prediction on service life of PHC piles in whole period

When predicting the service life of PHC piles without considering concrete stratification, the mortar layer thickness should be taken as 0. Fig. 18 shows the service life of seven common kinds of PHC piles in both of the diffusion and corrosion periods. It can

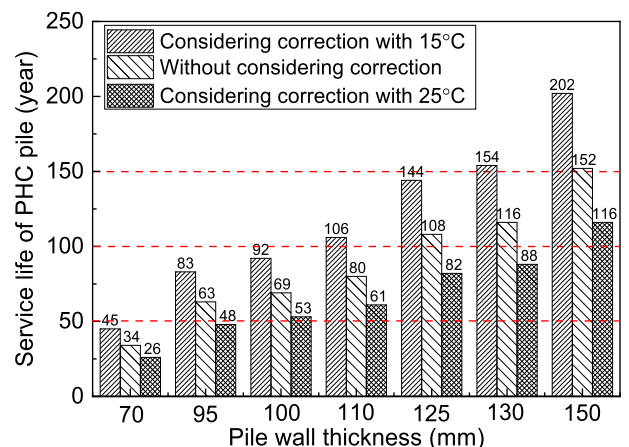


Fig. 17. Service life of PHC pile in chloride diffusion period considering temperature correction.

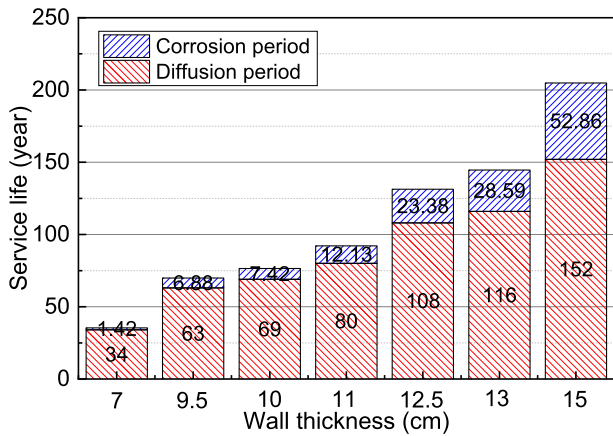


Fig. 18. Whole service life of PHC pile without considering concrete stratification.

be found that the service life in the diffusion period takes the dominant place in the whole service life, while the service life in the corrosion period takes a small part. When the wall thickness varies between 95 mm and 110 mm, the service life in the corrosion period is only about 10% of the service life in the diffusion period. In comparison, when the wall thickness ranges from 125 mm to 150 mm, this proportion increases to the range of 20% to 30%. The pile service life in the corrosion period obviously increases with the increase of wall thickness. Besides, for PHC piles with the wall thickness equal to 70 mm, the service life is only 35.42 years. Therefore, the PHC piles with the wall thickness of 70 mm should not be adopted in the marine environment, if the marine structures are required to be used over 50 years.

The concrete protective cover cannot only prevent the chloride ions from diffusing towards the steel bar, which can help extend the service life of PHC piles, but also can slow down the development of concrete crack from the surface of steel bar to the pile surface. Fig. 19 (a) and (b) show the service life of the seven common types of PHC piles in the diffusion and corrosion periods, respectively. Through data fitting, it can be found that the service life in the diffusion period increases linearly with the increase of concrete protective cover thickness, while the service life in the corrosion period increases exponentially. The fitted equations for the service life in the diffusion and corrosion periods are written, respectively, as below

$$t_1 = -76.47668 + 29.6753T_c \tag{56}$$

$$t_2 = 0.33e^{0.74885T_c} \tag{57}$$

where  $t_1$  and  $t_2$  are the service life of PHC piles in the diffusion and corrosion periods, respectively.

Compared with the concrete layer, the mortar layer has lower compactness and larger chloride diffusion coefficient, which is harmful for preventing the chloride ion penetration and can reduce the service life of PHC piles. Moreover, the tensile strength of mortar is smaller than that of concrete layer, which indicates that the steel bar corrosion can more easily lead to the cracking in the pile inner surface. This can shorten the pile service life as well. Therefore, the mortar layer is a great weakness for the durability of PHC piles and it is of great necessity to explore the effects of the mortar layer thickness on the pile service life. Fig. 20 shows the different service life of PHC piles with different mortar thicknesses that are 1 cm, 2 cm and 3 cm, respectively. It can be found that with the increase of mortar thickness, the service life in both the diffusion and corrosion periods shows a decreasing trend. However, different from the service in the diffusion period, the service life in the corrosion period shows a sharp decline as the mortar

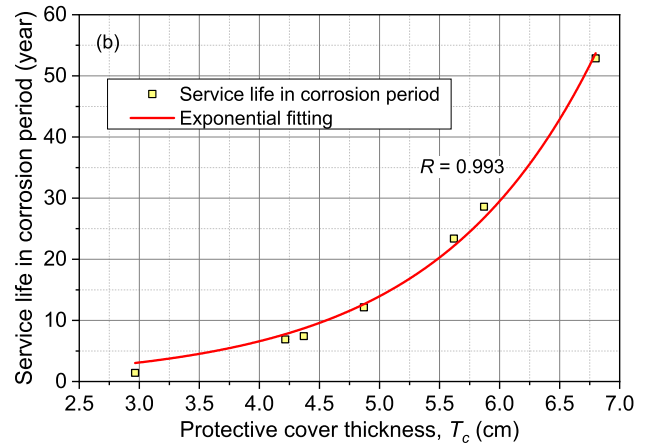
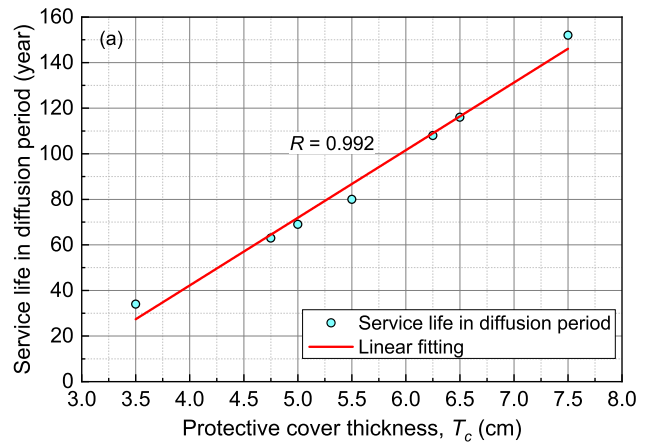


Fig. 19. Effects of protective cover thickness on whole service life of PHC pile: (a) diffusion period; (b) corrosion period.

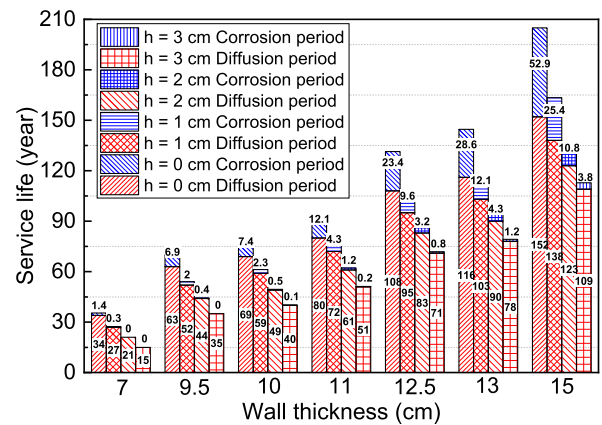


Fig. 20. Effects of mortar layer thickness on whole service life of PHC pile.

layer thickness increases. For concrete structures served in the marine environment, the PHC piles with the wall thickness at least 110 mm should be selected if the required service life of concrete structures are 50 years, and if the required service life is 100 years, the wall thickness of selected PHC piles should be larger than 150 mm.

To extend the service life of PHC piles in the marine environment, there is an economical, effective and simple method that seals the end of PHC piles so as to avoid the penetration of chloride ions into the mortar layer. For closed-end PHC piles, only outer

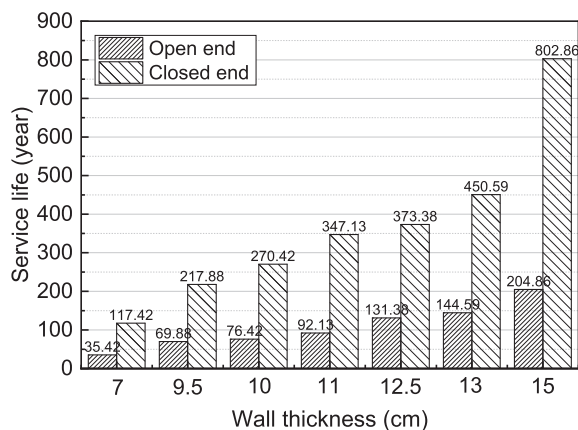


Fig. 21. Effects of open end and closed end on whole service life of PHC pile.

concrete layer will suffer from the chloride attack. Therefore, the proposed method for the service life in the diffusion period is not applicable any more and instead the method presented by Wang [32] should be adopted to estimate the pile service life in the diffusion period. Note that the proposed method for predicting the service life in the corrosion period is not only applicable for open-ended piles but also closed-ended piles. Fig. 21 shows the closed-end effects on the service life of PHC piles. It can be observed that when the end of PHC pile is sealed, the service life will be extended to a large extent. Compared with the open-ended PHC pile, the service life of closed-end pile increases by 3 to 4 times, which illustrates that sealing the ends of PHC piles indeed can effectively extend the service life of PHC piles in the marine environment.

## 6. Discussions and suggestions

After being prestressed, centrifugal processing and steam curing, the compactness and strength of concrete made into PHC piles have been improved significantly and thus theoretically, the chloride penetration resistance of PHC piles should be stronger than that of common concrete structures. However, the ring structure of PHC piles leads to the chloride penetration from both the pile inner and outer surfaces. Under such bilateral penetration condition, on one hand, the chloride penetration rate is greatly increased compared with the chloride diffusion just from the pile outer surfaces, which can significantly reduce the service life of PHC piles; on the other hand, once the chloride ion concentration around the steel bar reaches the critical concentration, the steel bar begins to corrode and the corrosion expansion pressure will lead to the cracking of both inner and outer surfaces if the concrete protective cover is relatively thin. Compared with solid piles that cracking and chloride penetration can only occur at the outer surface, the diffusion rate of chloride ions in PHC piles will be increased a lot and the cracking of both inner and outer surfaces can occur, which will cause great damages to the load carrying capacity of PHC piles. Therefore, as PHC piles are employed in the marine environment, great attention should be paid to the durability design and it is strongly suggested that the pile end should be sealed in case that the sea water enters the hollow space of PHC piles.

## 7. Conclusions

This paper adopted the Fick's second law to develop the diffusion equation of chloride ions in PHC piles, which incorporates the concrete stratification property and the temperature effects of PHC piles. The significance of related parameters was discussed in detail and proper values of the selected key parameters were

determined to predict the service life of PHC piles in the diffusion period. The corrosion expansion mechanism of steel bars was modeled based on the cavity expansion theory and the corresponding ultimate corrosion expansion pressure that gives rise to the cracking occurrence in the protective cover was derived to determine the pile service life in the corrosion period. The conclusions drawn from this study are specifically summarized as follows

- (1) In the marine environment where the temperature difference is within 15 °C, the temperature correction coefficients of the pile inner and outer surfaces are very close to each other and the coefficient difference is within 2 folds. However, when the temperature difference exceeds 15 °C, the temperature correction difference coefficient dramatically increases and low temperature leads to a larger difference between the correction coefficients of pile inner and outer surfaces.
- (2) Both the concrete stratification and the temperature have great influences on the chloride ion diffusion in PHC piles and should be taken into account when predicting the pile service life, while the effect of initial chloride ion concentration of PHC piles can be neglected.
- (3) The mortar layer thickness has great effects on the service life of PHC piles. With the increase of mortar layer thickness, the pile service life in both diffusion and corrosion periods decreases, especially for the service life in the corrosion period. Besides, increasing the protective cover thickness and sealing the ends of PHC piles are two effective approaches for extending the pile service life.
- (4) After well incorporating the effects of concrete stratification and temperature, for concrete structures in the marine environment whose service life is required to be over 50 years, PHC piles with wall thickness large than 110 mm and the mortar layer thickness less than 10 mm should be employed; and for the service life of structures required to exceed 100 years, PHC piles with the wall thickness larger than 150 mm and the mortar layer thickness less than 30 mm should be adopted.

## CRediT authorship contribution statement

**Lin Li:** Conceptualization, Methodology, Software, Writing - review & editing. **Weibing Gong:** Software, Methodology, Data curation, Writing - original draft. **Jingpei Li:** Conceptualization, Supervision, Funding acquisition, Writing - review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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