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Revised Model of Chloride Diffusion in Concrete Bridge by Considering Complex Action of Load and Chloride Binding Capacity

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ABSTRACT

Coastal concrete bridges will suffer from deterioration of RC structural performance and resistance attenuation because of the chloride penetration and other environment factors. This article discusses current different chloride diffusion models and puts forward the revised model of chloride diffusion in concrete bridge by considering the complex action of load influence and chloride-binding capacity. Comparison of numerical predicted values and relative experimental tests show the presented chloride diffusion model to be more accurate. It provides a theoretical basis for the performance assessment and accurate prediction of the remaining life of highway concrete bridges.

Keywords: analysis, chloride diffusion, complex action, concrete bridge, revised model.

1. INTRODUCTION

Chloride ion is the main factor affecting the durability of in-service concrete bridge, which leads to rebar corrosion. Rebar corrosion and load variation shorten the remaining useful life of bridges. Konin, Francois, and Arliguie (1998) showed that load level has a significant impact on the penetration of chloride ion. Yoon and Wang (2000) demonstrated that the loading method and load level have an important impact on the corrosion of rebar. Shui (2005) explored the load action that affects the mechanics of chloride diffusion. Currently, the study on chloride ion diffusion is based on Fick's second diffusion law and considers the different factors.

2. THE REVISED CHLORIDE DIFFUSION MODEL

2.1 The existing chloride diffusion model

When all or part of voids of concrete structures are full of water, chloride ions enter into the concrete. Chloride ion penetration occurs by means of the suction of the capillary pore or crack penetration diffusion (Kropp & Hilsdorf, 1995).

Buenfeld, Glass, Hassanein, and Zhang (1998) assumed that chloride diffusion is a physics process, and the diffusion characteristic of materials does not change with time, and the concentration of diffusion, chloride diffusion equation is:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{1}$$

where C is chloride concentration, x is diffusion depth, t is diffusion time, and D is diffusion coefficient.

Costa and Appleton (1999a) assumed that chloride diffusion of solution is a semi-finite and unidirectional process, and that the process corresponds to Fick's second diffusion law:

$$C(x,t) = C_s\left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right] \tag{2}$$

where x, t, D are the same as in Equation (1), C_s is chloride concentration of concrete surface, $erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\,\mathrm{dt}$ is error function.

Based on Fick's second diffusion law, Yu, Sun, and Yan, (2002) deduced the new chloride diffusion equation considering the chloride combining capacity of concrete, time-dependent chloride diffusion coefficient and defects of concrete structure:

$$C_f = C_0 + (C_s - C_0)\left[1 - erf\frac{x}{2\sqrt{\frac{KD_0t_0^m}{(1+R)(1-m)}t^{1-m}}}\right] \tag{3}$$

where C_f is free chloride concentration, C_0 is initial chloride concentration of concrete, t_0 is base time, D_0 is diffusion coefficient corresponding to base time t_0, K is deterioration coefficient of chloride diffusion performance for concrete, R is the combining capacity of chloride (normal concrete, 2–4), and m is the time-dependent coefficient of chloride diffusion.

Based on Fick's second diffusion law, Hao (2004) developed the new chloride diffusion equation considering the stable and unstable environment. Chloride diffusion equation of stable environment:

$$C(x,t)=C_0+(C_s-C_0)\left[1-erf\left(\frac{x}{2\sqrt{k_c D_0 t_0^m t^{1-m}}}\right)\right] \tag{4}$$

Chloride diffusion equation of unstable environment:

$$C(x,t)=k\sqrt{t}\left\{\exp\left(-\frac{x^2}{4Dt}\right)-\left[\frac{x\sqrt{\pi}}{2\sqrt{Dt}}\left(1-erf\frac{x}{2\sqrt{Dt}}\right)\right]\right\} \tag{5}$$

where k is a empirical constant of chloride concentration for the concrete surface, and k_c is a maintenance coefficient.

Considering load factor, Wang (2010) researched the chloride diffusion model in a different environment:

$$C(x,t)=C_0+(C_s-C_0)\left[1-erf\left(\frac{x}{2\sqrt{\frac{f(\delta)D_0 t_0^{\alpha}}{1-\alpha}t^{1-\alpha}}}\right)\right] \tag{6}$$

where $f(\delta)$ is load factor; δ is stress level factor; $\delta=\frac{p}{p_u}$, P is tensile stress of load; p_u is ultimate flexural strength; α is related to water-cement ratio, admixture varieties, quantity, and environment.

Wang, Zhu, and Li (2004) developed the transport model of chloride diffusion theory considering comprehensive influence mechanism, determined the relation of temperature, time and deterioration action, and chloride diffusion coefficient:

$$\rho_f(x,t)=\rho_0+(\rho_s-\rho_0)\left[1-erf\left(\frac{x}{2\sqrt{D^*\cdot t}}\right)\right] \tag{7}$$

$$D^*=\frac{\lambda\cdot D_{ref}}{1+\frac{1}{\omega_e}\cdot\frac{\partial\rho_b}{\partial\rho_f}}\cdot\left(\frac{t_{ref}}{t}\right)^m\cdot\exp\left[\frac{U}{R}\cdot\left(\frac{1}{T_{ref}}-\frac{1}{T}\right)\right] \tag{8}$$

where t_{ref} is initial maintenance age of concrete, T_{ref} is initial temperature of concrete, D_{ref} is a referenced diffusion coefficient, ρ_b is the combining chloride concentration of concrete materials, ρ_f is free chloride concentration of concrete surface in x, ω_e is volume ratio of water content, U is activation energy of diffusion process, R is molar gas constant, and D^* is diffusion coefficient of temperature-time–dependent, chloride combining, and deterioration action.

Considering chloride combining capacity and flaw factor, Xue and Xiang (2010) put forward to chloride diffusion model:

$$C(x,t)=C_0+(C_s-C_0)\left[1-erf\left(\frac{x}{2\sqrt{\frac{KRD_0 t_0^m}{1-m}t^{1-m}}}\right)\right] \tag{9}$$

where the meaning of symbols in Equation (9) is the same as front equations.

2.2 Chloride diffusion model of load factor and chloride combining capacity complex

Buenfeld et al. (1998) proposed chloride diffusion coefficient is constant, but Mangat and Molloy (1994) only considered chloride diffusion coefficient is variation with time.

Here, load factor $f(\delta)$ is introduced into the chloride diffusion coefficient. Hence, the expression is written:

$$D(t)=f(\delta)D_0\left(\frac{t_0}{t}\right)^m \tag{10}$$

In terms of Yu and Xue work, further considering chloride combining capacity R, this article revised model of chloride diffusion, as follows:

$$C(x,t)=C_0+(C_s-C_0)\left[1-erf\left(\frac{x}{2\sqrt{\frac{f(\delta)RD_0 t_0^m}{1-m}t^{1-m}}}\right)\right] \tag{11}$$

where the meaning of c_0, c_s, $erf(x)$, R are the same as in Equation (9); the meaning of $f(\delta)$ is the same as in Equation (6).

2.3 The parameters of the revised model

(1) Load factor $f(\delta)$

To determine the value of load factor under different environments and stress states, He (2004) and Zhang (2001) simulated the experimental results of tidal cycle, sub-water area, and offshore atmospheric zone using quadratic polynomial to obtain the load factors. The relative expressions are shown in Table 1; the sensitive analysis of load factor is shown in Figure 1.

Table 1. Values of load factor.

Environment type	Stress state	$f(\delta)$
Tidal cycle	tension	$f(\delta)=1-0.1296\,\delta+0.8291\,\delta^2$
	press	$f(\delta)=1-1.2463\,\delta+1.9091\,\delta^2$
Subwater zone	tension	$f(\delta)=1+0.3012\,\delta+0.209\,\delta^2$
Offshore atmospheric zone	tension	$f(\delta)=1-0.3781\,\delta+0.5528\,\delta^2$

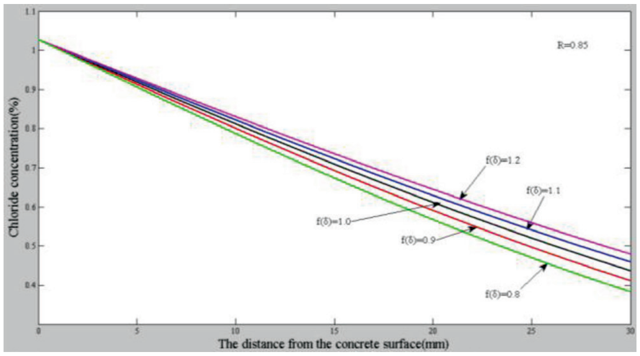


Figure 1. Sensitive analysis of load factor for chloride diffusion model.

Figure 1 gives the relationship of the distance from concrete surface versus chloride diffusion in different load factors. When $f(\delta) > 1$, the rate of chloride diffusion is fast, but when $f(\delta) < 1$, the rate of chloride diffusion is slow.

(2) Coefficient m

Costa & Appleton, 1999b, and BE95-1347 suggested the values for the coefficient *m*, as listed in Table 2.

Table 2. Suggested values of *m*.

Marine environment	Cement type			
	Ordinary portland cement	Flyash	Slag	Silica power
Subwater zone	0.30	0.69	0.71	0.62
Splash zone	0.37	0.93	0.60	0.39
Offshore atmospheric zone	0.65	0.66	0.85	0.79

(3) Chloride combining capacity of concrete R

Experiment and field test results (Mohammed & Hamada, 2003; Zhao, 2004;) showed that $R = 0.77 - 0.89$ for ordinary performance concrete or high performance concrete; when lacking the relative data, we can select $R = 0.85$.

(4) Chloride concentration of concrete surface C_s

Sub-water zone, tidal zone, splash zone, and offshore atmospheric zone have chloride source. Chlorides of sub-water zone in coastal area come from the salt in seawater; chlorides of tidal zone and splash zone come from dry and wet cycles of wave or spray water. Moreover, chlorides of offshore atmospheric zone come from the marine environment. Wang (2010) obtained the expression of chloride concentration of concrete surface and time for splash zone, tidal zone, sub-water zone, and offshore atmospheric zone by means of the number of experimental data and least square method, as listed in Table 3. Table 4 shows the values of chloride concentration for concrete surface of different environments developed by Vu and Stewart (2000). These values are taken to be log normally distributed. Thomas and Bentz (2000) summarized the chloride concentration on the surface of concrete in the sea salt fog area, as listed in Table 5. Concrete standard of civil engineering of Japan (The Chinese Academy of Engineering and Architecture Department in Water Resources, 2004) suggested the chloride concentration on concrete surface in offshore atmospheric zone, as listed in Table 6.

Table 3. Chloride concentration on the surface of concrete member.

Environment	Expression (%)	R^2
Splash zone	$C_s(t) = 0.2265 + 0.1223 \ln(t)$	0.96
Tidal zone	$C_s(t) = 0.3911 + 0.1575 \ln(t)$	0.93
Coastal atmospheric zone	$C_s(t) = 0.1008 + 0.0864 \ln(t)$	0.89
Underwater area	$C_s(t) = 1.938$	

Table 4. Chloride concentration on the surface of concrete member based on Stewart's study.

Environment	Mean (kg/m^3)	CV
Splash zone	7.35	0.70
Offshore atmospheric environment 0.1 km	2.95	0.70
Distance from coast 1 km	1.15	0.50
General atmospheric environment	0.03	0.50

Table 5. Chloride concentration on the surface of concrete (life-365).

Environment	Cumulative rate (%)	Value
Tidal zone/Splash zone	The instantaneous constant value	0.80
Sea salt fog area	0.10	1.0
Distance from coast 800 m	0.04	0.60
Distance from coast 1.5 km	0.02	0.60

Table 6. Chloride concentration on the surface of concrete (Japan).

Splash zone	Distance from coast (km)				
	Near the coast	0.1	0.25	0.5	1.0
0.65%	0.45%	0.225%	0.15%	0.1%	0.075%

Note: Chloride concentration of Tables 5 and 6 is percentage of concrete weight (2300 kg).

2.4 Case analysis

(1) Case 1

In offshore area, a simply-supported bridge –Qinggang Bridge, with spans of 13 + 12 + 12 + 13 m and width of 6 m, was constructed in 1968. The bridge was tested with five samples of chloride ions content. This article analyzed a sample of the outside of the lateral beam and deck water penetration. The parameters of the revised model are listed in Table 7.

Table 7. Parameters in the chloride diffusion model of Qinggang Bridge.

Parameters	Value	Parameters	Value
m	0.65	D_0	1.8×10^{-12} m²/s
R	0.85	t_0	28 d
$C_s(t)$	0.06%	$f(\delta)$	0.9427

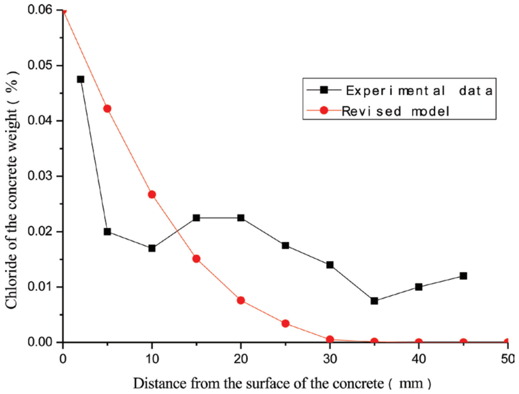


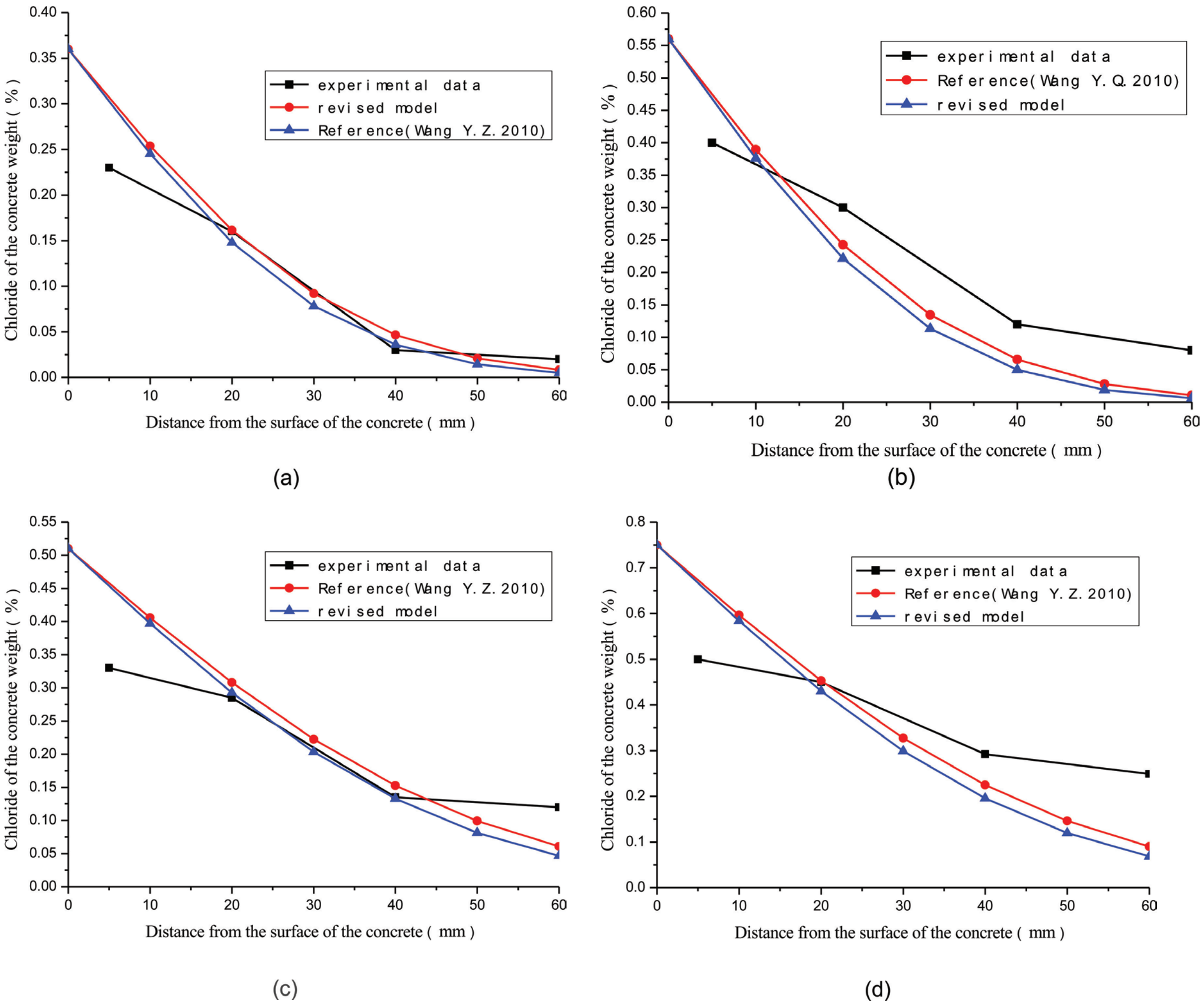
Figure 2. Comparison of testing values and predicted values on chloride content in concrete.

Figure 2 shows comparison of predicted values and testing values. The penetration of deck water leads to a large difference when cover depth is >15 mm.

(2) Case 2

Zhang and Wei (1999) chose the batch of ordinary Portland concrete samples exposed to engineering materials test station of seaport for south China, inspected the samples of continuous 3, 5, and 10 years, and obtained the series of data of relative chloride concentration. The samples were divided into plain concrete and reinforced concrete, which were made in accordance with Specification (JTJ228-87). Test method of chloride content is based on Ref. JTJ225-87. Environment is divided into tidal zone, sub-water zone, and splash zone. The parameters of revised model for tidal zone and splash zone are listed in Table 8. The predicted values are compared with results gained by Wang (2010), and the comparison curves are shown in Figure 3(a)–(d).

It is found from Figure 3 that the prediction values of revised model were close to test values exposed to



(a)

(b)

(c)

(d)

Figure 3. Comparison of testing values and values predicted by the different models in different cases.

splash zone, while the prediction values were different from the test values exposed to tidal zone. Therefore, it is limited only considering chloride combining capacity.

Table 8. Parameters in revised model.

Parameters	Splash zone	Tidal zone
m	0.37	0.37
R	0.85	0.85
$C_s(t)$	0.36, 0.51	0.56, 0.75
D_0	3.48×10^{-12} m^2/s	3.48×10^{-12} m^2/s
t_0	1a	1a
$f(\delta)$	1.0	1.0

3. CONCLUSIONS

This article discusses current different chloride diffusion models, and puts forward the revised model of chloride diffusion by considering the complex action of load influence and chloride binding capacity. The proposed model is verified by the relative testing data. Compared with the traditional single factor model, the revised model of concrete chloride diffusion is more reasonable and accurate. It may be used to predict the remaining useful life of concrete bridges.

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REFERENCES

BE95-1347. (1995). General guidelines for durability design and redesign Brussels, Belgium: European Union.

Buenfeld, N. R., Glass, G. K., Hassanein, A. M., & Zhang, J. (1998). Chloride transport in concrete subjected to electric field. *Materials in Civil Engineering, 10*(4), 220–228.

Costa, A., & Appleton, J. (1999a). Chloride penetration into concrete in marine environment-part II: Prediction of long term chloride penetration. *Materials and Structures, 32*(6), 354–359.

Costa, A., & Appleton, J. (1999b). Chloride penetration into concrete in marine environment-part I: Main parameters affecting chloride penetration. *Materials and Structures, 32*(4), 252–259.

Hao, X. L. (2004). *Durability and service life prediction of reinforced concrete structure exposed to chloride environments* (Master Dissertation). Xi'an University of Architecture and Technology.

He, S. Q. (2004). *Experimental studies on durability of reinforced concrete members in chloride environment*. (Master dissertation). Dalian University of Technology.

JTJ225-87. (1987). *Test method for concrete of harbor engineering*. Industry standard of the People's Republic of China.

JTJ228-87. (1987). *Corrosion prevention specification for reinforced concrete structures of harbor*. Industry standard of the People's Republic of China.

Konin, A., Francois, R., & Arliguie, G. (1998). Penetration of chlorides in relation to the micro-cracking state into reinforced ordinary and high strength concrete. *Materials and Structures, 31*, 310–316.

Kropp, J., & Hilsdorf, H. K. (1995). *Performance criteria for concrete durability*. London, England: E&FN Spon.

Mangat, P. S., & Molloy, B. T. (1994). Prediction of long term chloride concentration in concrete. *Materials and Structures, 27*(7), 338–346.

Mohammed, T. U., & Hamada, H. (2003). Relationship between free chloride and total chloride contents in concrete. *Cement and Concrete Research, 33*(3), 1487–1490.

Shui, J. F. (2005). *Durability study for reinforced concrete bridges exposed in marine environment* (The Master Dissertation). Dalian University of Technology, Dalian.

The Chinese Academy of Engineering and Architecture Department in Water Resources. (2004). The durability of concrete structure design and construction guide. Beijing, China: China Architecture & Building Press.

Thomas, M. D. A., & Bentz, E. C. (2000). Life-365 computer program for predicting the service life and life-cycle costs of reinforced concrete exposed to chlorides. 2 October.

Vu, K. A. T., & Stewart, M. G. (2000). Structural reliability of concrete bridges including improved chloride-induced corrosion models. *Structural Safety, 22*, 313–333.

Wang, R. C., Zhu, L., & Li, Z. F. (2004). A study on multi-nismic chloride diffusion and transport model and sensitivity. *Journal of Harbin Institute of Technology, 36*(6), 824–830.

Wang, Y. Z. (2010). Chloride diffusion model of RC member in various marine environments considering loading effect. *Waterway and Harbor, 31*(2), 125–131.

Xue, P. F., & Xiang, Y. Q. (2010). Corrected diffusion model of chloride in concrete and its engineering application. *Zhejiang University (Engineering Science), 44*(4), 831–836.

Yoon, S., & Wang, K. (2000). Interaction between loading, corrosion and serviceability of reinforced concrete. *ACI Materials Journal, 97*(6), 637–644.

Yu, H., Sun, W., Yan, L., & Ma, H. (2002). Study on prediction of concrete service life I—theoretical model. *The Chinese Ceramic Society, 30*(6), 686–690.

Zhang, B. L., & Wei, S. S. (1999). Test of reinforced concrete structure at sea port of south China exposure ten years. *Port and Waterway Engineering,* (3), 6–13.

Zhang, D. F. (2001). *Durability study of modern PC structure*. Nanjing, China: Southeast University.

Zhao, Y. (2004). Service life design of reinforced concrete structures exposed to chlorine environment. *Concrete, 26*(1), 3–21.