Research Journal of Applied Sciences, Engineering and Technology 5(5): 1786-1790, 2013
DOI:10.19026/rjaset.5.4939
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: July 31, 2012 Accepted: September 03, 2012 Published: February 11, 2013

Research Article

Durability Analysis of Subway Station in Chloride Environment

[1,2]Yang LuFeng, [1]Yu Bo and [1]Hong Bin
[1]Key Laboratory of Disaster Prevention and Structural Safety of Ministry of Education, Department of Civil Engineering and Architecture, Guangxi University, Nanning, 530004, China
[2]Agency of Housing and Urban-Rural Development, Guangxi Autonomous Zhuang Region, Nanning, 530028, China

Abstract: In this study, a finite element model for chloride ions transport in saturated concrete was proposed based on the Fick's second law of diffusion. The governing partial differential equation was solved numerically in space as a boundary-value problem and in time as an initial-value problem by means of the finite element formulations. The maximum allowable value of chloride diffusion coefficient within different locations of subway station with service life of 100a was achieved and suggestions for durability analysis of subway station in chloride environment were also proposed.

Keywords: Chloride attack, concrete durability, diffusion coefficient, subway station

INTRODUCTION

Chloride induced corrosion of reinforcing steel is one of major causes of deterioration of subway station in chloride environment. Chloride ions may be incorporated into concrete from the mix ingredients at the time of manufacture or from external sources, such as deicing salts, seawater and groundwater. Chloride ions transport in concrete is a rather complicated process which involves diffusion, capillary suction, migration in an electrical field, a pressure induced flow and wick action when water absorption and water vapor diffusion (Martin-Perez *et al*., 2001). However, chloride ions transport mainly by the ionic diffusion due to the existing concentration gradient between the exposed surface and the pore solution of cement matrix within the saturated concrete. Conciatori proposed coupled nonlinear partial differential equations to simulate transport phenomena of various substances in concrete based on the Fick's diffusion law and on kinematics equations (Conciatori *et al*., 2008). Oh and Jang (2007) developed a model of chloride penetration into concrete structures taking temperature, age, relative humidity, chloride binding into account. Boddy *et al*. (1999) proposed a multi-mechanistic chloride transport model considering diffusion, convective flow and chloride binding.

Although several numerical models for describing chloride transportation within concrete have been developed, particular durability analysis of subway station in chloride environment is still desirable. In this study, a finite element model for chloride transportation within saturated concrete was proposed based on the Fick's second law of diffusion. The maximum allowable value of chloride diffusion coefficient for different locations of subway station with service life of 100a was achieved and suggestions for durability analysis of subway station in chloride environment were proposed.

CHLORIDE TRANSPORTATION MODEL

According to the Fick's second law of diffusion, the penetration of chloride ion within saturated concrete can be described as:

$$\frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D\frac{\partial C}{\partial y}\right)=\frac{\partial C}{\partial t} \tag{1}$$

where,

C = The chloride concentration (%, mass percent of concrete)
t = The expose time of concrete in chloride environment (a)
x & y = The depths from concrete surface (mm)
D = The chloride diffusion coefficient (mm^2/a)

which can be defined by:

$$D(t)=D_0\left(\frac{t_0}{t}\right)^n \tag{2}$$

where,

Corresponding Author: Yu Bo, Key Laboratory of Disaster Prevention and Structural Safety of Ministry of Education, Department of Civil Engineering and Architecture, Guangxi University, Nanning, 530004, China

D_0 = The reference diffusion coefficient at age t_0
N = The age factor depending on the concrete composition

In order to obtain a solution of Eq. (1), both initial and boundary conditions can be specified as:

$$C(P \in \Omega, t = 0) = C_0 \ ; \ C(P \in \Gamma, t) = C_s \quad (3)$$

where,
C_0 = The initial chloride concentration of model at spatial Ω when time $t = 0$
C_s = The surface chloride concentration of model at boundary Γ

Base on the weighted residual method, Eq. (1) can be rewritten as:

$$\int_{\Omega^e} \omega_i \left[\frac{\partial C}{\partial t} - \frac{\partial}{\partial x}\left(D \frac{\partial C}{\partial x} \right) - \frac{\partial}{\partial y}\left(D \frac{\partial C}{\partial y} \right) \right] \mathrm{d}\Omega = 0 \quad (4)$$

where,
Ω^e = The space of finite element
ω_i = An allowable virtual weight function
Ω = Represents the domain of the problem

By the finite element method, the concentration field and its time derivative may be expressed as:

$$C = \sum_{e=1}^{M} \sum_{i=1}^{n} N_i^e(x, y) C_i^e(t) = \sum_{e=1}^{M} [N]^e \{C\}^e \quad (5)$$

$$\frac{\partial C}{\partial t} = \sum_{e=1}^{M} [N]^e \{\dot{C}\}^e \quad (6)$$

where,
$[N]^e$ = $[N^e_1, N^e_2, \ldots, N^e_n]$ is the element shape function
$\{C\}^e$ = $[C^e_1, C^e_2, \ldots, C^e_n]^T$ is the element nodal concentration vector
N = The number of nodes
M = The number of elements

The variational statement of Eq. (4) is:

$$\int_{\Omega} [N]^T \left[[N]\{\dot{C}\}^e - \frac{\partial}{\partial x}\left([D][B]\{C\}^e \right) - \frac{\partial}{\partial y}\left([D][B]\{C\}^e \right) \right] \mathrm{d}\Omega = 0 \quad (7)$$

where,
[B] = Grad ($[N]^e$)
grad(.) = The grad operator

Assuming that $\{C\}^e$ and $\{\dot{C}\}^e$ do not vary over the element, Eq. (7) may be reduced to:

$$[M]^e \{\dot{C}\}^e + [K]^e \{C\}^e = 0 \quad (8)$$

Table 1: Design parameters of subway station

Parameter	Magnitude	Unit
Initial chloride concentration (C_0)	0.0072	%
Surface chloride concentration (C_s)	0.18	%
Critical chloride concentration (C_{cr})	0.05	%
Age factor (n)	0.2, 0.4, 0.6	-
Concrete cover depth (α)	40, 50, 60	mm

where,
$[M^e] = \int \Omega^e [N]^{eT} [N]^e d\Omega$ is the distribution matrix
$[K^e] = \int \Omega^e [B]^T [D][B] d\Omega$ is the diffusion matrix

The global equations can be set up by assembling the element equations and a system of linear first order differential equations in the time domain can be obtained by:

$$[M]\{\dot{C}\} + [K]\{C\} = 0 \quad (9)$$

where,
$\{C\}$ = The global vector of unknown nodal concentration
(M) = The global distribution matrix
(K) = The global diffusion matrix

The solution of the Eq. (9) can be carried out using following numerical time integration scheme as:

$$\left([M]/\Delta t + \theta [K] \right)\{C_{n+1}\} + \left[-[M]/\Delta t + (1-\theta)[K] \right]\{C_n\} = 0 \quad (10)$$

where,
Δt = The selected time increment
θ = A parameter ranging from 0 to 1.0, depending on the method of integration

DURABILITY ANALYSIS OF SUBWAY STATION

The corrosion process is generally divided into initiation and propagation stages for a complete durability design, only the initiation stage is considered in this study. Corrosion is assumed to initiate when the chloride concentration at the steel layer reaches a specified threshold value. The geometry of a subway station is shown in Fig. 1, while the design parameters are listed in Table 1. Chloride ions transport within three typical locations of subway station is considered, as indicated in Fig. 1.

The finite element mesh and chloride concentration distribution within three typical locations of subway station (denoted as the Case 1, Case 2 and Case 3 respectively) after 100a are shown in Fig. 2. It is clear that the contour line of chloride concentration in the Case 1 is always parallel to the edge of the finite element model, which displays obvious one-

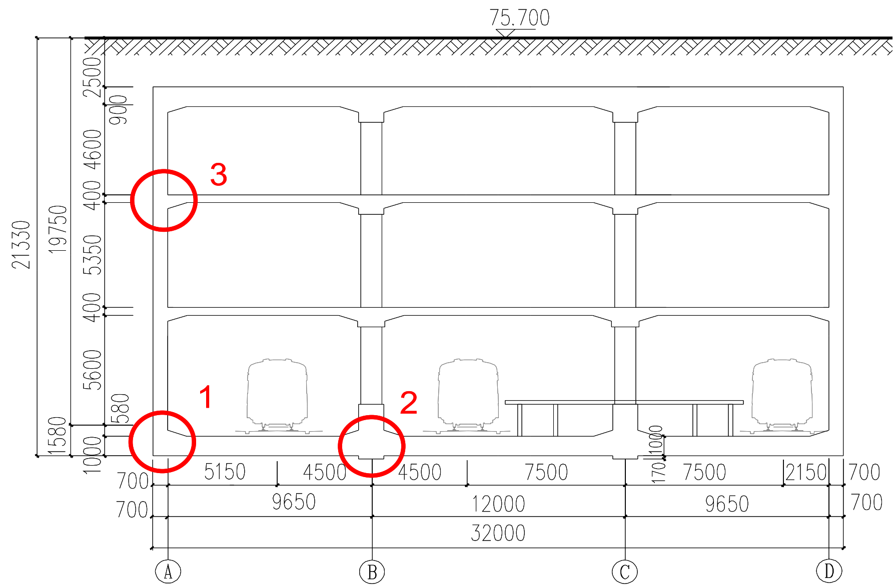


Fig. 1: Cross section of subway station

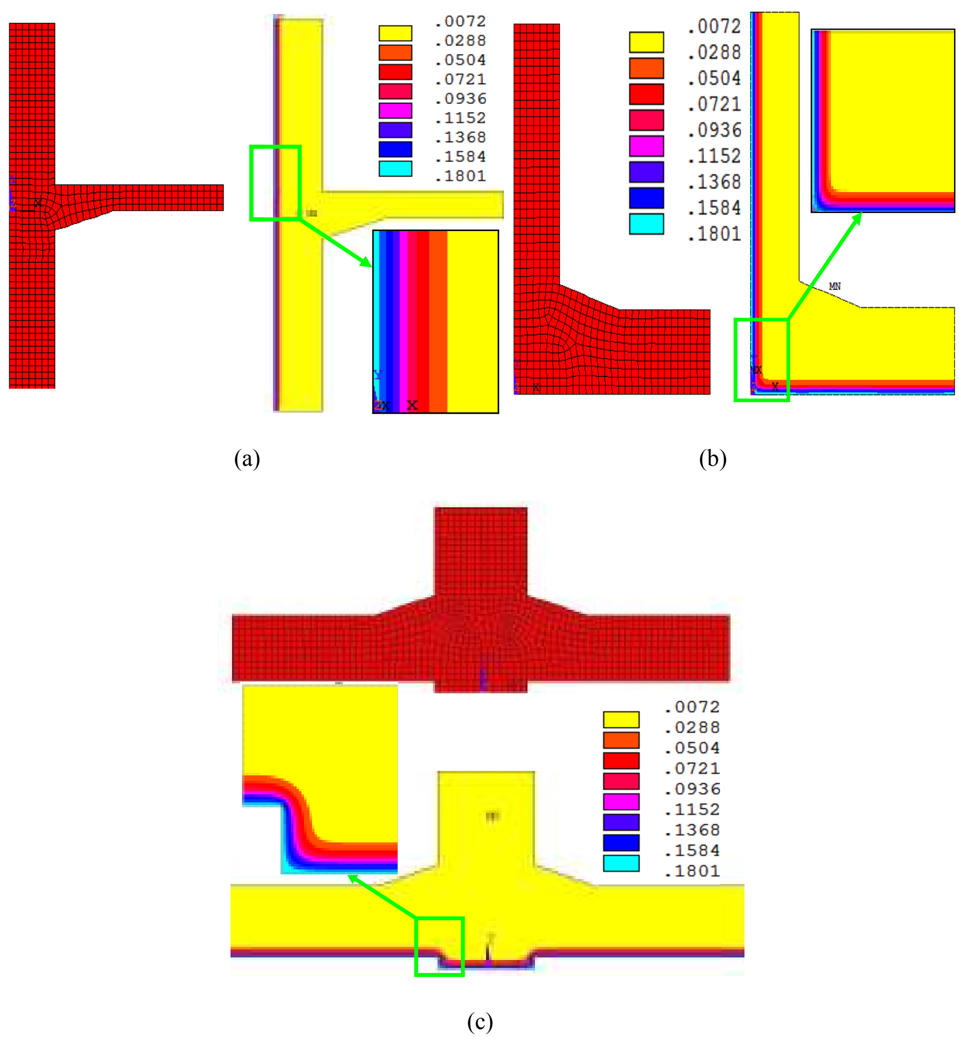
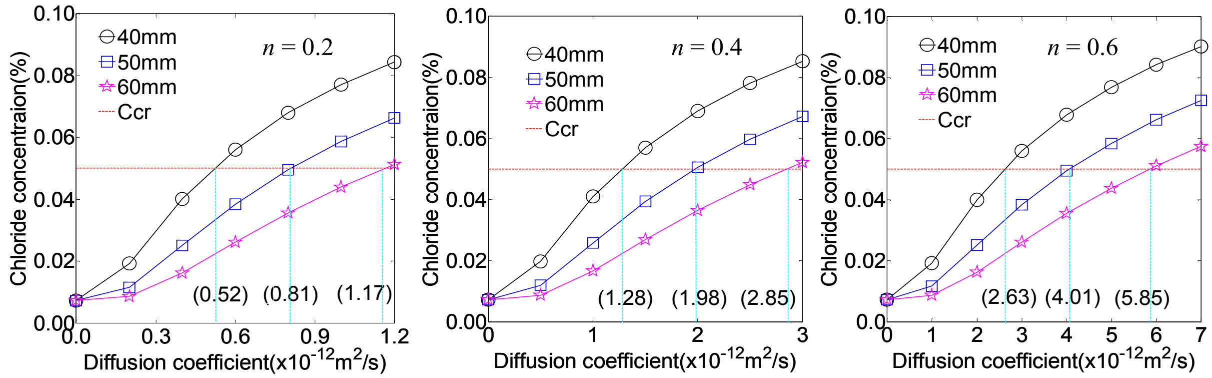
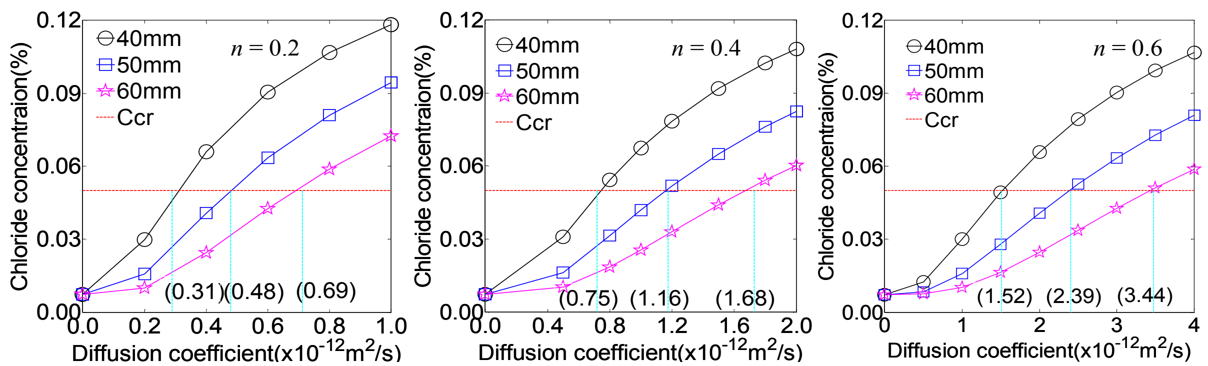


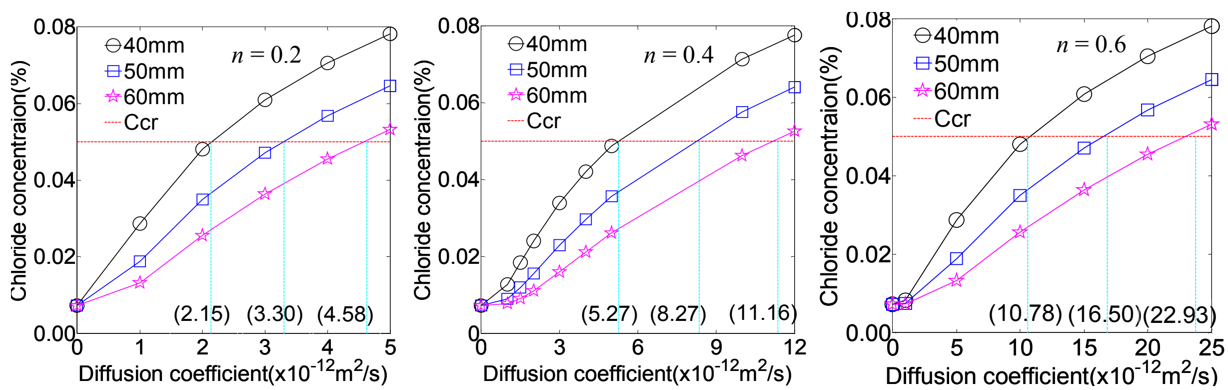
Fig. 2: Finite element mesh and chloride distribution in different cases, (a) Case 1, (b) Case 2, (c) Case 3



(a)



(b)



(c)

Fig. 3: Maximum allowable value of chloride diffusion coefficient for different cases, (a) Case 1, (b) Case 2, (c) Case 3

dimensional diffusion; while the contour lines of chloride concentration near the corners in both the Case 2 and Case 3 shows two-dimensional diffusion. It should be noted that the chloride concentrations within the exposed corners in the Case 2 and Case 3 are the same, while the chloride concentration within the inside corner in the Case 3 is smaller. Further, the chloride concentration near the surface of concrete is quite high, while the chloride concentration far from the surface keeps as a constant of 0.0072% (initial chloride concentration).

The chloride concentrations at the surface of reinforcing steel within three typical locations of subway station after 100a are shown in Figure 3, when different age factor n and the cover depth a are considered. For Case 1, the maximum allowable value of chloride diffusion coefficient decreases from 2.85×10^{-12} m^2/s to 1.28×10^{-12} m^2/s when the cover depth a decreases from 60 to 40 mm in the case of the age factor $n = 0.4$, while the maximum allowable value of chloride diffusion coefficient decreases from 5.85×10^{-12} to 1.17×10^{-12} m^2/s when the age factor n decreases from 0.6 to 0.4 in the case of the cover depth a = 60 mm.

Similar trends can be found for Case 2 and 3. That is to say, the larger the age factor n or the cover depth a is, the larger the maximum allowable value of chloride diffusion coefficient will be. Furthermore, in three cases the maximum allowable value of chloride diffusion coefficient for Case 3 is the largest and for Case 2 is smallest, which implies that the requirements for durability design of different locations is quite different. Above results provides suggestions for durability analysis of subway station in chloride environment.

CONCLUSION

A finite element model for chloride ions transport in the subway station was proposed based on the Fick's second law of diffusion. The maximum allowable value of chloride diffusion coefficient of subway station with service life of 100a was achieved. The results show that the larger the age factor n or the cover depth a is, the larger the maximum allowable value of chloride diffusion coefficient will be. The durability of subway station in chloride environment can be improved by increasing the thickness of concrete cover or manufacturing concrete of high age factor.

ACKNOWLEDGMENT

The financial support received from the Guangxi Lab Center of Science and Technology (LGZX201002) is gratefully acknowledged.

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