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Sensitivity analysis of simplified diffusion-based corrosion initiation model of concrete structures exposed to chlorides

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Abstract

This paper presents the results of a sensitivity analysis of the diffusion-based corrosion initiation model for reinforced concrete structures built in chloride-laden environments. Analytical differentiation techniques are used to determine the sensitivity of the time to corrosion initiation to the four governing parameters of the model, which include chloride diffusivity in concrete, chloride threshold level of steel reinforcement, concrete cover depth, and surface chloride concentration. For conventional carbon steel, the time to corrosion initiation is found to be most sensitive to concrete cover depth, followed by chloride diffusion coefficient, with normalized sensitivity coefficients of about 2 and −1. For corrosion resistant steels, the time to corrosion initiation is most sensitive to the surface chloride concentration and chloride threshold level followed by the concrete cover depth and chloride diffusion coefficient. The results of this sensitivity analysis are discussed in detail, including the variations in predicted time to corrosion initiation induced by variations of the four model parameters and their implications for the design and maintenance of concrete structures built in corrosive environments.
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1. Introduction

The chloride-induced corrosion of the steel reinforcement is identified as the main cause of deterioration of different types of concrete structures (e.g. bridges, parking garages, off-shore platforms, etc.). The sources of chlorides are the seawater and deicing salts used during winter. The corrosion of the steel reinforcement leads to concrete fracture through cracking, delamination and spalling of the concrete cover, reduction of concrete and reinforcement cross sections, loss of bond between the reinforcement and concrete, and reduction in strength and ductility. As a result, the safety and serviceability of concrete structures are reduced. One of the earliest studies on corrosion of reinforcing steel embedded in concrete structures was reported by Stratfull [22], in which chlorides and moisture were identified as the main causes for extensive corrosion in reinforced concrete bridge piers built in a marine environment after only seven years from initial construction. In the last three

decades, the chloride-induced corrosion of reinforced concrete structures has been extensively studied [8,19,15,6], particularly, as a result of the high costs of highway bridge repair in North America and Europe from the effects of deicing salts used during winter or from seawater for coastal structures.

A reliable prediction of the time to corrosion initiation of concrete structures exposed to chlorides is critical for the selection of a durable and cost-efficient design and for the optimization of the inspection and maintenance of built structures, which is essential to minimize the life cycle costs. Existing models are mostly based on the assumption of a Fickian process of diffusion for predicting the time and space variations of chloride content in concrete and on the concept of chloride threshold to define the corrosion resistance of reinforcing steel to chloride attack. Therefore, the governing parameters of this diffusion-based corrosion initiation time include the concrete cover depth, chloride diffusion coefficient in concrete, surface chloride concentration, and chloride threshold level assuming the presence of moisture and oxygen for the corrosion to proceed. In practice, the design of durable concrete structures is mainly based on specifying a minimum

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concrete cover depth (depending on the environmental exposure), a maximum water-to-cement ratio (to achieve low chloride diffusivity), and as well the use of more corrosion resistant reinforcing steels (e.g. stainless steel).

However, a considerable level of uncertainty may be associated with one or more of the above identified parameters. This is due to: (i) heterogeneity and aging of concrete with temporal and spatial variability of its chloride diffusivity; (ii) variability of concrete cover depth, which depends on quality control, workmanship and size of structure; (iii) variability of surface chloride concentration, which depends on the severity of the environmental exposure; and (iv) uncertainty in chloride threshold level that depends on the type of reinforcing steel, type of cementing materials, test methods, etc. [1]. It is clear that the combination of these uncertainties leads to a considerable uncertainty in the model output, i.e. the time to corrosion initiation. This uncertainty in the model output could have serious consequences in terms of reduced service life, inadequate planning of inspection and maintenance and increased life cycle costs.

Therefore, undertaking a sensitivity analysis becomes imperative to assess the impact of uncertainties from the input parameters on the uncertainty of the model output. In the literature, several methods and techniques have been used for the sensitivity analysis of different types of models in different fields of applications, including Monte Carlo simulations, response surface methods, differential analysis techniques, nominal range sensitivity analysis, etc. [21]. Fewer sensitivity studies are found in the literature that deal with the performance of concrete structures that incorporate or evaluate the impact of the uncertainties in the model parameters on the model output, such as service life [5,11,12,13,14].

In this paper, a sensitivity analysis of the diffusion-based model for time to corrosion initiation using the differential analysis technique is undertaken to identify the most significant parameters and quantify their impacts on the time to corrosion initiation. This consists of evaluating the variations in the time to corrosion initiation caused by variations in the input data of the model, which include concrete cover depth, chloride diffusion coefficient, surface chloride concentration, and chloride threshold level. The results of a sensitivity analysis can provide valuable insights and a better understanding of the chloride diffusion-induced corrosion of reinforcing steel in concrete and its governing parameters. A sensitivity analysis can be used to identify the importance of uncertainties in the model input for the purpose of prioritizing additional data collection or research on the parameters that are found significant. Furthermore, the results of a sensitivity analysis can provide effective decision support in the design of durable new structures, as well as in the optimization of inspection and maintenance of existing structures.

2. Diffusion-based corrosion initiation model

2.1. Chloride ingress into concrete structures

The corrosion of concrete structures can be described as a two-stage process: (i) corrosion initiation stage; and (ii) corrosion propagation stage [19] as illustrated in Fig. 1. For chloride-induced corrosion, the initiation stage corresponds to the period of time during which chlorides penetrate the concrete but no damage is observed. The corrosion initiation time is defined as the time at which the concentration of chlorides at the steel surface reaches a critical or threshold value. The propagation stage corresponds to the period of time during which corrosion products accumulate and initiate fracture of concrete and ultimately failure. The service life of concrete structures in chloride-laden environments can be defined as the sum of the durations of the two stages. In general, the durability and serviceability of concrete structures depend greatly on the duration of the initiation stage. As a result, a reliable prediction model of chloride penetration into a reinforced concrete structure is of utmost importance in predicting the time to corrosion initiation, as well as the total service life.

Aggressive agents such as chlorides, water, and oxygen penetrate into concrete through the pore spaces in the cement paste matrix and micro-cracks. The rate of penetration is dependent primarily on the quality of concrete and more particularly on the water–cement ratio of the concrete mix and the presence of supplementary cementing materials (e.g. silica fume, fly ash, or slag) and/or protective systems that delay or slow down chloride ingress. In porous solids, such as concrete, moisture may flow via the diffusion of water vapor, and via non-saturated or even saturated capillary flow in finer pores [10]. Chloride ingress into concrete from external sources is therefore due to multiple transport mechanisms, such as diffusion and adsorption. However, adsorption occurs in concrete surface layers that are subjected to wetting and drying cycles, and it only affects the exposed concrete surface down to 10–20 mm [23,20]. Beyond this adsorption zone, the diffusion process will dominate [20].

Chloride diffusion is a transfer of mass by random motion of free chloride ions in the pore solution resulting in a net flow from regions of higher to regions of lower concentration [7]. The rate of chloride ingress is proportional to the concentration gradient and the diffusion coefficient of the concrete (Fick's first law of diffusion). Since in the field, chloride ingress occurs under transient conditions, Fick's second law of diffusion can
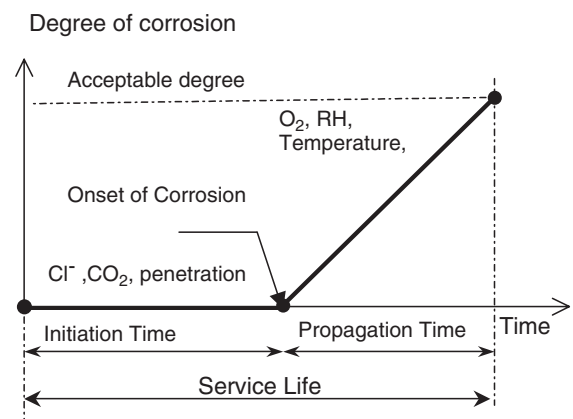

Fig. 1. Service life of concrete structures subjected to corrosion (adapted from Ref. [19]).

be used to predict the time variation of chloride concentration for one-dimensional flow, as follows:

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

Under the assumptions of a constant diffusion coefficient, constant surface chloride content C_s as the boundary condition, and the initial condition specified as $C=0$ for $x>0$, $t=0$, Crank's solution of Eq. (1) yields [7]:

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

where: $C(x,t)$ is the chloride concentration at depth x after time t; C_s is the chloride concentration at the surface; D is the diffusion coefficient; t is the time of exposure; and erf is the error function.

2.2. Corrosion of reinforcing steel

As seen in Tuutti's corrosion model in Fig. 1, the corrosion initiation stage corresponds to the process of chloride transport onto a steel surface, while the steel remains passivated with a corrosion rate lower than a defined level, e.g. 0.1 μA/cm² [9]. The onset of corrosion of the reinforcing steel is assumed to start when the concentration of chlorides at the level of the reinforcement has reached the so-called "chloride threshold level" C_{th}, which destroys the passivation of steel. Therefore, the duration of the initiation stage is from time zero to the onset of corrosion. The initiation stage and onset of corrosion in Tuutti's model can be stated mathematically as follows:

Initiation stage: $C(d_c,t) < C_{th}$ for $0 \leq t < T_i$ (3a)

Onset of corrosion: $C(d_c,t) = C_{th}$ for $t = T_i$ (3b)

where T_i is the time to onset of corrosion (equivalent to time to corrosion initiation) and d_c is the depth of concrete cover over the reinforcing steel. Substituting the condition of onset of corrosion in Eq. (3b) into Eq. (2), and assuming the same initial and boundary conditions, the time to corrosion initiation is determined as follows:

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

The above equation represents a transformation of Crank's solution of chloride concentration in concrete into a deterministic model of the time to corrosion initiation as an explicit function of the parameters, C_s, C_{th}, D, and d_c. These governing parameters can be categorized as follows: (i) structural parameter: concrete cover depth; (ii) material parameters: type of concrete and corresponding chloride diffusivity (D), which is
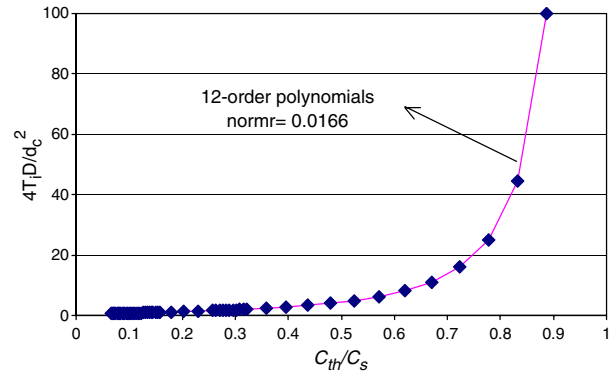

Fig. 2. Relationship between time to corrosion initiation and diffusion model parameters.

an indicator of the accessibility of concrete to chloride penetration; and type of reinforcing steel and corresponding chloride threshold level (C_{th}), which is a measure of its corrosion resistance; and (iii) environmental parameter (C_s), which is a measure of the corrosion load or risk on the structure.

Given the complexity of the error function and its inverse, a 12th order polynomial was found to be a best fit for Eq. (4) (a normal residual of 0.000001), as shown in Eq. (5).

$$T_i = f(C_s, C_{th}, D, d_c) = \frac{d_c^2}{4D}\sum_{m=0}^{12} A_m\left[\frac{C_{th}}{C_s}\right]^m \tag{5}$$

where the coefficients A_0 to A_{12} of the polynomial are listed in Table A in Appendix. A plot of $\frac{4DT_i}{d_c^2}$ versus $\frac{C_{th}}{C_s}$ is shown in Fig. 2.

3. Sensitivity analysis using differentiation technique

3.1. Uncertainty in corrosion initiation time

Despite the simplicity and extensive use of the above diffusion-based corrosion initiation model, considerable uncertainties are associated with its governing parameters and predictions. There are various sources of uncertainty, which include physical uncertainty, statistical uncertainty, and model uncertainty. The physical or inherent uncertainty is that identified with the inherent random nature of the main parameters of the model (e.g. uncertainties in concrete cover depth, surface chloride concentration, chloride diffusion coefficient, and chloride threshold level). The statistical uncertainty arises from estimating the mean value and possibly the standard deviation of each of the governing parameters from a limited sample size. The model uncertainty arises from the use of simplified mathematical models or relationships between the basic variables to represent the actual physical phenomena of chloride ingress and corrosion initiation. The main factors that contribute to the uncertainty of the diffusion-based model can be summarized as follows:

1. Assumptions of chloride transport mechanism governed by diffusion and one-dimensional flow solution from the surface into a half space;

2. Use of the simplified concept of chloride threshold level to define the corrosion resistance of reinforcing steel embedded in concrete structures. A considerable scatter of this threshold value is found in the literature [1].
3. Assumption of time-invariance and independence of concrete parameters:
   A. The diffusion coefficient is not a constant but rather depends on time, temperature, and depth because of the heterogeneous nature and aging of concrete, as mentioned earlier. For many concrete structures (e.g. bridge decks), the top surface is subjected to a continually changing chloride exposure. As a result, the chloride concentration at the surface varies with time; however at some shallow depth, it can be assumed as a quasi-constant [23,10].
   B. The concrete cover depth is variable and the level of variability depends on the quality of construction and size of the structure.
   C. The coefficients of variation of the governing parameters are quite high and may vary between 10% and 40% and for some, up to 80% [6,13].

Fig. 3 illustrates the proposed procedure for the incorporation of parameter uncertainty in model prediction of time to corrosion initiation in this paper. The previous sections have discussed (1) the diffusion-based model with the four governing parameters; and (2) the time to corrosion initiation is established based on the diffusion model and Tuutti's corrosion model. In summary, this section has concentrated on the uncertainties in the four parameters to be used in the sensitivity analysis in the next section.

3.2. Need for sensitivity analysis

It is clear from the above that a significant uncertainty or error can be associated with the prediction of the time to corrosion initiation (T_i) by using the above simplified diffusion model. The following questions then arise:

1. How to assess the errors in predicting the time to corrosion initiation by using the simplified diffusion model?
2. Which parameters have the greatest impact on T_i?
3. Which parameters require more focus and investigation to reduce the error in predicting T_i?
4. How to use these results for engineering purposes, to achieve effective design, inspection, and maintenance of concrete structures.

The first question can be answered by undertaking an analysis of the sensitivity of T_i to the four governing parameters. One result of the sensitivity analysis (see Fig. 3) is to provide the levels of variation (or uncertainty) in T_i that are induced by variations in each of the four parameters over a feasible range of variation, which must be quantified and understood before this model is used in service life predictions. For instance, the time to corrosion initiation varies over a wide range (e.g., the variation is from 10 years to 50 years for a design value T_i of 30 years) due to a realistic variation of the parameters (e.g., actual concrete cover is found to vary from 10 to 50 mm, when the design value was 30 mm). It is therefore clear that the use of the above deterministic model has serious shortcomings.

Another result of the sensitivity analysis (see Fig. 3) is to provide a ranking of parameter importance, which can then be
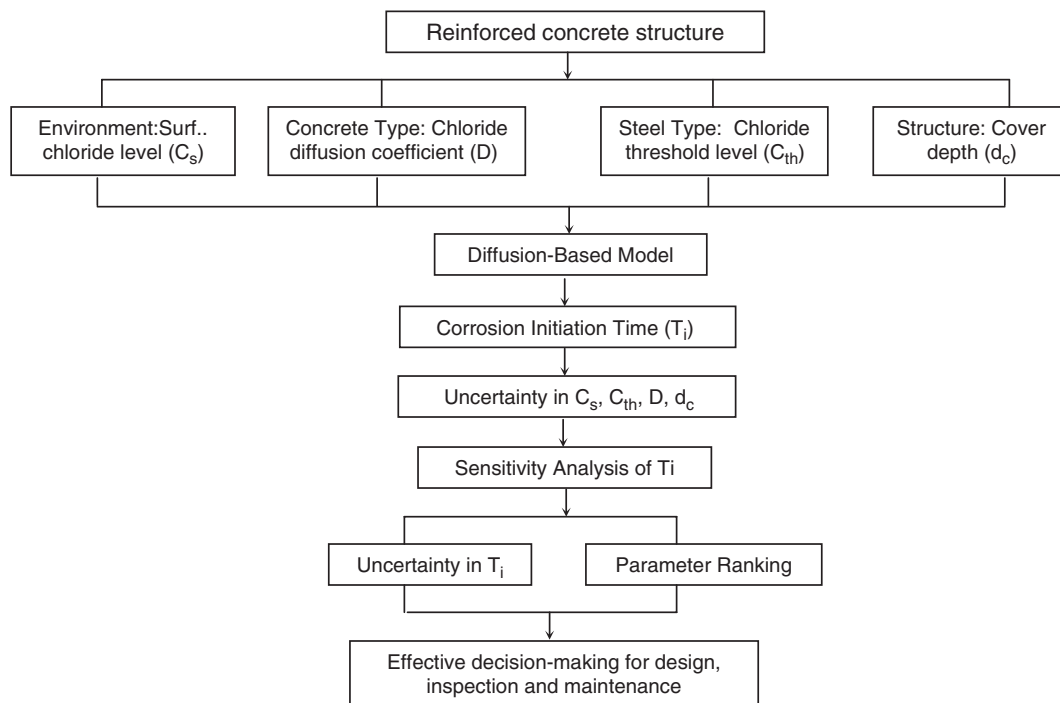

Fig. 3. Incorporation of parameter uncertainty in model prediction.

used to answer the questions raised above. By identifying the most relevant parameters affecting the time to corrosion initiation (T_i), it is possible to provide the decision maker with very relevant information regarding which parameters to control to achieve a given design service life, or T_i, and how to implement measures (quality control, inspection, maintenance) in order to reduce the uncertainties with those critical parameters in order to reduce the uncertainty in T_i.

Therefore, when this diffusion-based model is used to study the sensitivities of T_i to variations in its governing parameters, the variations are no longer noise but are used to quantify their impact on T_i. The results of the sensitivity study will therefore help in the effective decision-making for design, inspection, and maintenance (see Fig. 3). Several methods have been developed and applied for sensitivity and uncertainty analysis, including: (i) nominal range sensitivity analysis; (ii) difference in log–odds ratio; (iii) differential analysis; (iv) Monte Carlo simulation; (v) response surface methods; (vi) Fourier amplitude sensitivity test; (vii) Bayesian sensitivity analysis, etc. [21,14]. These methods vary in level of complexity, data requirements, representation of the sensitivity and specific uses.

In this paper, the differential analysis method is used to investigate the sensitivity of the diffusion-based time to corrosion initiation model to the four basic parameters of concrete structures exposed to chlorides. This method is easy to apply and provides relevant information on the impact of the different parameters on the model output and ranking of their relative importance. It requires a limited amount of data related to the governing parameters, namely their mean or base values and possibly their standard deviations, which is not the case for Monte Carlo simulation, which requires complete probabilistic distributions of all parameters. The description of the technique is given in the next section.

3.3. Sensitivity of corrosion initiation time using differentiation analysis

Differential sensitivity analysis is based on using a Taylor series to approximate the model under consideration. This approximate model is used as a surrogate for the original model in the sensitivity analysis. The diffusion-based corrosion initiation time model of Eq. (4) can be represented as the following function:

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

where the governing parameters are the input variables and are represented by the vector:

$$X = [X_1, X_2, X_3, X_4] \tag{7}$$

A first-order Taylor series approximation of T_i has the following form, with X_0 representing a base value vector (or reference vector):

$$T_i(X) \cong T_i(X_0) + \sum_{j=1}^{4} \frac{\partial f(X_0)}{\partial X_j}(X_j - X_{j0}) \tag{8}$$

The values of the partial derivatives are a measure of the local sensitivity. Higher order expressions can also be derived. The order of the approximation depends on the curvature of the surface of $T_i = f(X)$.

Eq. (8) can be rewritten in the following form:

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

Let

$$\Delta T_i = T_i(X) - T_i(X_0) \tag{10a}$$

$$\Delta X_j = X_j - X_{j0} \tag{10b}$$

and

$$T_i(X_0) = T_{i0} \tag{10c}$$

In this approach, inference about the variability of T_i or $f(X)$ is made by changing one parameter or one factor at a time and keeping the other parameters constant (equal to their base values) and investigating the change in T_i, therefore:

$$\frac{\partial f}{\partial x_k} = 0 \qquad k = 1, 2, \dots, n \text{ with } k \neq j \tag{11a}$$

and

$$\frac{\partial f}{\partial x_j} = f'(x_j) \tag{11b}$$

Therefore, Eq. (9) becomes:

$$\frac{\Delta T_i}{\Delta X} \frac{X_{j0}}{T_{i0}} = \frac{\partial f(X_0)}{\partial X_j} \frac{X_{j0}}{T_{i0}} = S(X_j) = S_j \tag{12a}$$

where S_j is the normalized first-order sensitivity coefficient of T_i to X_j, which provides a measure of the relative change in T_i that results from a relative change in X_j, when the other variables are kept constant. It should be noted that the change or perturbation in X_j should be small, i.e. a small fraction of its base (or mean) value.

$$S_j = \frac{\partial f(X_0)}{\partial X_j} \frac{X_{j0}}{T_{i0}} \qquad j = 1, \dots, 4 \tag{12b}$$

Given the assumption of one variable parameter at a time, it is possible to include the higher order terms of the Taylor series approximation to determine the higher order sensitivity coefficients $S_h(X_j)$ by using the following equation:

$$\Delta T_i = f(X_j + \Delta X_j) - f(X_j) = f'(X_j)\Delta X_j + \dots + \frac{f^n(X_j)}{n!}(\Delta X_j)^n$$
$$+ \frac{f^{n+1}(\theta X_j)}{(n+1)!}(\Delta X_j)^{n+1} \tag{13}$$

where f^n denoted the nth order derivative of $f(X_j)$ for $X_j < \theta X_j < X_j + \Delta X_j$. Substituting Eq. (13) into Eq. (12b) yields:

$$
\begin{aligned}
S_{hj} &= S_h(X_j) \\
&= \frac{X_{j0}}{T_{i0}} * \left[f'(X_{j0}) + \ldots + \frac{f^n(X_{j0})}{n!} (\Delta X_j)^{n-1} + \frac{f^{n+1}(\theta X_j)}{(n+1)!} (\Delta X_j)^n \right]
\end{aligned}
\tag{14}
$$

Since S_j (or S_{hj}) is a dimensionless quantity, the sensitivities to the independent variables with different dimensions could be compared. From the values of coefficients S_j, the following conclusions can be made:

1. The sign of the coefficient S_j indicates whether X_j and T_i tend to move up or down together or in opposite directions. A positive value of S_j means that a change in X_j will result in a change in T_i in the same direction, and vice versa.
2. The absolute values of these coefficients can be used to rank the relative importance of the individual parameters. It can be concluded that T_i is more sensitive to the variable X_m rather than X_n if the absolute value of $S(X_m)$ is greater that of $S(X_n)$, denoted by $|S(X_m)| > |S(X_n)|$.

Using Eq. (12b), the first-order sensitivity coefficients of T_i to C_s, C_{th}, D, or d_c, can be obtained as follows:

$$
S(d_c) = f'(d_c) \frac{d_c}{T_i} = 2
\tag{15}
$$

$$
S(D) = f'(D) \frac{D}{T_i} = -1
\tag{16}
$$

Let

$$
g(C_s, C_{th}) = \mathrm{erf}^{-1} \left(1 - \frac{C_{th}}{C_s} \right)
\tag{17}
$$

Then

$$
S(C_s) = f'(C_s) \frac{C_s}{T_i} = -\frac{C_{th}}{C_s} \frac{\sqrt{\pi}}{\mathrm{erf}^{-1} \left(1 - \frac{C_{th}}{C_s} \right) e^{-[g(C_s, C_{th})]^2}}
\tag{18}
$$

and

$$
S(C_{th}) = f'(C_{th}) \frac{C_{th}}{T_i} = \frac{C_{th}}{C_s} \frac{\sqrt{\pi}}{\mathrm{erf}^{-1} \left(1 - \frac{C_{th}}{C_s} \right) e^{-[g(C_s, C_{th})]^2}}
\tag{19}
$$

The first-order sensitivity coefficients of T_i to d_c and D are easily computed and are found to be constant. The first-order sensitivity coefficients of T_i to C_s or C_{th}, however, are complex functions of the variables C_s and C_{th}, so are the higher order sensitivity coefficients. It is therefore impractical to use Eq. (14) to calculate ΔT_i from ΔC_s or ΔC_{th}. As noted before, $\frac{4DT_i}{d_c^2}$ versus $\frac{C_{th}}{C_s}$ is equivalent to ξ versus γ, where $\xi = \frac{1}{x^2}$, $\gamma = 1 - y$, and $y = \mathrm{erf}(x)$, and the numerical relationship between ξ and γ is obtainable (e.g. Fig. 2) given the numerical relationship between x and y. As a result, $\Delta T_i / T_i$ versus $\Delta C_{th} / C_{th}$ can be derived from the above as equivalent to $\Delta \xi / \xi$ versus $\Delta \gamma / \gamma$, considering that the other variables are

kept constant. The numerical correlation between $\Delta \xi / \xi$ and $\Delta \gamma / \gamma$ is obtained if the base values of ξ and γ is specified. Similarly, the numerical correlation between $\Delta T_i / T_i$ and $\Delta C_s / C_s$ can be obtained using the same approach. A more practical approach is to plot first the variations of $\Delta T_i / T_i$ versus $\Delta C_s / C_s$ (or $\Delta C_{th} / C_{th}$) and then a regression analysis can be carried out to obtain the analytical correlation that yields satisfactory precision.

The higher order derivatives of T_i to D or d_c are easily obtained, from which high-order sensitivity coefficients $S_h(D)$ and $S_h(d_c)$ of T_i to D and d_c can be obtained as follows:

$$
\frac{\Delta T_i}{T_i} = -\frac{\frac{\Delta D}{D}}{\frac{\Delta D}{D} + 1}
\tag{20a}
$$

$$
S_h(D) = -\frac{1}{\frac{\Delta D}{D} + 1}
\tag{20b}
$$

$$
\frac{\Delta T_i}{T_i} = 2 \frac{\Delta d_c}{d_c} + \left(\frac{\Delta d_c}{d_c} \right)^2
\tag{21a}
$$

$$
S_h(d_c) = 2 + \frac{\Delta d_c}{d_c}
\tag{21b}
$$

It should be noted that the four variables C_s, C_{th}, D, and d_c are assumed to be independent variables in this paper in order to illustrate the dependence of T_i on each of them. In reality, D and C_{th} may be correlated because both are related to concrete properties. The chloride diffusion coefficient is a material property of concrete dependent primarily on its pore structure and saturation of the pore solution; the parameter C_{th} of the reinforcing steel depends also on the concrete chemistry, mainly the pH level of the concrete pore solution. However, C_{th} is treated here as an independent steel property because other parameters are kept constant when the sensitivity to C_{th} is analysed.

4. Results of sensitivity analysis

4.1. Ranges of variation of governing parameters

Realistic ranges of variation of the four governing parameters used in this study, C_s, C_{th}, D, and d_c, are summarized below from a literature review, with emphasis on bridge deck applications.

4.1.1. Surface chloride concentration

Weyers et al. [23] classified the corrosive environments surrounding bridge decks into four categorizes in terms of surface chloride concentration C_s: light, moderate, high, and severe exposures. As shown in Table 1, the mean values, C_s, of the four exposures are 1.8, 3.5, 5.3, and 7.4 kg/ m^3, respectively; and the variations in these categories from the mean values, $\Delta C_s / C_s$, are from -100% to $+33\%$, $\pm 32\%$, $\pm 11\%$, and $\pm 20\%$, respectively. For example, a concrete structure exposed to a moderate environment can be estimated to have a $C_s = 3.5$ kg/m^3, if an accurate value is not available (which is

Table 1
Sensitivity of corrosion initiation time to environmental exposure for carbon steel

Condition	Low (kg/m^3)	Moderate (kg/m^3)	High (kg/m^3)	Severe (kg/m^3)
Range	$0 < C_s < 2.4$	$2.4 < C_s < 4.7$	$4.7 < C_s < 5.9$	$5.9 < C_s < 8.9$
Mean value	1.8	3.5	5.3	7.4
Variation from mean value	−100% to 33%	−32% to 32%	−11% to 11%	−20% to 20%
Variation in T_i	−25% to ∞	−18% to 40%	−6% to 7%	−9% to 12%

Note 1 Kg/m^3 = 0.276% of cement weight for normal weight concrete.

often the case); this estimated mean value is associated with a variation of ±32%.

4.1.2. Chloride threshold level

The chloride threshold concentration C_{th} is defined as the critical chloride content at which the passivation of the steel in concrete will be destroyed. It depends on the type of steel, electrochemical environment in concrete, and testing method [3,1] and consequently, a considerable variation is expected for these parameters. Different types of steel have different C_{th}, and even one type of steel (e.g. carbon steel) has a wide range of reported C_{th}.

In this regard, the values from one research investigation are considered for this study in order to minimize the variation induced by the testing methods. Trejo and Pillai [17,18] reported that the mean values of C_{th} for carbon steel [2], micro-composite steel, stainless steel SS304 and SS316LN, are 0.52, 4.6, 5.0, and 10.8 kg/m^3, respectively, as summarized in Table 2. Since the experimental designs and test procedures were the same for these different steels, their reported variations from the mean values can be considered as the "intrinsic" variations of the steels, which are ±40%, ±16%, ±19%, and ±12%, respectively, as seen in Table 2.

4.1.3. Chloride diffusion coefficient

The chloride diffusion coefficient D of concrete is a material property that is a measure of the rate of chloride penetration into concrete. The value of D depends on both concrete mix design, such as water/cement ratio, quantity of mineral admixtures, aggregation fraction, etc., and other parameters such as temperature and age of concrete [4,16]. The typical values of D for normal Portland cement concrete

(e.g. w/c=0.4) were reported between 10^{-12} and 10^{-11} m^2/s [16,24], e.g. $D = 4 \times 10^{-12}$ m^2/s for a normal concrete with w/c=0.4 and $D = 10^{-11}$ m^2/s for w/c=0.55 [24]. The incorporation of mineral admixtures (e.g. fly ash, slag, silica fume), however, can lead to orders of magnitude reduction of D in the long term [16]. In this study, D is considered to vary from 10^{-12} to 10^{-11} m^2/s.

4.1.4. Concrete cover depth

The concrete cover depth d_c is a design parameter that varies with the severity of the environmental exposure and depends on the quality of workmanship and control during construction. For cast-in-place bridge decks, its value could vary from 20 to 80 mm for average to below average quality control [13].

4.2. Ranking of parameter importance

As expected, it can be seen from Eqs. (15)–(19) that the sensitivity coefficients of the time to corrosion initiation T_i to concrete cover, $S(d_c)$, and to chloride threshold level, $S(C_{th})$ are positive, which means that increasing d_c or/and C_{th} will increase T_i. On the other hand, the sensitivity coefficients of the time to corrosion initiation T_i to surface chloride concentration, $S(C_s)$, and to chloride diffusion coefficient, $S(D)$ are negative, which means that increasing C_s or/and D will decrease T_i.

The values of $S(d_c)$ and $S(D)$, are constant and equal to 2 and −1, respectively, which indicate that T_i is much more sensitive to d_c than D. On the other hand, the values of $S(C_{th})$ and $S(C_s)$ are both functions of the C_{th}/C_s ratio, which depends primarily on the corrosion resistance of the reinforcing steel and environmental exposure. Fig. 4 represents plots of the variations of the sensitivity coefficients of T_i to the four governing

Table 2
Sensitivity of corrosion initiation time to chloride threshold level for different exposures

Steel type and environment	Conventional carbon steel (kg/m^3)	Micro-composite steel—MMFX (kg/m^3)	Stainless steel SS304 (kg/m^3)	Stainless steel SS216LN (kg/m^3)
Variations in chloride threshold level				
Range	$0.30 < C_{th} < 0.71$	$3.8 < C_{th} < 5.3$	$4.1 < C_{th} < 6.0$	$9.5 < C_{th} < 12.0$
Mean value	0.52	4.6	5.0	10.8
Variation from mean value [a]	−40% to 40% [a]	−16% to 16%	−19% to 19%	−12% to 12%
Variations in corrosion initiation time				
Light C_s = 1.8 kg/m^3	−40% to 60%	+	+	+
Moderate C_s = 3.5 kg/m^3	−28% to 32%	+	+	+
High C_s = 5.3 kg/m^3	26% to −24%	−80% to +	−84% to +	+
Severe C_s = 7.4 kg/m^3	−24% to 19%	−40% to 96%	−50% to 400%	+

[a] Simplified range, e.g., −42% to −38% taken as −40% to 40%; + not applicable for $C_{th} \geq C_s$.
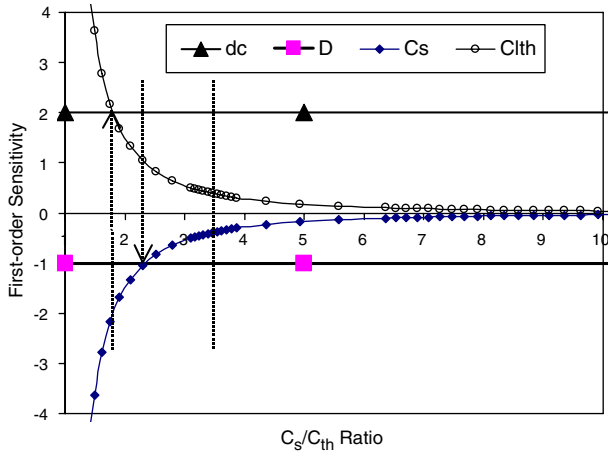
Fig. 4. Sensitivities of T_i to D, d_c, C_s, C_{th} as functions of C_s/C_{th} ratio.

variables versus the C_s/C_{th} ratio, which is varied from 1 to 10, representing an increasingly corrosive environment for a given steel reinforcement. Fig. 4 shows that both $|S(C_{th})|$ and $|S(C_s)|$ decrease exponentially with increasing C_s/C_{th} ratios from values higher than 4 and decrease asymptotically towards zero.

4.2.1. Case of conventional black carbon steel

From Tables 1 and 2, C_s/C_{th} ratios for conventional black carbon steel may vary from 3.5 to 14.2 depending on the environmental exposures. In this range, as shown in Fig. 4, the time to corrosion initiation is most sensitive to concrete cover, then to chloride diffusion coefficient, and least to surface chloride concentration or chloride threshold, which yields the ranking of sensitivities shown in Eq. (22). It means that increasing concrete cover depth for carbon steel reinforcement is the most effective measure to increase the service life, followed by increasing the quality of concrete.

$$|S(d_c)| > S(D)| > |S(C_{th})| = |S(C_s)| \tag{22}$$

4.2.2. Case of corrosion resistant steels

From Tables 1 and 2, C_s/C_{th} ratios for corrosion resistant steels could be less than 1.6. In this range, as shown in Fig. 4, the time to corrosion initiation is most sensitive to surface chloride concentration or chloride threshold, then concrete cover, and least to chloride diffusion coefficient, which yields the ranking shown in Eq. (23). It implies that for concrete structures using high corrosion resistant steels, it is critical to use a precise value of chloride threshold in order to properly assess the service life.

$$|S(C_{th})| = |S(C_s)| > |S(d_c)| > |S(D)|. \tag{23}$$

4.3. Sensitivity of time to corrosion initiation to diffusion model parameters

4.3.1. Sensitivity to chloride diffusion coefficient

Eq. (20a) evaluates the effect of a relative change in D, (denoted by $\Delta D/D$), on T_i, and the impact of $\Delta T_i/T_i$ of $\Delta D/D$

is plotted in Fig. 5, from which the following two main observations can be made:

1. For variations in D of less than 10%, $S_h(D)$ is approximately equal to -1, which is the first-order sensitivity e.g., a 10% increase in D will decrease T_i by about 9%.
2. The increase and decrease in T_i are asymmetrical with D; a much greater change in T_i will be made by a decrease in D than an increase in D for the same percentage. For example, a 50% reduction in D, increases T_i by 100%, while a 50% increase in D will reduce T_i by about 33%.

Therefore, a precise assessment of D should be sought in practice, since variations of D of ±50%, (which are small variations in practice as noted earlier), could lead to variations in T_i ranging from -33.3% to $+100\%$. It also implies that a small decrease in chloride diffusion coefficient would greatly extend the time to corrosion initiation (consequently the service life). On the other hand, for a concrete with unknown D, it is more appropriate to estimate it in a conservative manner, to avoid an overestimation of the service life. The practical effect of D is further illustrated by the following study in which D is varied from 10^{-12} to 10^{-11} m^2/s.

4.3.1.1. Pseudo case-study #1.

Suppose two reinforced concrete structures are designed with $D = 0.5 \cdot 10^{-11}$ m^2/s for a design time to corrosion initiation (or design service life) T_i of 50 years and 30 years, respectively. For D varying from the design value, say from 10^{-12} to 10^{-11} m^2/s, Fig. 6 shows how the design service life can be influenced. If D is increased to 10^{-11} m^2/s, Fig. 6 shows that the service life will be reduced to 25 years and 15 years, respectively. If D is decreased to $3 \cdot 10^{-12}$ m^2/s, the service life will be extended to 83 years and 50 years, respectively. Considering this range of D as feasible in practice, D can be considered as an effective parameter to control the service life T_i of concrete structures.

4.3.2. Sensitivity to concrete cover depth

Eq. (21a) shows the sensitivity $S(d_c)$ of T_i to d_c, and the correlation between $\Delta T_i/T_i$ and $\Delta d_c/d_c$ is plotted in Fig. 5.

1. For small variations of d_c less than 10%, $S(d_c)$ is approximately equal to 2, i.e. a 10% increase in d_c will increase T_i by 21%.
2. The increase and decrease in T_i are asymmetrical with d_c, i.e. an increase in d_c will induce a much greater increase in T_i than a decrease of d_c for the same percentage, e.g. a 50% increase in d_c will increase T_i by 125%, while a decrease in d_c by 50% will reduce T_i by 75%.
3. Compared to D, d_c has a larger impact on T_i, e.g. the variations of d_c for ±50%, (which is a small variation in practice), could lead to variations in T_i from -75% to $+125\%$.

4.3.2.1. Pseudo case-study #2.

Suppose two reinforced concrete structures are designed with a concrete cover depth
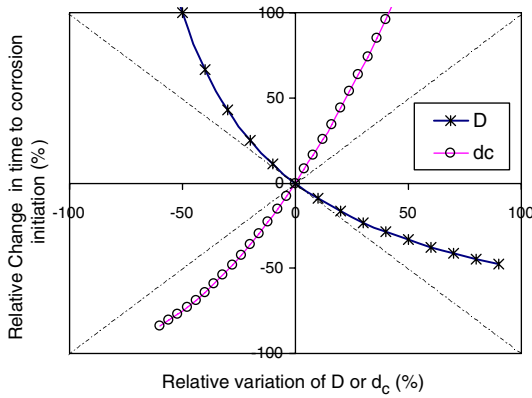
Fig. 5. Sensitivities of T_i to chloride diffusion coefficient and concrete cover depth.

Fig. 7. Impact of concrete cover depth on corrosion initiation time.

$d_c = 50$ mm for a design service life T_i of 50 years and 30 years, respectively. Fig. 7 shows how the design value of T_i can be changed by varying the design value of d_c between 20 to 80 mm. If the value of d_c is 20 mm, T_i will be reduced to 8 and 4.8 years, respectively; if the actual cover is 80 mm, T_i will be increased to 128 and 77 years, respectively.

4.3.3. Sensitivity to surface chloride concentration

As noted before, the variation of $\Delta T_i / T_i$ with $\Delta C_s / C_s$ is a function of C_{th} and C_s. Using the base or mean values of C_s given in Table 1 with $C_{th} = 0.52$ kg/m^3 (case of conventional carbon steel), the variations of $\Delta T_i / T_i$ with $\Delta C_s / C_s$ are illustrated in Fig. 8 for the four environmental exposures identified earlier. From Fig. 8, the following observations can be made:

1. The variations of $\Delta C_s / C_s$ from each mean value are from -100% to $+33\%$, $\pm 32\%$, $\pm 11\%$, and $\pm 20\%$, for the light, moderate, high, and severe conditions, respectively. These variations will yield variations in T_i of -25% to ∞, -18% to 40%, -6% to 7%, -9% to 12%, respectively, for the four exposures. For example, a concrete structure exposed to a moderate environment can be estimated to have a $C_s = 3.5$ kg/m^3,
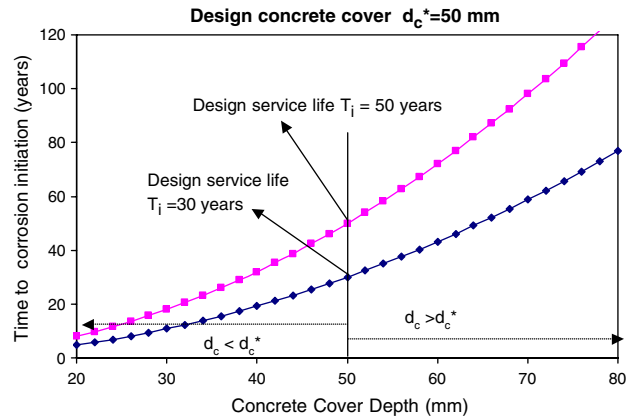
if an accurate value is unknown. Since this estimated mean value is associated with a variation range of $\pm 32\%$, the resulted variation in T_i will be from -18% to 40%. It means that if the design service life is $T_i = 50$ years, the actual T_i could range from 40 to 70 years.

2. The variations in T_i are more significant for the lighter exposure conditions. Under different exposure conditions; T_i is increased more significantly by decreasing C_s for light exposure conditions, e.g. a 50% decrease in C_s would extend the time to onset of corrosion by 261%, 95%, 69%, and 51% for light, moderate, high, and severe conditions, respectively.

3. A decrease in C_s will induce a much greater increase in T_i than an increase in C_s, e.g., for carbon reinforcing steel under a high exposure condition, a 50% decrease in C_s increases T_i by 69%, while a 100% increase in C_s only decreases T_i by 30%.

4. The higher the reduction in C_s, the higher the increase in T_i, e.g., for carbon reinforcing steel under a high exposure condition, a 50% decrease in C_s increases T_i by 69%,
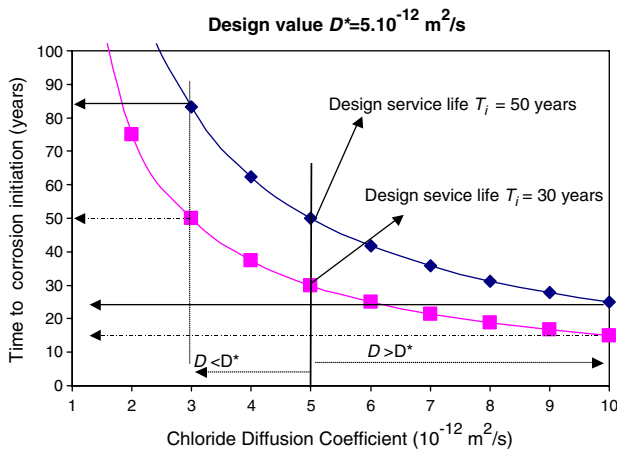

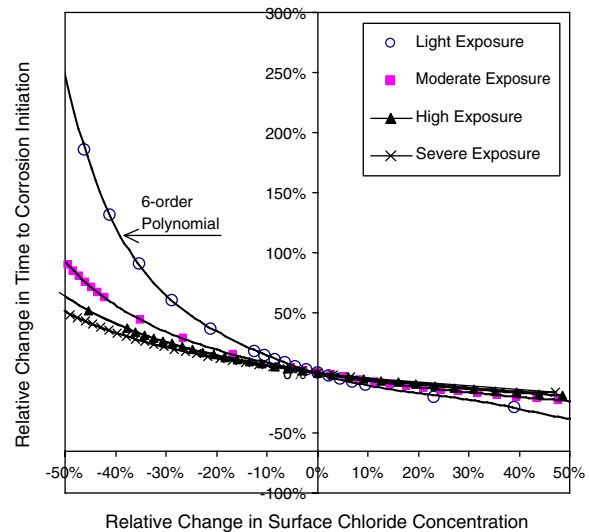Fig. 6. Impact of diffusion coefficient on corrosion initiation time.

Fig. 8. Impact of surface chloride concentration on corrosion initiation time.

however, a 70% decrease in C_s increases T_i by as much as 179%.

Polynomials are used to regress the correlation between $T_i/\Delta T_i$ and $\Delta C_s/C_s$. After trial-and-error, their correlation can be fitted precisely by a 6th-order polynomial, for $-50\% < \Delta C_s/C_s < 50\%$:

$$\frac{\Delta T_i}{T_i} = \sum_{m=0}^{6} B_m \left[\frac{\Delta C_s}{C_s}\right]^m \tag{24}$$

where the coefficients B_m are listed in Table B in Appendix.

4.3.4. Sensitivity to chloride threshold level

The variations $\Delta C_{th}/C_{th}$ associated with the mean values C_{th} for each of the four types of steel (Table 2)) are used to calculate the variations induced in T_i, for each of the four exposure conditions, if applicable (assuming $C_{th} \le C_s$). The variations of $\Delta T_i/T_i$ with $\Delta C_{th}/C_{th}$ are also illustrated in Fig. 9 for black carbon steel under four exposure conditions. The results can be summarized as follows:

1. Assume $C_{th} = 0.52$ kg/m^3 for carbon steel, if an accurate value is not available (often the case). Since this mean value is associated with a variation range of $\pm 40\%$, the variations associated with T_i, will be -40% to 60%, -28% to 32%, -26% to 24%, and -24% to 19%, for light, moderate, high, and severe exposure conditions, respectively. This means if the design service life is $T_i = 50$ years, the actual T_i could range from 30 to 80 years for a light exposure condition.
2. The closer C_{th} is to C_s, the more T_i is sensible to C_{th}. In other words, the higher the value of C_{th}, the more sensible T_i is to C_{th}. This is also verified by comparing different types of steels, e.g. for severe corrosion exposure $C_s = 7.4$, the variation associated with carbon steel, micro-composite steel, and SS304 are -24% to 19%, -40% to 96%, -50% to 400%, respectively.
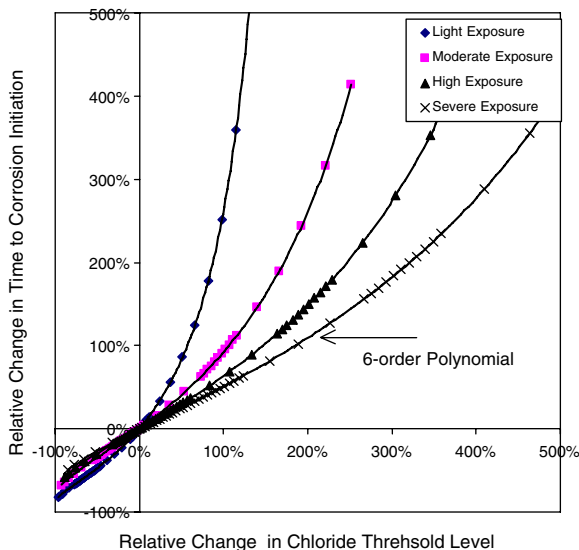

Fig. 9. Impact of chloride threshold level on corrosion initiation time.

3. An increase in C_{th} will induce a similar amount of change in T_i as a decrease in C_{th}, e.g. under a high exposure condition, a 50% change of C_{th} changes T_i approximately by 30%.
4. The increase rate of T_i by increasing C_{th} is higher for larger increases, e.g. under a high exposure condition, e.g., a 100% increase in C_{th} increases T_i by 69%, while a 300% increase in C_{th} increases T_i by as much as 280%. It means that if the carbon steel is replaced by a steel with 3 times higher corrosion resistance (SS304 is 5 times more corrosion resistant), T_i will be increased by 3 times. Therefore, increasing of C_{th} can be considered as an effective measure to increase T_i. Under different environmental exposure conditions; T_i is increased significantly by increasing C_{th} under lighter exposure condition, e.g. a 50% increase in C_{th} would extend T_i by 260%, 100%, 69%, and 36% for light, moderate, high, and severe conditions, respectively. It means that the effectiveness of using a more corrosion resistant steel will be lowered with the increasing severity of environmental exposure.

Similarly, polynomials are used to regress the correlation between $\Delta T_i/T_i$ and $\Delta C_{th}/C_{th}$ for carbon steel. After trial-and-error, this relationship can be fitted by a 6th-order polynomial, for $-100\% < \Delta T_i/T_i < 400\%$:

$$\frac{\Delta T_i}{T_i} = \sum_{m=0}^{6} C_m \left[\frac{\Delta C_{th}}{C_{th}}\right]^m \tag{25}$$

where the coefficients C_m are listed in Table C in the Appendix.

5. Summary and conclusions

The sensitivity of time to corrosion initiation of the reinforcing steel to the four governing parameters of the diffusion-based corrosion initiation model, namely the cover depth, chloride diffusivity, surface chloride concentration and chloride threshold level was investigated. The variations in time to onset of corrosion induced by realistic variations of the four governing parameters were determined. These results have important applications in both modeling and practice:

1. The sensitivities of the time to corrosion initiation to concrete cover and chloride diffusion coefficient are independent of the ratio of surface chloride content and chloride threshold of the steel. The concrete cover depth has a higher impact on time to onset of corrosion than does the diffusion coefficient.
2. Considering a feasible range of chloride diffusion coefficients that is relatively easy to achieve in practice for normal concrete, say from 10^{-12} to 10^{-11} m^2/s, decreasing the chloride diffusion coefficient is considered as an effective measure of extending the time to onset of corrosion. A 50% decrease in the chloride diffusion coefficient increases the time to corrosion by 100%. Increasing the concrete cover is an even more effective parameter than chloride diffusion coefficient, since a 50% increase of concrete cover increases the time to onset of corrosion by 125%.

3. The sensitivity of the time to corrosion to the surface chloride content is a function of the ratio of surface chloride content and chloride threshold of the steel. A 50% decrease in surface chloride content would extend the time to onset of corrosion by 261%, 95%, 69%, and 51% in light, moderate, high, and severe conditions, respectively.

4. The sensitivity of the time to corrosion to the chloride threshold level is a function of the ratio of surface chloride content and chloride threshold of the steel. Considering only the "intrinsic" variations ($\pm 40\%$) associated with conventional black carbon steel that are mainly caused by the heterogeneous nature of concrete materials, the variation in time to onset of corrosion will be -40% to 60%, -28% to 32%, -26% to 24%, and -24% to 19%, for light, moderate, high, and severe exposure conditions, respectively. Comparing different corrosion resistant steels, the sensitivity is higher for more corrosion resistant steels with higher chloride thresholds. In practice, increasing chloride threshold is an effective measure to increase the time to onset of corrosion, but the effectiveness of using a more corrosion resistant steel will be lowered with the increasing severity of the exposure, e.g. a 50% increase in chloride threshold will extend the time to onset of corrosion by 260%, 100%, 69%, and 36% for light, moderate, high, and severe conditions.

In summary, a sensitivity analysis was presented in this paper to quantify the error in the predicted time to corrosion initiation by using the simplified deterministic diffusion model with parameters that can have high levels of uncertainty. The impact of each design parameter on the service life of concrete structures that is critical for a durable design was also evaluated. The results of this sensitivity analysis can be used as a guide for the design of durable concrete structures built in chloride-laden environments and for the optimization of inspections and priorities of data collections.

Notation

$C(x,t)$	concentration of chlorides in concrete at depth x and time t;
C_s	surface chloride concentration;
C_{th}	threshold chloride concentration for initiation of corrosion of reinforcing steel;
D	chloride diffusion coefficient into concrete;
d_c	depth of concrete cover to the reinforcement;
$S_j = S(X_j)$	normalized sensitivity coefficient of time to corrosion to parameter X_j;
$S_{hj} = S_h(X_j)$	normalized high-order sensitivity coefficient of time to corrosion to parameter X_j;
t	time (age);
T_i	time to initiation of corrosion of reinforcing steel;
X_j	jth parameter of the model;
X_{j0}	base (or mean) value of jth parameter of the model;
X_j^*	design value of parameter X_j;
X	vector of input variables;
ΔX_j	variation of X_j from its base value.

Appendix A

Table A
Coefficients of polynomial in Eq. (5)

A_6	$=3.87E+06$	A_{12}	$=1.50E+06$
A_5	$=-1.04E+06$	A_{11}	$=-7.45E+06$
A_4	$=1.95E+05$	A_{10}	$=1.66E+07$
A_3	$=-2.40E+04$	A_9	$=-2.11E+07$
A_2	$=1.85E+03$	A_8	$=1.75E+07$
A_1	$=-7.59E+01$	A_7	$=-9.90E+06$
A_0	$=1.78E+00$	Normal residue	0.000001

Table B
Coefficients of polynomial in Eq. (24)

	C_s/C_{th} ratio			
	3.5	6.7	10.2	14.2
B_6	$4.70E+01$	$4.94E+00$	$2.40E+00$	$3.38E+00$
B_5	$-2.72E+01$	$-3.79E+00$	$-1.65E+00$	$1.43E-01$
B_4	$-4.41E+00$	$7.59E-01$	$4.69E-01$	$7.09E-02$
B_3	$3.68E-01$	$-6.93E-01$	$-5.66E-01$	$-7.18E-01$
B_2	$2.39E+00$	$8.79E-01$	$6.23E-01$	$4.63E-01$
B_1	$-1.26E+00$	$-7.46E-01$	$-5.87E-01$	$-5.00E-01$
B_0	$-3.75E-03$	$1.35E-04$	$-1.66E-04$	$5.56E-05$

Table C
Coefficients of polynomial in Eq. (25)

	C_s/C_{th} ratio			
	3.5	6.7	10.2	14.2
C_6	$1.06E-01$	$-2.36E-03$	$-5.43E-04$	$-1.59E-04$
C_5	$2.18E-01$	$2.29E-02$	$6.82E-03$	$2.60E-03$
C_4	$7.47E-02$	$-3.90E-02$	$-2.57E-02$	$-1.47E-02$
C_3	$3.05E-01$	$8.23E-02$	$6.33E-02$	$4.75E-02$
C_2	$7.08E-01$	$1.33E-01$	$1.16E-02$	$-3.37E-02$
C_1	$1.22E+00$	$7.28E-01$	$5.80E-01$	$5.05E-01$
C_0	$-9.93E-04$	$-1.07E-03$	$9.56E-04$	$9.86E-04$
Normal residue	0.02	0.01	0.01	0.01

References

[1] C. Alonso, C. Andrade, M. Castello, P. Castro, Chloride threshold values to depassivate reinforcing bars embedded in a standardized OPC mortar, Cement and Concrete Research 30 (2000) 1047–1055.

[2] ASTM A 615/A 615M-01b, Standard Specification for Deformed and Plain Billet Steel Bars for Concrete Reinforcement, ASTM International, West Conshohocken, Pa, 2002.

[3] P.B. Bamforth, W.F. Price, An International Review of Chloride Ingress Into Structural Concrete, Transport Research Laboratory Report, vol. 359, Transport Research Laboratory, Edinburgh, Scotland, 1997.

[4] D.P. Bentz, Influence of silica fume on diffusivity in cement based materials: II. Multi-scale modeling of concrete diffusivity, Cement and Concrete Research 30 (2000) 1121–1129.

[5] A. Boddy, E. Bentz, M.D.A. Thomas, R.D. Hooton, An overview and sensitivity study of a multimechanistic chloride transport model, Cement and Concrete Research 29 (1999) 827–837.

[6] P.D. Cady, R.E. Weyers, Chloride penetration and deterioration of concrete bridge decks, Cement, Concrete and Aggregates 5 (2) (1983) 81–87.

[7] Crank, The Mathematics of Diffusion, 2nd edition. Clarendon Press, Oxford, 1975.

[8] V.K. Gouda, Corrosion and corrosion inhibition of reinforcing steel, British Corrosion Journal 5 (1970) 198.

[9] J.A. Gonzalez, S. Algaba, C. Andrade, Corrosion of reinforcing bars in carbonated concrete, British Corrosion Journal 15 (3) (1980) 135–139.

[10] J. Kropp, H.K. Hilsdorf (Eds.), Performance Criteria for Concrete Durability, RILEM Report, vol. 12, E&FN Spon, London, 1995.

[11] Z. Lounis, A.J.M. Siemes, M. Lacasse, K. Moser, Further steps towards a quantitative approach to durability design, Materials and Technologies for Sustainable Construction, CIB World Congress, Gävle, Sweden, 1998, pp. 315–328.

[12] Z. Lounis, Reliability-based life prediction of aging bridge decks, in: D. Naus (Ed.), Life Prediction and Aging Management of Concrete Structures, RILEM Publications, France, 2000, pp. 229–238.

[13] Z. Lounis, Uncertainty modeling of chloride contamination and corrosion of concrete bridge, in: N.O. Attoh-Okine, B. Ayyub (Eds.), Applied Research in Uncertainty Modeling and Analysis, Springer, 2004, pp. 491–511, Chapter 22.

[14] R.E. Melchers, Structural Reliability—Analysis and Prediction, Ellis Horwood, Chichester, UK, 1987.

[15] A. Rosenberg, C.M. Hansson, C. Andrade, Mechanisms of corrosion of steel in concrete, in: J. Skalny (Ed.), Materials Science of Concrete *I*, The American Ceramic Society, Inc., Westerville, OH, 1989, pp. 285–313.

[16] M.D.A. Thomas, P.B. Bamforth, Modeling chloride diffusion in concrete — effect of fly ash and slag, Cement and Concrete Research 29 (1999) 187–495.

[17] D. Trejo, R.G. Pillai, Accelerated chloride threshold testing—Part I: ASTM A 615 and A 706 reinforcement, ACI Materials Journal 100 (6) (2003) 519–527.

[18] D. Trejo, R.G. Pillai, Accelerated chloride threshold testing—Part II: Corrosion-resistant reinforcement, ACI Materials Journal 101 (1) (2004) 57–64.

[19] K. Tuutti, Corrosion of Steel in Concrete, CBI Research Report, vol. 4:82, Swedish Cement and Concrete Research Institute, Stockholm, 1982.

[20] K. Tuutti, Chloride induced corrosion in marine concrete structures, Durability of Concrete on Saline Environment, Uppsala, 1996, pp. 81–93.

[21] A. Saltelli, S. Tarantola, F. Campolongo, Sensitivity analysis as an ingredient of modeling, Statistical Science 15 (4) (2000) 377–395.

[22] R.F. Stratfull, The corrosion of steel in a reinforced concrete bridge, Corrosion 13 (March 1956) 173–178.

[23] R.E. Weyers, B.D. Prowell, M.M. Sprinkel, Concrete Bridge Protection, Repair, and Rehabilitation Relative to Reinforcement Corrosion: A Methods Application Manual, 1993, SHRP-S-360.

[24] J. Bijen, Benefits of slag and fly ash, Construction and Building Materials 10 (5) (1996) 309–315.