The Service Life of Circular Section Member under Chlorine Ion Erosion

Ming Zhou*, Jinsong Tu, Qingyun Ge

School of Architecture and Civil Engineering, West Anhui University, Lu'an 237012, China

*Corresponding author e-mail: 349596500@qq.com

Abstract: The concrete structure, when being eroded, suffers premature destruction due to poor durability. This is primarily attributed to overlooking the impact that the shape and diffusion of dimension exert on the chlorine ion diffusion while designing the durability of the concrete structure. The method that is used for calculation of the durability of circular section members under chlorine ion erosion was proposed herein with the service life ending when chloride concentration on the surface of rebar reaches the critical concentration of chloride concentration. Furthermore, efforts were made through giving examples in analysis of the distribution rule of chlorine ion contained in the circular section members when attacked by traditional single-dimension and two-dimension chlorine ions as well as the service life of concrete members with different sections. The examples demonstrate that if circular section members were adopted to design the durability of the concrete structure in resisting chlorine ion erosion, the durability the concrete mix-ratio scheme requires would be extended and achieved, beneficial to making it less difficult to prepare concrete and cutting construction cost. Therefore, it concludes the circular section member is more durable than rectangular section member.

1. Introduction

Owing to its durability, fire resistance and competitive price, concrete has been most widely used among all of the building materials around the world. Unfortunately, such structures as the cross-sea bridge, marine architectures, costal architectures and pile foundation in saline soil in the context of chlorine ion, are frequently subjected to premature damage as a result of chloride erosion. Consequently, the North America and Europe have to devote large sums of money, considerable labors and time to renovate the roads and bridges [1] destructed by chloride erosion, which has aroused great attention from scientific researchers, structure designers, maintainers and owners.
Over forty years of Collepardi et al. [2] firstly proposing the control equation that chloride ion diffuses in the concrete, different methods of numerical computation, test, and durability design have emerged for study of durability of the concrete structure in materials and environment. With respect to materials, Rangaraju et al. [3], Parande et al. [4], Song et al. [5] and other scholars across the world, have get to recognize that mineral admixtures could increase concrete’s capacity to withstand the destruction of chlorine salt, coming up with rational suggestions on mixing admixtures into the concrete. In terms of numerical calculation, Funanshi [6] took the lead in utilizing the finite difference method to analyze the service life of concrete structure influenced by one-dimensional chlorine ion erosion. Yang Lufeng et al. introduced the finite element method [7] and boundary element method [8] to study the law that one-dimension and two-dimension diffusion of chlorine ion follows, meanwhile giving attention to the service life of concrete structure. Bastidas-Arteaga et al. [9], Teng Haiwen et al. [10] analyzed the diffusion law of chlorine ion in the concrete by taking combined environmental factors into account. Despite of the fact that the existing research results have underlain a number of durability norms such as European General Standard [11] United States Standard [12] Japan Concrete Guide [13] and China’s Durability Standard [14-15], the worldwide concrete structures in the context of chlorine salt designed in compliance with these standards are still facing the risk of being eroded. There are two contributors to it: on one hand, the process of chloride diffusion and mechanism is highly intricate, the existing research results have failed to give definite explanation of the effect that various factors have on the service life of concrete; on the other hand, variety in testing methods and difference among them as well as disparity in definition of parameters and value settings have led to man-made degradation of durability in the process of design. Additionally, a part of existing research and durability design have left out the effect that diffusion dimensionality and structure form exert on the diffusion rule of chlorine ion and the service life of the concrete structure.

The concrete structure being attacked by chlorine ion goes through three erosion periods: induction period, development period and destruction period [16]. Given the induction and development periods are very short relative to the induction period [17], it regarded the induction period, that is the period the chloride concentration on the surface of rebar reaches the critical concentration, as the end of the service life of concrete members. The fixed valve method was employed to study the service life of traditional one-dimension, two-dimension and circular section members as well as the capacity of members with different forms in withstanding chlorine ion.

2. Fixed value method for prediction of traditional service life

Traditionally, one-dimension and two-dimension diffusion of chlorine ion in the concrete can be described in Fick’s Second Law [2]:

\[
\frac{\partial C}{\partial t} = D \left( \frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right), C (M \in \Gamma, t) = C_s, C (M \in \Omega, t = 0) = C_0
\]

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\]

In the formula, \( \Gamma \) means exposed surface of the diffuser; \( Q \) diffusion field; \( M \) certain point in the diffuser; \( t \) diffusing time (a); \( C_s \) concentration of chlorine ion on the surface (percentage of chlorine ion in the quality of concrete, %); \( C_0 \) original concentration of chlorine ion (%); \( D \) diffusion coefficient (×10⁻⁸ cm²/s); \( C \) concentration of chlorine ion (%).

When the concentration of chlorine ion in the concrete [18],

\[
C(x, t) = C_0 + (C_s - C_0) \left[ 1 - \text{erf} \left( \frac{x}{\sqrt{4Dt}} \right) \right]
\]

\[
C(x, y, t) = C_0 + (C_s - C_0) \left[ 1 - \text{erf} \left( \frac{x}{\sqrt{4Dt}} \right) \cdot \text{erf} \left( \frac{y}{\sqrt{4Dt}} \right) \right]
\]
The service life \( T_{1D} \) and \( T_{2D} \) of traditional one-dimension and two-dimension diffusion of chlorine ion during induction period are shown below respectively:

\[
T_{1D} = \frac{d^2}{4D_s} \text{erf}^{-1} \left( \frac{C_{cr} - C_s}{C_{cr} - C_0} \right)
\]

(5)

\[
T_{2D} = \frac{d^2}{4D_s} \text{erf}^{-1} \left( \frac{C_{cr} - C_s}{C_{cr} - C_0} \right)
\]

(6)

In the formula, \( d \) means the thickness of the layer protecting rebar (mm); \( C_{cr} \) the critical concentration of chlorine ion (%) when the passive layer of rebar gets damaged.

3. Analytical solution and service life of circular section chloride diffusion

When the periphery (apart from the top and bottom) of the cylindrical concrete member is exposed to chlorine salt, the chlorine ion will get access to the concrete along the cylinder. The diffusion control equation and boundary conditions based on FICK’s Second Law are presented below:

\[
\frac{\partial C}{\partial t} = D \left( \frac{\partial^2 C}{\partial r^2} + \frac{1}{r} \frac{\partial C}{\partial r} \right)
\]

(7)

In the equation, \( R \) means section radius; the boundary and initial conditions are presented below:

\[
C(r = R, t \neq 0) = C_s, \quad C(r, t = 0) = C_0
\]

(8)

The closed-form solution to the distribution and diffusion of chloride concentration in the cylinder is presented below:

\[
C(r, t) = C_s - \sum_{n=0}^{\infty} \frac{2(C_s - C_0)e^{-D\beta_n^2t}}{\beta_n R J_1(\beta_n R)} J_0(\beta_n r)
\]

(9)

In the equation, \( \beta_n \) is calculated from the root of \( J_0(\beta R) = 0 \); 1-order and 2-order Bessel functions of the first kind \( J_0(x) \), \( J_1(x) \) are presented below:

\[
J_0(x) = 1 - \frac{x^2}{2^2 \times (1!)^2} + \frac{x^4}{2^4 \times (2!)^2} + ...
\]

(10)

\[
J_1(x) = \frac{x}{2} - \frac{x^3}{2^3 \times 2!} + \frac{x^5}{2^5 \times (3!)^2} - ...
\]

(11)

Being the monotonic function of \( t \), it is not easy for the equation to express the service life by display. In view of this, the service life \( T_c \) of the circular section member in induction period can be figured out though solving the root of the following equation in numerical method (dichotomy for instance):

\[
C_s - C_{cr} - \sum_{n=1}^{\infty} \frac{2(C_s - C_0)e^{-D\beta_n^2t_c}}{\beta_n R J_1(\beta_n R)} J_0(\beta_n (R - d)) = 0
\]

(12)

4. Analysis of examples

In the example 1, there are various kinds of reinforced concrete cylinders attacked by chloride salt with diameters of 500mm, 700mm, 1000mm, and 2000mm respectively. It assumes that the concrete cylinder is exposed to chlorine ion for 28 days as initial age, the initial concentration of chlorine ion of members
expressed by $C_0$ and the concentration of chlorine ion on the surface expressed by $C_s$ are 0% and 1.0% respectively. The same concrete composition and stainless rebar are introduced. The critical concentration for depassivation expressed by $C_{cr}$ is 0.5% and the diffusion coefficient $D$ is 126.144 mm$^2$/a. The purpose is to get the law that the circular section member, one-dimensional and two-dimensional chloride concentration changes with depth when diffusion time is set 50 years. As shown in the figure 1, it calculates the concentration of the circular section, one-dimensional and two-dimensional chlorine ions at the depth of 50mm and 70mm. In the figure 2 and figure 3, X-coordinate is the distance between points in diffusion filed and the member surface. Two dimension is the closest distance of the point on the rectangular section diagonal away from the neighboring both boundaries. Y-coordinate is concentration of chlorine ion. “C-” in the example means a circular section member with the number behind it representing diameter of section. ID means traditional one-dimensional diffusion. “$C_{cr}$=0.6” is critical concentration limit line. It has calculated the service life of one-dimensional and two-dimensional members and circular section members with different diameters in the equation (5), (6) and (12) herein, the results of which are shown in the table 1.

![Figure 1](image)

**Figure 1** Changing trend of chloride concentration with depth

**Table 1** Service life $T$ of Members with Different Protecting Thickness

| Diffusion type | Service life (a) |
|----------------|-----------------|
|                | d=50mm | d=70mm   |
| C300           | 28.66  | 47.56    |
| C500           | 31.84  | 56.04    |
| C700           | 34.43  | 62.12    |
| C1000          | 37.63  | 72.35    |
| 1D             | 41.83  | 80.00    |
| 2D             | 13.28  | 26.27    |

We can get from the figure 1 that the distribution law governs the chloride concentration of the circular section member when diffusion time is set 50 years. In other words, the chloride concentration at the same depth is decreasing with increasing section diameter, at the same time, lower than one-dimensional concentration and approaching to one dimension. The erosion-caused damage that circular section members
suffer is more than one-dimensional chloride diffusion. This suggest that the member’s appearance and diameter have been left out in the process of durability design and treated the circular section member as one-dimensional chloride diffusion law, thus underestimating chloride erosion and subjecting member structure to nature. Consequently, it is not necessarily guaranteed provide predetermined designed service life to members even though related norms, documents, environmental factors and materials characteristics are all integrated into design and maintenance. In addition, in case of the identical diffusion time, the concentration of traditional two-dimensional chloride diffusion is markedly higher than that of circular section. Given this, when it intends to use the traditional two-dimensional diffusion model and service life model to predict the chloride distribution law and service life of circular section members, it could overestimate chloride erosion, making it more difficult to design marine structure and increasing building cost.

![Figure 2](image1.png)  
**Figure 2** Changing trend of cl− with time at the depth of 50mm

![Figure 3](image2.png)  
**Figure 3** Changing trend of cl− with time at the depth of 70mm

It can be seen from the figure 2 and 3 that the chloride concentration is increasing with time at the depth of 50mm and 70mm. At the earlier period of diffusion, the chlorine ion is coming together at higher speed, but at slower speed over the time. The table 1 tells that on the same conditions, the service life of circular section members is extending with radius increasing and shorter than that of traditional one-dimensional chloride diffusion members. Along with increasing radius, the service life is closing to one-dimensional diffusion members. The service life of traditional one-dimensional chloride diffusion members is far shorter than that of one-dimensional diffusion members and circular section members. The service life of structure sees noticeable increase when protective layers become thicker. When the thickness is increased from 50mm to 70mm, both one-dimensional, two dimensional and circular section members almost double their service life.

The example 2 involves a cross-sea bridge with service life designed 100 years. There are two optional sections for the bridge pier when designed, i.e. 2000mm×2000mm rectangular section and circular section with diameter 2000mm. These two sections are all well meeting demand for carrying capacity. It now asks for optimization of the design program in terms of durability. It has been known that the chloride concentration on the surface of other buildings where the bridge locates is 0.8%. The chloride concentration for depassivation is 0.5% with stainless rebar adopted as materials. The corner part of rectangular section is the area where two-dimensional chlorine ion diffuses and generally stress moves towards. Hence, it is a key
position for durability design. In real cases, more often than not, rebar corrosion in this position results in failure of members as a whole. It is natural to regard initial corrosion time of this position as the end point of service life of rectangular section, which is also case for this example. The diffusion coefficients are $2 \times 10^{-8}$ cm$^2$/s, $4 \times 10^{-8}$ cm$^2$/s, $6 \times 10^{-8}$ cm$^2$/s. The equations (5), (6), (12) herein are utilized to get the tendency of the service life of rectangular and circular section members when the thickness of protective layers is changing. The tendency is represented in the figure 4 where X-coordinate is the protecting thickness and Y-coordinate is the service life of members. “C-” and “R-” in the example mean circular section and rectangular section respectively. The number following them is diffusion coefficient (unit $\times 10^{-8}$ cm$^2$/s).

![Figure 4](image_url) Changing law of service life with changing protecting thickness

![Figure 5](image_url) Changing law of service life with different diffusion coefficient

The figure 4 tells that the durability of circular and rectangular section members is remarkably improved with increasing protective thickness. However, increasing thickness will inflict more cracking risk on members, greatly contributing to diffusion and concentration of chlorine ion in the cracked concrete. So, it is not advisable to provide more thickness to the protective layers of the concrete that does not undergo special treatment and disposition. To ensure a sound durability of buildings being attacked by chlorine ion, it is necessary to focus attention on concrete materials and rational appearance of members. The figure 4 shows that on the condition of the same diffusion coefficients, the service life of circular section members is markedly longer than that of rectangular section. On the condition of the same form, the service life of concrete is obviously extended with diffusion coefficients down. We can understand that the shape design of structure and concrete composition design are of quite importance, not affordable to be neglected.

To get a further understanding of the diffusion coefficient (materials effect) of concrete, when protecting thickness is defined 50mm, 60mm, 70mm, the equations (5), (6), (12) herein are utilized to get the tendency of the service life of rectangular and circular section members with different diffusion coefficients. The tendency is represented in the figure 5 where X-coordinate is diffusion coefficient and Y-coordinate is the service life of members. “C-” and “R-” mean circular section and rectangular section respectively. The number following them is protecting thickness (unit mm). The figure 5 tells that the service life changes dramatically when diffusion coefficient stands between $0.5 \times 10^{-8}$ cm$^2$/s and $1.5 \times 10^{-8}$ cm$^2$/s, and the service life in this range is almost longer than 50 years, especially for the circular section member with the service life approaching to 100a. When diffusion coefficient is more than $1.5 \times 10^{-8}$ cm$^2$/s, yet the service life of members tends to be gentle as the diffusion coefficient is increasing. Meanwhile, the rectangular section
member has a shorter service life than 50a. It is found that with respect to the member that is required to serve longer, concrete disposition have to meet higher demand when rectangular members are adopted. If there is a cap on the protective layer, it is more difficult to collocate concrete. For instance, when protective thickness is 60mm and service life is designed 100a, the limit of diffusion coefficient is $0.9 \times 10^{-8}$ cm$^2$/s, and the value of diffusion coefficient of circular section members is capped at $2.1 \times 10^{-8}$ cm$^2$/s. Although such means as rational concrete disposition could extend the service life of concrete, it would make it tougher for concrete allocation for the members to serve longer if it is designed from the perspective of concrete materials. The accompanying results are adding complexity to construction and more volatile diffusion coefficients of concrete. If the diffusion coefficient is slightly higher than the limited one, premature failure of structure will occur. This is one of the reasons behind premature failure of structure attacked by chlorine ion. Therefore, when it demands longer service life, it is highly advisable to give priority to the shape and rational mix proportion in a view to guarantee higher durability and safe margin, lower building cost and construction complexity to some extent.

5. Conclusion

It proposed the equation calculating and methods figuring out the service life of circular section concrete members in corrosion induction period. The examples herein prove that with radius of circular section increasing, the changing law of chlorine ion with depth is tending to the traditional one-dimensional diffusion law. It is not affordable to overlook the member shape, environment and concrete disposition in designing durability. In case the traditional one-dimensional diffusion model is introduced to predict the service life of circular section members, it would underestimate chloride erosion, subjecting members to risks. In case the traditional two-dimensional diffusion model is used to predict the distribution law of chlorine ion in the circular section member, it would underestimate the capacity of circular sections withstanding chlorine ions.

Through combination of the structure shape and service life of structures with different shapes, it could choose appropriate mixing ratio from allocated concrete for member construction, so as to meet multiple combinations of durability, facilitate concrete disposition and construction and reduce building cost.

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