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The Effect of Shape on Chloride Penetration of Circular Reinforcement Concrete Columns and Its Durability Design

Gu Yin * and Li Pan

College of Civil Engineering, Fuzhou University, Fuzhou 350108, China; lipan121121@163.com
* Correspondence: cinoa@fzu.edu.cn; Tel.: +86-13305912728

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Abstract: The reinforced concrete (RC) circular element is usually simplified as slab one on the issue of chloride diffusion simulation, without considering the effect of the geometrical shape. In the paper, a modified slab diffusion model is proposed for circular section. A formulation for estimating the error caused by neglecting the effect of shape on chloride diffusion is derived. The formulation demonstrates that radius significantly affect the error. When shape is neglected, the effects of model parameters, including the diffusion coefficient, radius, cover concrete thickness and age factor, on the corrosion initiation time are investigated. The result shows the radius has a slight effect on calculating the corrosion initiation time compared with other model parameters. Furthermore, the influence of shape on estimating on reliability index for different service time is also discussed. A guideline is proposed for properly using the modified slab diffusion model instead of the original one to predict service life. Finally, the impact of the shape of the RC circular column on the durability design against chloride corrosion is studied. The design result when the column is simplified as a slab element indicates a lower required minimum concrete cover thickness. The minimum thickness should be improved by 5 mm as a conservative choice based on the result of the slab element.

Keywords: reinforced concrete circular column; chloride corrosion; circular diffusion model; durability design

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1. Introduction

Reinforced concrete circular columns are widely used for infrastructure construction. The columns exposed to the marine environment without added protection are continuously affected by chloride corrosion [1]. Corrosion activates the degradation of materials, causing loss of the bearing capacity of the column. The existing literature reported that a large cost of repair and replacement of US bridges every year are due to corrosion [2]. For the purpose of reducing the economic loss and insuring service security, predicting the chloride concentration on the surface of rebar during long-term servicing accurately using a reliable diffusion model is crucial.

Collepardi et al. [3] first used the one-dimensional (1D) Fick's second law to obtain a chloride diffusion solution considering a constant diffusion coefficient. Mangat and Molloy [4] found a power law relationship between the diffusion coefficient and concrete age. They considered the diffusion coefficient as variable with time, updating and improving the 1D diffusion mathematic model. On the basis of this new diffusion model, several modified diffusion models are currently applied for the estimation of chloride penetration. For example, in the Duracrete report, a simplified 1D diffusion mathematical model considering the environment, test, and execution factors into diffusion coefficients was adopted as the basic model in durability design [5]. This diffusion model in the Duracrete report is also widely used to predict the time to corrosion initiation of RC structure subject to chloride corrosion [6,7]. Costa and Appleton [8] modified the model considering the surface chloride concentration as time-dependent parameter. Andrade et al. [9] also developed the model considering the effect of concrete skin on diffusion mechanism.

Obviously, numerous slab diffusion models based on 1D coordinates are available. However, in recent years, researchers are continuously clarifying the impact of the surface geometry element on chloride diffusion. Val and Trapper [10] employed finite difference (Crank–Nicolson) based on the two-dimensional (2D) Fick's second law to calculate the probability of corrosion initiation in each bar inside a rectangular cross-section. The developed computer program replaces the difficult metathetic solution method with finite element analysis (FEA), which is effective in simulating chloride diffusion in an irregular section. Muthulingam et al. [11] adopted the FEA to describe chloride diffusion in a rectangular cross-section, obtaining the non-uniform corrosion state of rebar encased in concrete. Shafei et al. [12] estimated the corrosion initiation time of rebar in an RC circular column with three-dimensional (3D) coordinates using the same analysis method. Hu et al. [13] used the FEA to calculate the chloride concentration distribution of prestressed T-beam. For an RC structure, the achieved construction quality usually involves high scatter and variability. Meanwhile, the surrounding environment affects chloride penetration through concrete steadily. A probability-based estimation of the chloride diffusion process is necessary. Compared with FEA, a concise mathematical diffusion model is more convenient in achieving this. For a circular section, Morga and Marano [14] proposed a circular diffusion formulation dependent on Fick's second law with polar coordinates, assuming a constant diffusion coefficient. The results showed that for a circular RC section, the chloride concentration estimated by the circular diffusion model is higher than that estimated by the slab model for the same position. Nevertheless, the earlier experimental study has revealed that the diffusion coefficient was a time-dependent variable [15]. Nilsson et al. [16] gave a detailed explanation about the character of the diffusion coefficient in term of long-term transport processes. Song et al. [17] pointed out that the diffusion coefficient decreases with time because of further hydration of the cement. On the basis of field investigations of six coastal concrete bridges of different ages built using ordinary Portland cement, Pack et al. [18] used regression analysis to prove that the diffusion coefficient strongly depends on time and decreases with age. Wu et al. [19] found that the diffusion model considering the diffusion coefficient as a function of time fits data measured in a filled well. As for the slab diffusion model, the circular diffusion model proposed by Morga and Morano [14] still requires improvement.

The durability design issue of an RC structure near a marine environment remains a growing concern. Significant research has been conducted for more rational chloride diffusion simulation. At the preliminary stage, the durability design, usually dependent on a prescriptive (deemed-to-satisfy) approach, is used in most design codes (ACI 2005; CNS 2008; CEN 2002) [20–22]. The improvement of the research on topic of chloride corrosion promotes the use of a probability-based approach. A chloride diffusion model as a basic design model in this approach significantly influences the durability design result. However, the slab diffusion model is commonly applied for RC elements on the durability design. The effect of the shape of the RC circular column on the design result requires further investigation. In this paper, considering time-dependence and shape effect, a basic diffusion model of chloride penetration in an RC circular column is deduced. The proposed diffusion model for a circular section is compared with the slab diffusion model neglecting the shape effect. The durability design difference between the two models is discussed for an RC circular column.

2. Circular Diffusion Model for a Cross-Section of an RC Circular Column

2.1. Theoretical Derivation

The transport mechanisms for chloride penetration into concrete are rather complicated. In general, diffusion, viewed as the primary avenue, is considered. Chloride diffusion through a circular concrete cross-section is described by Fick's second law in polar coordinates as:

$$\frac{\partial C(\rho,t)}{\partial t} = D(\frac{1}{\rho}\frac{\partial C(\rho,t)}{\partial \rho} + \frac{\partial^2 C(\rho,t)}{\partial \rho^2}) \tag{1}$$

where D is the diffusion coefficient and C (ρ, t) represents the chloride concentration at a distance ρ from the center of the circular section at an instant t.

The initial boundary conditions before chloride diffusion are the following: (a) the chloride concentration is assumed as constant on the external surface of the column $C(R,t) = C_0 t \in [0,+\infty]$, and (b) the initial chloride concentration inside the concrete at time zero is assumed at zero $C(\rho,0) = 0\ t \in [0,R]$.

As the concrete servicing age increases for the situation neglecting the effect of the surrounding, D is expressed as follows [23]:

$$D(t) = D_{\mathrm{ref}}\left(\frac{t_{\mathrm{ref}}}{t}\right)^m = D_{\mathrm{i}} t^{-m} \tag{2}$$

where D_{ref} is the diffusion coefficient at the referenced time t_{ref} and m represents the exponent coefficient.

According to the adaptation of variable separation methodology ($C(\rho,t) = F(\rho)T(t)$) and replacing D with $D(t)$ according to Equation (2), Equation (1) is updated as:

$$\frac{\partial(F(\rho)T(t))}{\partial t} = D_{\mathrm{i}} t^{-m}\left(\frac{1}{\rho}\frac{\partial(F(\rho)T(t))}{\partial \rho} + \frac{\partial^2(F(\rho)T(t))}{\partial \rho^2}\right) \tag{3}$$

Equation (3) is transformed as:

$$\frac{T'(t)t^m}{D_{\mathrm{i}} T(t)} = \frac{1}{F(\rho)}\left(\frac{1}{\rho}F'(\rho) + F''(\rho)\right) \tag{4}$$

The left side of Equation (4) contains a function of t only, and the right side of Equation (4) involves a function of ρ only, with constant λ making Equation (4) true. Therefore, Equation (4) is transformed into a mutually independent unary differential equation expressed as:

$$\frac{T'(t)t^m}{D_{\mathrm{i}} T(t)} = \lambda \tag{5}$$

$$\frac{1}{F(\rho)}\left(\frac{1}{\rho}F'(\rho) + F''(\rho)\right) = \lambda \tag{6}$$

The solution of Equation (5) is obtained as:

$$T(t) = A\exp\left(\frac{1}{1-m}t^{1-m}\lambda D_i\right) \tag{7}$$

Equation (6) is viewed as a Bessel differential equation, and thus, its solution is expressed as:

$$F(\rho) = BJ_0(\lambda\rho) + CY_0(\lambda\rho) \tag{8}$$

where J_0 represents the Bessel's first function with order zero and Y_0 denotes the Bessel's second function with order zero. The parameters A, B, and C are undetermined coefficients, and on the basis of Equations (7) and (8), the specific formulation of $C(\rho,t) = F(\rho)T(t)$ is:

$$C(\rho,t) = A\exp\left(\frac{1}{1-m}t^{1-m}\lambda D_i\right)(BJ_0(\lambda\rho) + CY_0(\lambda\rho)) \tag{9}$$

Furthermore, boundary conditions (a) and (b) are utilized, and the circular diffusion model is expressed as follows:

$$C_{\mathrm{cir}}(x,t) = C_0\left\{1 - \frac{2}{R}\sum_{n=1}^{\infty}\frac{1}{\alpha_n}\frac{J_0((R-x)\alpha_n)}{J_1(R\alpha_n)}e^{-\left(\frac{1}{1-m}\alpha_n{}^2 D_{\mathrm{i}}t^{1-m}\right)}\right\} \tag{10}$$

where $C(x,t)$ represents the chloride concentration at distance x from the external surface at time t, R denotes the radius of the RC circular column, J_1 is Bessel's first function with order one, and α_m depends on the solution of $J_0(R\alpha_m) = 0$.

Assuming that the circular section is oversimplified as a slab element directly, the corresponding slab diffusion model is given as [23]:

$$C_{\mathrm{slab}}(x,t) = C_0\left[1 - erf\left\{x/\left(2\sqrt{\frac{1}{1-m}D_{\mathrm{i}}t^{1-m}}\right)\right\}\right] \tag{11}$$

2.2. Statistical Properties of Model Parameters

The statistical properties of the model parameters involved are closely connected with the environment around the concrete structure, thereby performing greater randomness [24]. In general, the exposure classes of the coastal column are the following: the submerged, splashing and tidal, and atmospheric zones. In the durability design work of the Hong Kong–Zhuhai–Macau (HZM) project against the chloride attack, Li et al. [25] summarized the probability distribution of the surface chloride concentration C_0 and age factor m as presented in Table 1.

Table 1. The statistical distribution of surface chloride concentration and age factor.

Parameters	Exposure Condition	Distribution Type	Mean Value	Standard Deviation
C_0 (%binder)	Atmospheric zone	Lognormal distribution	2	0.31
	Splashing and tidal zone		5.4	0.82
	Submerged zone		4.5	0.68
m	Atmospheric zone	Normal distribution	0.53	0.08
	Splashing and tidal zone		0.47	0.028
	Submerged zone		0.44	0.028

Because of the means of both diffusion coefficient and concrete cover thickness as a design control object, Li et al. [25] modeled the diffusion coefficient with lognormal distribution with a coefficient of variation of 0.2 and concrete cover thickness with normal distribution with a standard deviation of 5.3 mm. To facilitate subsequent analysis, for Portland cement concrete, the mean predicted 28-day diffusion coefficient of concrete is calculated as follows [26]:

$$D_{28} = 10^{-12.06+2.4(w/c)} \tag{12}$$

where D_{28} represents the diffusion coefficient for 28 days of t_{ref} and w/c is the water-to-cement ratio.

2.3. Validation Using a Numerical Model

Effects of zero numbers of zero-order Bessel functions on the accuracy of the circular diffusion model are firstly discussed. The RC circular column with a radius of 50 cm in atmospheric zone is taken as an example, and the w/c for Portland cement type of that is 0.5. According to Equation (12), the mean value of D_{28} is 4.35 cm^2/a. The mean values of C_0 and m selected from Table 1 are 2% of the weight of the binder and 0.53, respectively. The diffusion depth is set at 5 cm. The final analysis result is presented in Figure 1. Figure 1 clearly indicates that the estimation results of the circular diffusion model keep stable when zero numbers exceed 20.

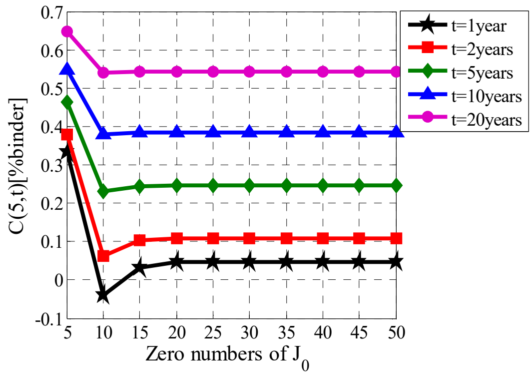


Figure 1. Effects of zero numbers of zero-order Bessel functions J_0 on the accuracy of circular diffusion model.

Transient analysis of the thin material transfer module in the COMSOL Multiphysics software undertakes the simulation of chloride diffusion. Considering concrete material in a section as homogeneous, the comparison between the distribution of chloride concentration at whole section estimated by the numerical model and that estimated by the circular diffusion model is displayed in Figure 2. The result verifies the accuracy and applicability of the circular diffusion model obtained by variable separation methodology.

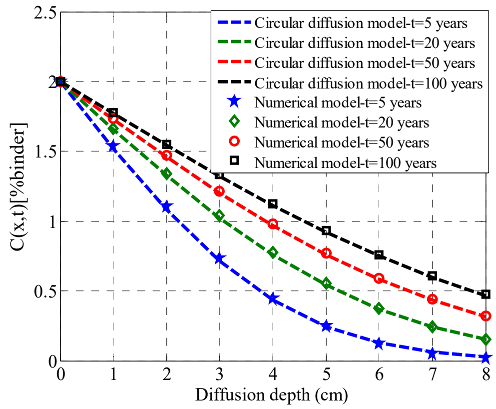
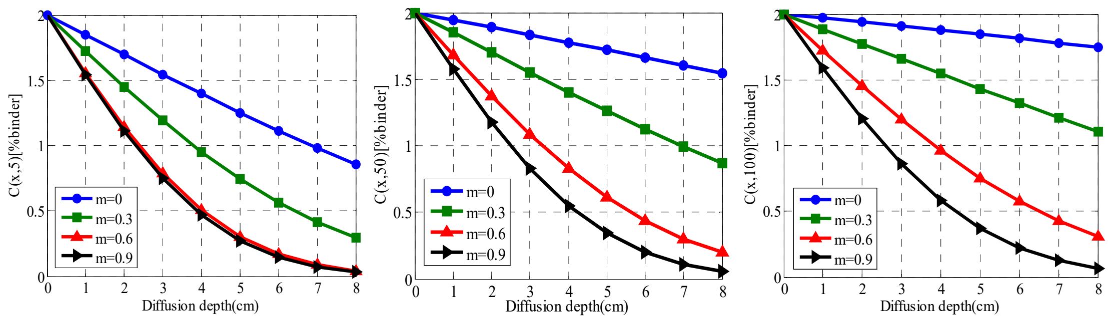


Figure 2. A comparison between the circular diffusion and numerical models.

2.4. The Effect of a Time-Variant Diffusion Coefficient on Chloride Diffusion

The model parameters, including D_{28} and C_0, stay the same as in Section 2.3 with a series of assumed m of 0, 0.3, 0.6, and 0.9. For a given diffusion time, the chloride distribution and the diffusion depth under different m values are exhibited in Figure 3. In particular, the diffusion coefficient attains a constant value over time for m = 0. Clearly, in Figure 3 the distribution of chloride concentration is significantly overestimated at m of 0. The larger diffusion time and smaller age factor the more evident that is. Consequently, it will lead to an underestimation of the service life of the RC column. The higher the m, the faster the diffusion coefficient degrades simultaneously. This explains the lower concentrations at the same diffusion depth for higher m.



(**a**) t = 10 years (**b**) t = 50 years (**c**) t = 100 years

Figure 3. The influence of time-variant diffusion coefficients on chloride concentration distribution.

3. Comparison between Circular and Slab Diffusion Models

3.1. Chloride Concentration Estimation

The sound and reliable estimation of chloride ion concentration on the surface of steel bars is significant. Here, this concentration, labeled C, is compared for estimates from the slab diffusion and the circular diffusion model. The 28-day diffusion coefficient D_{28} is set at 4.35 cm^2/a, with an age factor m of 0.53, and the surface chloride concentration C_0 is assumed at 2% of the binder weight. The effect of the shape on the chloride concentration on the surface of rebar during diffusion process is analyzed, as shown in Figures 4 and 5. Figures 4 and 5 highlight that for an RC circular section, the slab diffusion model underestimates the chloride concentration. As the radius increasing, the difference between the circular diffusion and slab diffusion models deceases gradually, implying that the effect of the circular cross-section diminishes slowly.

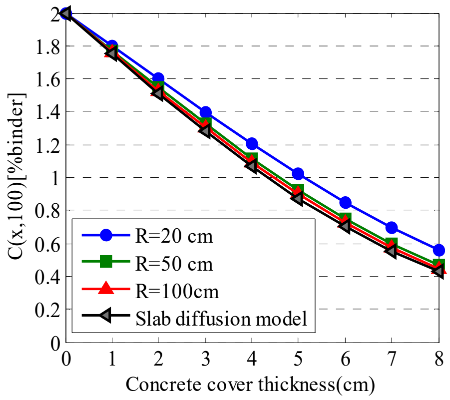


Figure 4. The chloride concentration versus concrete cover thickness at a diffusion time of 100 years.

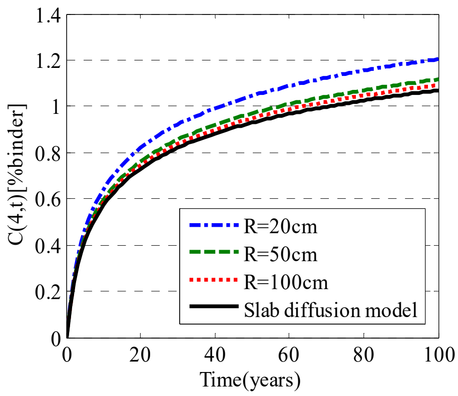


Figure 5. The chloride concentration versus diffusion time at a concrete cover thickness of 5 cm.

For an RC circuar column, C_{cir}/C_{slab} is introduced to measure the error on the work of using the slab diffusion model. The impact of the model parameters on C_{cir}/C_{slab} is disscused according to the sensitivity analysis methodology. Diffusion time, radius of the RC circualr column, and concrete cover thickness are labeled as t, R, and x, respectively. Obvioulsy, according to Equations (11) and (12), it can be found that C_{cir}/C_{slab} has no relation with C_0. The change interval of other model parameters are listed in Table 2. During this analysis, one model parameter varies, with the others kept fixed. The final result is presented in Figure 6. It can be seen in Figure 6 that both higher x and smaller R will lead to the increase in C_{cir}/C_{slab}. Nevertheless, m, D_{28}, and t have a very slight influence on this value. Distinctly, both R and x are more sensitivitive to C_{cir}/C_{slab} than the other model parameters.

Table 2. Parameter value range of sensitivity analysis.

Parameters	Mean Value	Lower Limitation	Upper Limitation
D_{28}	3.435 cm^2/a	2.51 cm^2/a	4.36 cm^2/a
m	0.53	0.37	0.69
R	50 cm	20 cm	80 cm
x	4 cm	0 cm	8 cm
t	50a	0a	100a

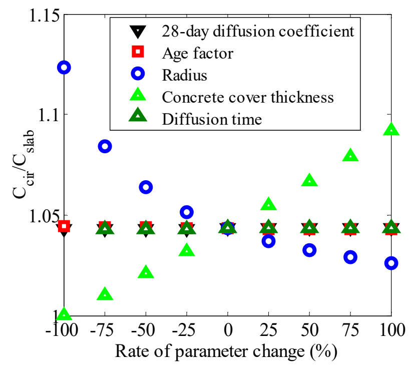


Figure 6. Sensitivity analysis of C_{cir}/C_{slab} with respect to the model parameters.

On the basis of the observation from the sensitivity analysis, C_{cir}/C_{slab} is rewritten as a function using the radius of column and the concrete cover thickness. Assuming that D_{28}, m, t, and R are fixed at the mean value, the C_{cir}/C_{slab} variation against x is plotted in Figure 7. The regression fitting result indicates that C_{cir}/C_{slab} can also be modeled using a linear function. Hence, C_{cir}/C_{slab} is expressed as follows:

$$\frac{C_{cir}}{C_{slab}}(R, x) = k(R) \times x + b(R) \tag{13}$$

where the coefficents k and b are functions with R only.

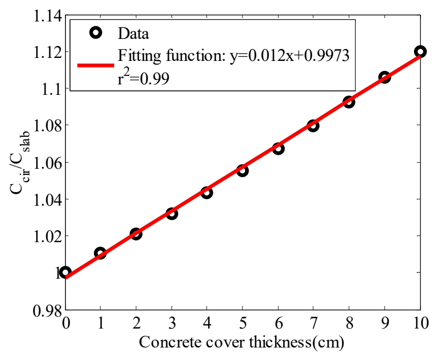


Figure 7. Plot of C_{cir}/C_{slab} versus cover thickness.

Considering a series of R, the values of k and b corresponding to each R are obtained by adopting the same regression fitting analysis with Figure 7. The final results are presented in Figures 8 and 9. In Figures 8 and 9, the specific forms of $k(R)$ and $b(R)$ are expressed after the regression fitting analysis again. Figure 8 shows that the coefficent b varies slightly with R and is simplified as a constant value of 1. Thus, the final form of Equation (13) for calculating $C_{\text{cir}}/C_{\text{slab}}$ is expressed as follows:

$$\frac{C_{\text{cir}}}{C_{\text{slab}}}(R,x) = 1.8R^{-1.3}x + 1 \tag{14}$$

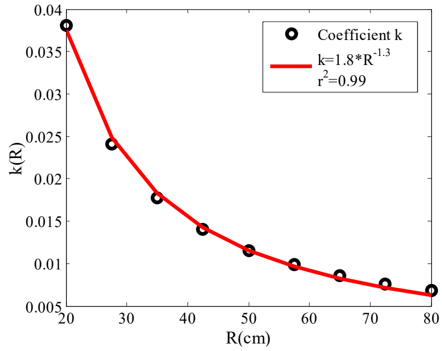


Figure 8. Variation of the coefficient k as a function of radius.

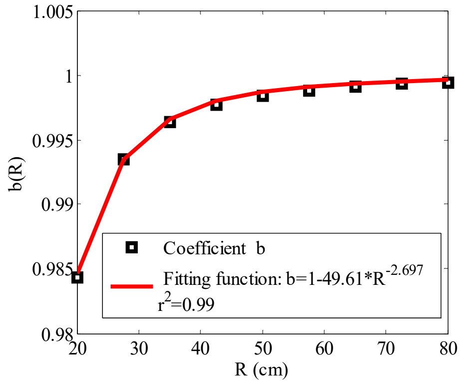


Figure 9. Plot of the concrete b versus radius.

According to Equation (14), the new diffusion model for circular section based on modifying slab diffusion model is expressed as:

$$C_{\text{cir}}(x,t) = K_s C_0 \left[1 - erf\left\{x/\left(2\sqrt{\frac{1}{1-m}D_{\text{i}}t^{1-m}}\right)\right\}\right] \tag{15}$$

where K_{s} represents the shape influence coefficient of circular section, $K_{\text{s}} = 1.8\ R^{-1.3}\ x + 1$.

The error η for using the slab diffusion model in estimating C for the RC circular column is expressed as:

$$\eta_C = 1 - \frac{C_{\text{cir}}}{C_{\text{slab}}}(R,x) = 1.8R^{-1.3}x \tag{16}$$

η_c corresponding to the concrete cover thickness of 4, 5, and 6 cm estimated by using Equation (16), is displayed in Figure 10. Figure 10 shows that the maximum error is over 20%. And for errors within 5%, the modified slab diffusion model (Equation (15)) is preferable for a circular column radius below 60 cm.

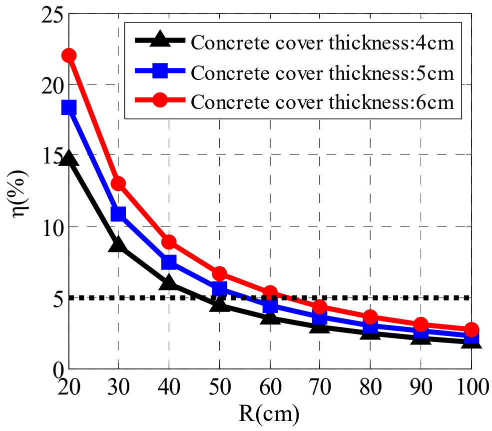


Figure 10. The effect of radius on η_c for different concrete cover thicknesses.

3.2. The Pre-Corrosion Initiation Time for the RC Circular Column

The chloride threshold concentration C_{cr} is closely related to the time required for corrosion initiation of a concrete structure. The JSCE (Japan Society of Civil Engineering) proposed a value of 1.2 kg/m^3 for the C_{cr} [27], but Stewart et al. [24] emphasized that, according to numerous studies, the value ranges from 0.6 to 1.2 kg/m^3. Since this value depends on the steel material, concrete material composition, and external environment, the statistical variation in the property is unsurprising, but highlights the need for further research on the C_{cr}. The C_{cr} applied in the durability design of the HZM project adopted here is summarized in Table 3.

Table 3. The probability distribution of chloride threshold concentration C_{cr}.

Exposure Class	Distribution Type	Mean Value (%Binder)	STANDARD Deviation (%Binder)
Atmospheric zone	Lognormal distribution	0.85	0.13
Splashing and tidal zone	Beta distribution (L = 0.45%, U = 1.25%)	0.75	0.23
Submerged zone	Beta distribution (L = 1%, U = 3.5%)	2	0.72

Note: L represents lower limitation and U represents upper limitation.

During the pre-corrosion initiation period, the chloride concentration at the rebar depth is equal to the C_{cr}. The time to corrosion initiation of RC circular column is calculated by modified slab diffusion model (Equation (15)), which, calculated by original slab diffusion model (Equation (11)), are expressed as:

$$T_{\text{i-cir}} = \left\{ \frac{x^2}{4\left[erf^{-1}\left(1 - \frac{C_{cr}}{(1.8R^{-1.3}x+1)C_s}\right)\right]^2} \cdot \frac{1-m}{D_i} \right\}^{\frac{1}{1-m}} \tag{17}$$

$$T_{\text{i-slab}} = \left\{ \frac{x^2}{4\left[erf^{-1}\left(1 - \frac{C_{cr}}{C_s}\right)\right]^2} \cdot \frac{1-m}{D_{\text{i}}} \right\}^{\frac{1}{1-m}} \tag{18}$$

ΔT_{i} represents the difference value between $T_{\text{i-cir}}$ and $T_{\text{i-slab}}$. A sensitivity analysis of model parameters for ΔT_{i} is also performed. The ranges of the intervals for C_0 and C_{cr} are presented in Table 4, and the ranges of the interval of the other parameters in Table 2 are employed. In Table 4, the mean values of the model parameters are selected from the atmospheric zone, kept the same background with Table 2. The final analysis result is presented in Figure 11. Figure 11 reveals that higher C_{cr}, c, x, and m increase ΔT_{i}, whereas higher C_0, D_{28}, and R decrease ΔT_{i}. Compared with other parameters, R and D_{28} only mildly affect ΔT_{i}.

Table 4. The ranges of parameter values for surface chloride and threshold chloride concentrations.

Parameters	Mean Value	Lower Limitation	Upper Limitation
C_0 (%binder)	2	1.38	2.62
C_{cr} (%binder)	0.85	0.59	1.11

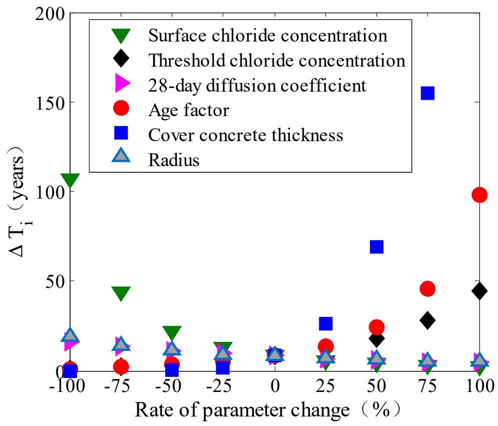


Figure 11. The sensitivity analysis of model parameters for this difference ΔT_i.

3.3. *Durability Design of the RC Circular Column against Chloride Degradation*

3.3.1. Basic Model

For a concrete structure against chloride corrosion, the durability limit states (DLS) is defined as the corrosion initiation state of the rebar. The full probability method is applied on this design. On the basis of Equations (15) and (11), the two different basic design models for an RC circular section under the target life t_d are rewritten as follows:

$$G = C_{cr} - (1.8R^{-1.3}x + 1)C_0\left[1 - erf\left(x/\left(2\sqrt{\frac{1}{1-m}D_i t_{SL}{}^{1-m}}\right)\right)\right] \quad (19)$$

$$G = C_{cr} - C_0\left[1 - erf\left(x/\left(2\sqrt{\frac{1}{1-m}D_i t_{SL}{}^{1-m}}\right)\right)\right] \quad (20)$$

The Life-365 program suggested that for durability design, the decrease law of the diffusion coefficient is truncated once t exceeds 30 years as shown below [26]:

$$D(t)\big|_{t>t_D} = D(t_D) \quad t_D = 30\,\text{years} \quad (21)$$

The reliability index β as an important reference value of assessing the durability performance is calculated as follows:

$$\beta = \Phi^{-1}(1 - p_f) \quad (22)$$

where Φ represents a normal distribution and p_f is the failure probability corresponding to the DLS.

Monte Carlo simulation is adopted to calculate the failure probability. In this method, the sampling is constructed based on the statistical distribution assigned for each random variable. Then, the states of safety and failure are evaluated using Equation (19) or Equation (20) above. Indeed, p_f is calculated using the following expression:

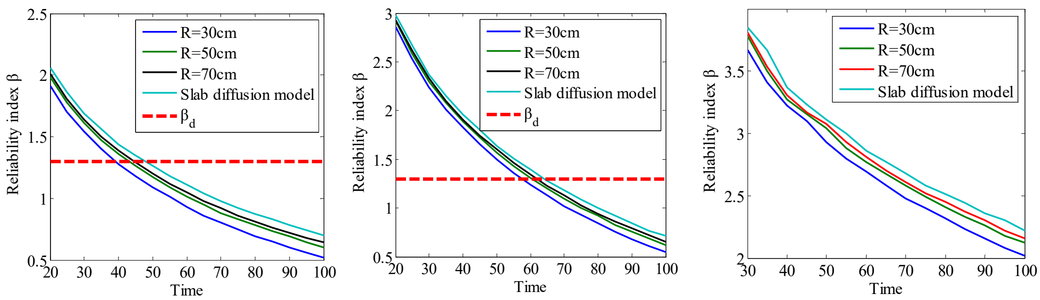
$$p_f = \frac{1}{N}\sum_{i=1}^{N} I(x_i) \quad (23)$$

where N represents the number of samples and the function $I(x_i)$ is:

$$I(x_i) = \begin{cases} 1 & G \leq 0 \\ 0 & G > 0 \end{cases} \tag{24}$$

3.3.2. The Effect of RC Circular Section Shape on the Estimation of Reliability Index

Taking reference on the field research results of Li et al. [28], for splashing, tidal and submerged zones the mean chloride diffusion coefficients of concrete was 2.32×10^{-12} m^2/s and the mean concrete cover thickness was 36 mm whereas the mean chloride diffusion coefficients and concrete cover thickness were 4.38×10^{-12} m^2/s and 52 mm for atmospheric zone. And water/cement ratio used in marine environment is 0.33. The statistical properties of model parameters in Tables 2 and 4 used in the HZM project are suitable for structural concrete having w/c = 0.35. Thus, these model parameters are available for service life prediction of RC circular column. The design reliability index β_d of the RC facilities in the HZM Project was set to 1.3 [29]. The same target reliability index is adopted in this paper. Sampling numbers of 100,000 is generated for Monte Carlo simulation. Under a series of radius of circular section, the reliability index for different service time is calculated, as shown in Figure 12. It can be seen from Figure 12 that the reliability index is overestimated when circular column is regarded as slab element. The data collected in Table 5 indicates that the service life of circular column is also overestimated by slab diffusion model. For the radius of column less 50 cm, the effect of RC circular column shape should be considered.



(**a**) Atmospheric zone (**b**) Splashing and tidal zone (**c**) Submerged zone

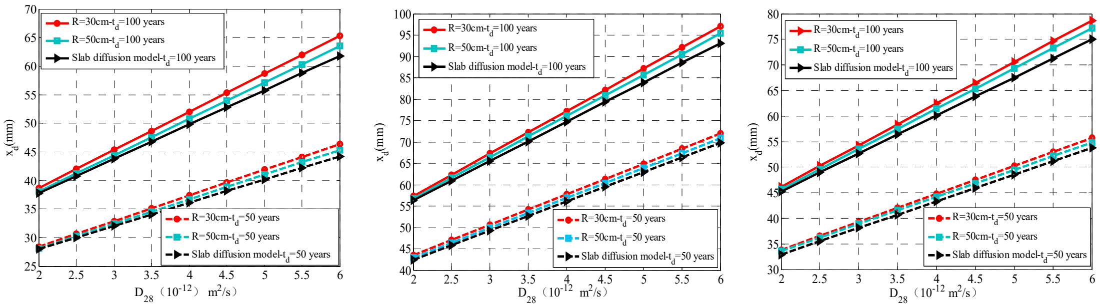
Figure 12. The effect of the shape of circular section on the service life prediction.

Table 5. Service life for different radius of circular section.

Time (Years)	R = 30 cm	R = 50 cm	R = 70 cm	Slab Diffusion Model
Atmospheric zone	39	42	45	46
Splashing and tidal zone	57	60	61	64

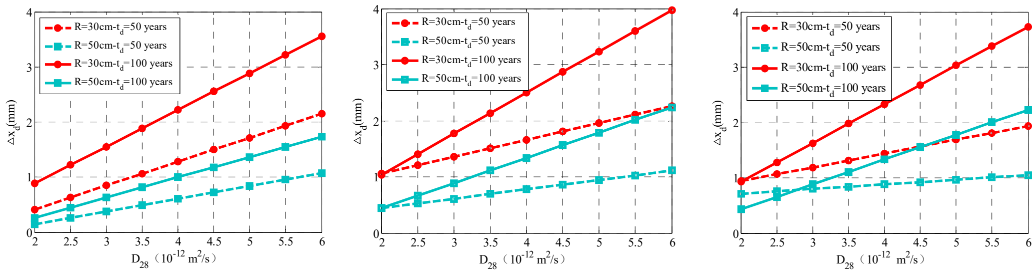
3.3.3. Chloride Diffusion Coefficient D_{28} and Concrete Cover Thickness x_d

Given the design value of the chloride diffusion coefficient D_{28}, the β_d is satisfied by adjusting the minimum concrete cover thickness x_d. The preliminary durability design result of x_d corresponding to a series of D_{28} is shown in Figure 13. Clearly, for the RC circular column, the value of the minimum cover thickness designed by the original slab diffusion model is lower than that designed by the modified slab one. The Δx_d is labeled as the difference between the design values of the minimum cover concrete thickness. Based on Figure 13, the Δx_d as a function of D_{28} is displayed in Figure 14, with an evident linear relationship. Meanwhile, the reduction of the radius also increases the Δx_d. For an expected lifetime of 50 years, the maximum value of Δx_d is 2 mm when the radius is 30 cm. This value increases to 4 mm when the lifetime is 100 years. These data illustrate that the RC circular column shape minimally affects the design results. As a conservative choice, the minimum concrete cover thickness increases by 5 mm based on the design result of the original slab diffusion model.



(**a**) Atmospheric zone (**b**) Splashing and tidal zone (**c**) Submerged zone

Figure 13. Minimum concrete cover thickness as a function of the 28-day chloride diffusion coefficient in different exposure zones.



(**a**) Atmospheric zone (**b**) Splashing and tidal zone (**c**) Submerged zone

Figure 14. The difference between the minimum concrete cover thickness designed by the modified slab diffusion model and the original slab one.

The circular RC column for the atmospheric zone assumes a t_d of 100 years, with a fixed 28-day diffusion coefficient of 6×10^{-12} m^2/a, and the relationship between Δx_d and β_d is shown in Figure 15. Obviously, the effect of β_d on Δx_d can be overlooked.

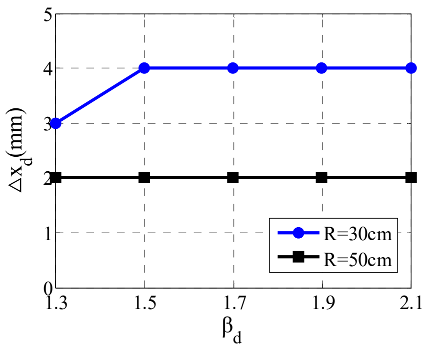


Figure 15. The effect of design reliability index (β_d) on Δx_d.

4. Conclusions

In this study, a circular diffusion model is first deduced by considering the diffusion coefficient as a time-dependent variable. The comparison between the circular diffusion and slab diffusion models in term of chloride diffusion, estimating the pre-corrosion initiation time and durability design are analyzed. Replacing the complicated form of circular diffusion model, a modified slab one for circular section is proposed. The ensuing conclusions are as follows:

(a) The use of a constant diffusion coefficient causes the overestimation of the chloride concentration distribution, shortening the service life of the structure.
(b) The shape of the circular section element accelerates chloride diffusion compared with the slab element. The error caused by adopting the slab diffusion model shows close relationships with the radius and the diffusion depth. The decrease of the radius of column and the increase of the diffusion depth enlarge this error. In general, the modified slab diffusion model is preferable for a radius below 60 cm.
(c) The pre-corrosion initiation time of the RC circular column is underestimated with the slab diffusion model. Each model parameter shows sensitivity for the difference value between the time estimated with slab diffusion model and that estimated for the modified slab one. The shape of the circular section affects minimally the estimation of the time to corrosion initiation compared with other model parameters.
(d) The service life of RC circular column is overestimated when the circular section is viewed as a slab element. The modified slab diffusion model should be used when the radius of the column below 50 cm.
(e) The RC circular section simplified as a slab element slightly affects the durability design against chloride corrosion. The minimum concrete cover thickness increases by 5 mm for the RC circular column based on the design result of the slab element.

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