

PREDICTION OF TIME TO CORROSION INITIATION OF STEEL IN MARINE CONCRETE STRUCTURES

DỰ ĐOÁN THỜI GIAN BẮT ĐẦU XẢY RA ĂN MÒN THÉP TRONG CÔNG TRÌNH BÊ TÔNG
Ở MÔI TRƯỜNG BIỂN

PART I: SENSITIVITY OF CORROSION INITIATION TIME TO CHLORIDE DIFFUSION COEFFICIENT AND CONCRETE COVER DEPTH

PHẦN I: ĐỘ NHẠY CỦA THỜI GIAN BẮT ĐẦU XẢY RA ĂN MÒN ĐỐI VỚI HỆ SỐ
KHUẾCH TÁN CỦA ION CLO VÀ CHIỀU DÀY LỚP VỎ BÊ TÔNG

Phan Cong Thanh, Hoang Thi Bich Thuy
Hanoi University of Technology

ABSTRACT

In this paper, a diffusion based model has been developed to predict time to corrosion initiation of steel in concrete due to chloride. Sensitivity analysis of the model was carried out on input parameters which are chloride diffusivity in concrete and concrete cover depth. It is show that the sensitivity of time to corrosion initiation to chloride diffusion coefficient and concrete cover depth is independent of the ratio of surface chloride content and chloride threshold level. It is indicated that the concrete cover depth has a greater impact on time to corrosion initiation that does the chloride diffusion coefficient. A decrease in th chloride diffusion coefficients is considered as effective way of extending time to corrosion initiation. A decrease of 50% in the chloride diffusion coefficient will lead to an increase of 100% in time to corrosion initiation. However, an increase of 50% in concrete cover depth will lead to an increase in time corrosion initiation by 125%.

TÓM TẮT

Bài báo đưa ra mô hình khuếch tán để dự đoán thời gian bắt đầu xảy ra ăn mòn cốt thép trong bê tông do ion clo. Phép phân tích độ nhạy của mô hình được thực hiện với các thông số đầu vào gồm độ khuếch tán của ion clo vào trong bê tông và chiều dày lớp vỏ bê tông. Kết quả cho thấy độ nhạy của thời gian bắt đầu xảy ra ăn mòn đối với hệ số khuếch tán của ion clo và chiều dày lớp bê tông không phụ thuộc vào tỷ lệ giữa nồng độ ion clo ở bề mặt bê tông và nồng độ ion clo ngưỡng. Ngoài ra, chiều dày lớp bê tông có ảnh hưởng đến thời gian bắt đầu xảy ra ăn mòn cốt thép lớn hơn so với hệ số khuếch tán của ion clo. Việc giảm hệ số khuếch tán của ion clo là biện pháp có hiệu quả để kéo dài thời gian bắt đầu xảy ra ăn mòn cốt thép. Khi giảm hệ số khuếch tán của ion clo 50% sẽ dẫn đến kéo dài thời gian bắt đầu xảy ra ăn mòn thêm 100% nữa. Tuy nhiên, việc tăng chiều dày lớp vỏ bê tông thêm 50% sẽ làm tăng thời gian bắt đầu xảy ra ăn mòn thêm 125% nữa.

I. INTRODUCTION

Corrosion of the steel reinforcement due to the penetration of chloride ions through concrete cover is an issue of primary concerns for reinforced concrete projects such as marine structures, bridges. In order to control this significant problem, numerous innovations in concrete technology have been made. One of these problems includes the development of time to corrosion initiation prediction model.

The time to corrosion initiation prediction model has been proving to be invaluable tools for several reasons. More and more owners want to be assured of the design life of the structure they intend to build. Several

projects in Europe, Asia, and North America have recently included specifications for chloride diffusion and permeability limits in order to achieve required service lives. Predicting the time mostly bases on the assumption of a Fickian process of diffusion. Therefore, there are four governing parameters of this diffusion which include chloride diffusivity in concrete, chloride threshold level of steel in concrete, concrete cover depth, and surface chloride concentration [1-3].

However, a considerable uncertainty may be associated with one or more above identified parameters. This is due to the variability of chloride diffusivity as a result of heterogeneity,

and aging of concrete, variability of concrete cover depth which depends on quality control, workmanship, and size of structures, variability of surface chloride concentration that depends on the severity of the environment, and variability of chloride threshold level that depends on the type of the reinforcing steel, cementing material, test method [4].

Therefore, a sensitivity analysis to assess the impact of uncertainties from the input parameters on the uncertainty of the model output is needed. The sensitivity analysis also provides a ranking of parameter importance. Then, decision makers can give more focus on what parameter to control to achieve a given service life and how to reduce the uncertainties in time to corrosion initiation (T_i). The results of the analysis can provide a valuable insight of corrosion of reinforcing steel in concrete induced by chloride diffusion and its governing parameters. In addition, these results also assist effective design of new structures, as well as optimization of inspection and maintenance of existing structures.

II. DIFFUSION BASED MODEL OF CORROSION INITIATION

2.1 Diffusion of chloride into concrete structures

The corrosion initiation time is defined when chloride concentration at reinforced steel reaches the threshold level. The propagation stage is the period when corrosion process initiates and ultimately damages concrete structures. Chloride diffusion is mass transfer by random motion of free chloride ions in the pore solution. The diffusion rate of chloride is proportional to the concentration gradient and the diffusion coefficient of concrete. The Fick's second law of diffusion can be used to calculate the variation of chloride concentration with time for one dimensional flow, as follows:

$$\frac{\partial C(x,t)}{\partial t} = \frac{\partial}{\partial x} \left[D \frac{\partial C}{\partial x} \right] \quad (1)$$

Under the assumption of a constant diffusion coefficient, constant surface concentration as boundary condition, and the initial condition as $C = 0$ for $x > 0$ at $t = 0$.

Crank's solution to equation (1) is as follow [5]:

$$C(x,t) = C_s \left[1 - \frac{2}{\pi} \int_0^{\frac{x}{2\sqrt{Dt}}} e^{-\eta^2} d\eta \right] = C_s \left[1 - \operatorname{erf} \left(\frac{x}{2\sqrt{Dt}} \right) \right] \quad (2)$$

where:

$C(x,t)$ - The chloride concentration at depth x after time t (mol/cm^3).

C_s - The chloride concentration at the surface (mol/cm^3).

D - The diffusion coefficient (cm^2/s).

t - Exposure time (s).

erf - Error function.

2.2 Corrosion of steel in concrete

The onset of corrosion of reinforcing steel is assumed to start when the concentration of chloride at steel surface reaches the chloride threshold level, C_{th} . At this level, the passive film of steel is destroyed. The duration of the initiation stage is from time zero to the onset of corrosion.

Initiation stage:

$$C(d_c,t) < C_{th} \text{ for } 0 \leq t \leq T_i \quad (3)$$

Onset of corrosion:

$$C(d_c,t) = C_{th} \text{ for } t = T_i \quad (4)$$

where:

T_i - Time to corrosion initiation (s).

d_c - Depth of concrete cover (cm).

C_{th} - Chloride threshold level (mol/cm^3).

Plug (4) into (2) and assume the same initial and boundary conditions, the time to corrosion initiation is derived as follows:

$$T_i = f(C_s, C_{th}, D, d_c) = \frac{d_c^2}{4D \left[\operatorname{erf}^{-1} \left(1 - \frac{C_{th}}{C_s} \right) \right]^2} \quad (5)$$

Due to complexity of the error function and its inverse, a numerical relationship between $\frac{4T_i D}{d_c^2}$ and $\frac{C_{th}}{C_s}$ will be obtained.

III. RESULTS AND DISCUSSION

3.1 Sensitivity of corrosion initiation time

Differential sensitivity is based on a Taylor series to approximate the model under the consideration. The time to corrosion initiation can be described as the following function:

$$T_i = f(C_s, C_{th}, D, d_c) = f(X_1, X_2, X_3, X_4) \quad (6)$$

The input variables are represented by the vector:

$$X = (X_1, X_2, X_3, X_4) \quad (7)$$

The first order Taylor series approximation of T_i can be represented as the following:

$$T_i(X) \cong T_i(X_0) + \sum_{j=0}^4 \frac{\partial f(X_0)}{\partial X_j} (X_j - X_{j0}) \quad (8)$$

The values of the partial derivatives are a measure of the local sensitivity. The equation (8) can be rewritten as the following:

$$\frac{T_i(X) - T_i(X_0)}{T_i(X_0)} = \sum_{j=1}^4 \frac{\partial f(X_0)}{\partial X_j} \frac{X_{j0}}{T_i(X_0)} \frac{(X_j - X_{j0})}{X_{j0}} \quad (9)$$

$$\text{Let } \Delta T_i = T_i(X) - T_i(X_0)$$

$$\Delta X_j = X_j - X_{j0}$$

$$\text{and } T_i(X_0) = T_{i0}$$

Variability of T_i is investigated by changing one parameter at a time and keep the other parameters constant, therefore:

$$\frac{\partial f}{\partial x_k} = 0 \quad k = 1, 2, \dots, n \text{ with } k \neq j$$

$$\text{and } \frac{\partial f}{\partial x_j} = f'(X_j)$$

Therefore, the equation (9) becomes:

$$\frac{\Delta T_i}{\partial X} \frac{X_{j0}}{T_{i0}} = \frac{\partial f(X_0)}{\partial X_j} \frac{X_{j0}}{T_{i0}} = S(X_j) = S_j \quad (10)$$

where S_j is the normalized first order sensitivity coefficient of T_i to X_j , which shows the relative change in T_i that results from a relative change in X_j , while the other parameters are kept constant. A perturbation in X_j should be small, i.e. small fraction of its base value.

$$S_j = \frac{\partial f(X_0)}{\partial X_j} \frac{X_{j0}}{T_{i0}} \quad (11)$$

From equation (11), the first order sensitivity coefficients of T_i to C_s , C_{th} , D or d_c can be calculated as the following:

$$S(d_c) = f'(d_c) \frac{d_c}{T_i} = 2 \quad (12)$$

$$S(D) = f'(D) \frac{D}{T_i} = -1 \quad (13)$$

The first order sensitivity coefficients of T_i to d_c , D are easily calculated and are found to be constant. However, the first order sensitivity of T_i to C_s , or C_{th} are complex functions of variables C_s and C_{th} so it is difficult to calculate ΔT_i from ΔC_s or ΔC_{th} . Another approach is to

consider $\frac{4T_i D}{d_c^2}$ versus $\frac{C_{th}}{C_s}$ as ξ versus γ where $\xi = \frac{1}{x^2}$, $\gamma = 1 - y$, and $y = \text{erf}(x)$. The

numerical relationship between ξ and γ is obtainable as shown in figure 1.

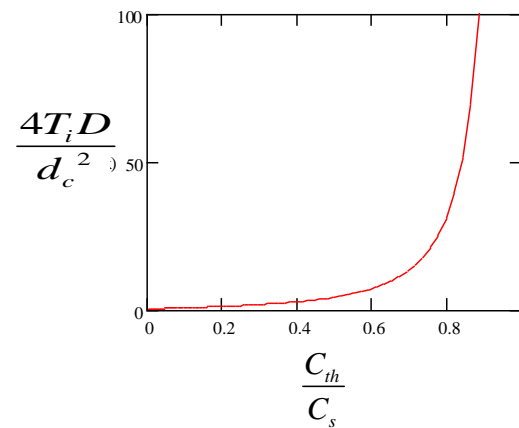


Fig.1 The relationship between time to corrosion initiation and diffusion model parameters

Therefore, $\frac{\Delta T_i}{T_i}$ versus $\frac{\Delta C_{th}}{C_{th}}$ which is equivalent to $\frac{\Delta \xi}{\xi}$ versus $\frac{\Delta \gamma}{\gamma}$ can be determined. The relationship between $\frac{\Delta T_i}{T_i}$ and $\frac{\Delta C_s}{C_s}$ can be obtained with the same approach. It is also easy to derive $\frac{\Delta T_i}{T_i}$ as follows:

$$\frac{\Delta T_i}{T_i} = -\frac{\frac{\Delta D}{D}}{\frac{\Delta D}{D} + 1} \quad (14)$$

$$\frac{\Delta T_i}{T_i} = 2 \frac{\Delta d_c}{d_c} + \left(\frac{\Delta d_c}{d_c}\right)^2 \quad (15)$$

3.2 Sensitivity to chloride diffusion coefficient

The equation (14) shows a relative change in D on T_i . The graph of this equation is illustrated on figure 2.

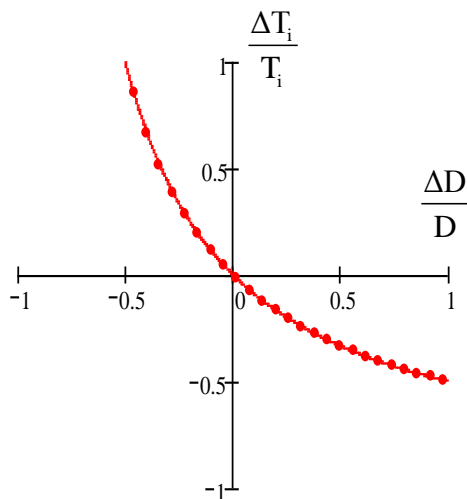


Fig.2 Sensitivity of time to corrosion initiation (T_i) to chloride diffusion coefficient (D)

It is shown that an increase of 50% in D will lead a decrease of -31% in T_i and a reduction of 50% in D will cause an increase

100% in T_i . It also implies that a small decrease in chloride diffusion will greatly extend the time to corrosion initiation.

3.3 Sensitivity to concrete cover depth

The relationship between $\frac{\Delta T_i}{T_i}$ and $\frac{\Delta d_c}{d_c}$ is described in the equation (15). The graph of this equation is plotted in figure 3.

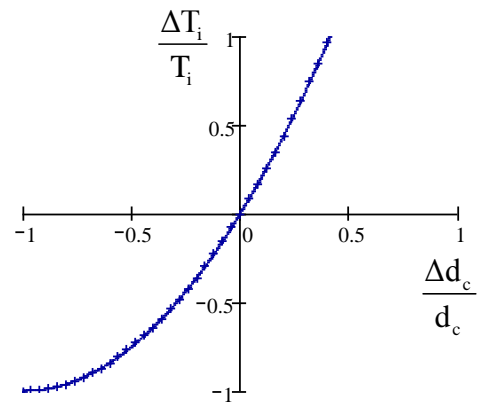


Fig.3 Sensitivity of time to corrosion initiation (T_i) to concrete cover depth (d_c)

From the graph, it is seen that:

- An increase of 50% in d_c will lead to an increase of 125% in T_i , while a decrease of 50% in d_c will cause a reduction of 75% in T_i .
- It is clear that d_c , compared to D, has a greater impact on T_i .

IV. CONCLUSIONS

1. Diffusion based model has been established for prediction of time to corrosion initiation of steel in concrete due to chloride.
2. Sensitivity of time to corrosion initiation to concrete cover and chloride diffusion coefficient are independent of the ratio of surface chloride content and chloride threshold level.
3. The concrete cover depth has a greater impact on time to corrosion initiation than does the chloride diffusion coefficient. A decrease in the chloride diffusion

coefficients is considered as effective way of extending time to corrosion initiation. A decrease of 50% in the chloride diffusion coefficient will lead to an increase of 100%

in time to corrosion initiation. An increase of 50% in concrete cover depth will lead to an increase in time corrosion initiation by 125%.

Acknowledgement

The authors gratefully acknowledge the receipt of a grant from the Flemish Interuniversity Council for University Development cooperation (VLIR UOS) which enabled them to carry out this work.

REFERENCES

1. *Tamer El Maaddawy, Khaled Soudki*; A model for prediction of time from corrosion initiation to corrosion cracking; *Cement & Concrete Composites* 29, pp 168-175 (2007).
2. *Andrea Boddy, Evan Bentz, M.D.A. Thomas, R.D. Hooton*; An overview and sensitivity study of a multimechanistic chloride transport model; *Cement and Concrete Research* 29, pp 827-837 (1999).
3. *G. Morcous, Z. Louni*; Prediction of Onset of Corrosion in Concrete Bridge Decks Using Neural Networks and Case-Based Reasoning; *Computer-Aided Civil and Infrastructure Engineering* 20, pp 108-117 (2005).
4. *Mark G. Stewart, Ali Al-Harthy*; Pitting corrosion and structural reliability of corroding RC structures: Experimental data and probabilistic analysis; *Reliability Engineering and System Safety* 93, pp 373-382 (2008).
5. *J. Crank*; The mathematics of diffusion; Clarendon press, Oxford, 2nd edition (1975).

Contact: Hoang Thi Bich Thuy - Tel: (+84)912.573.910, Email: hbthuy-cprc@mail.hut.edu.vn
Corrosion and Protection Research Center, Hanoi University of Technology
No. 1, Dai Co Viet road, Hanoi, Vietnam