



Probabilistic modeling of chloride-induced corrosion in concrete structures using first- and second-order reliability methods

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ABSTRACT

Concrete structures are subjected to chloride-induced corrosion that can lead to shortened service life. Reliable predictions of life cycle performance of concrete structures are critical to the optimization of their life cycle design and maintenance to minimize their life cycle costs. This paper presents two simplified semi-analytical probabilistic models based on the first- and second-order reliability methods to model the uncertainty of the key parameters including surface chloride concentration, chloride threshold, cover depth and diffusion coefficient, which govern the chloride ingress into concrete and corrosion of reinforcing steel. A case study of a reinforced concrete highway bridge deck is used to illustrate the capability and efficiency of these simplified probabilistic models in modeling the uncertainty and predicting the time-dependent probability of corrosion. The models enable to quantify the impact of the different governing parameters on probability of corrosion and service life, which can be used to develop cost-effective management strategies.

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1. Introduction

The main cause of deterioration of different types of concrete structures (bridges, marine structures, off-shore platforms, parking garages, etc.) is due to chloride-induced corrosion of the steel reinforcement. The primary source of chlorides is from the external environment, either from deicing salts using during the winter months or from seawater. The rate of ingress or penetration of chlorides is dependent primarily on the quality of concrete and more particularly on the water–cement ratio of the concrete mix, 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 (e.g. protective membrane). In porous media, such as concrete, chlorides can penetrate concrete via different physical mechanisms, such as diffusion, capillary absorption, electrical migration, presence of cracks and permeation due to hydraulic pressure heads [25]. Furthermore, the penetration process is also influenced by chemical reactions, such as chloride binding.

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 serviceability, strength, safety and service life of concrete structures are reduced.

In the last three decades, chloride-induced corrosion has been extensively studied [43,39,8], particularly, as a result of the high costs of highway bridge repair in North America and Europe from the effects of chloride-induced corrosion and deterioration of concrete infrastructure. Most of these studies are based on the assumption of a 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. Despite the large amount of research, the design of concrete structures for durability is mainly based on prescriptive rules, such as specifying minimum concrete cover depth (depending on the environmental exposure), maximum water-to-cement ratio (to achieve low chloride diffusivity), use of more corrosion resistant reinforcing steels (e.g. stainless steel), and use of protection systems. However, a considerable level of uncertainty may be associated with one or more of the above 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 the structure; (iii) variability of surface chloride concentration, that depends on the severity of the environmental exposure, precipitation, washing of structure; 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 or service life. This uncertainty in the model output could have serious consequences in terms of inadequate design, planning of

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inspection and maintenance which in turn will shorten the service life of the structure and increase the life cycle cost [50,11]. Therefore, for an effective performance-based life cycle design that includes the use of mechanistic service life models will lead to a minimization of cost at the same time provides the level of service life required.

The objectives of this paper are threefold: (i) present a performance-based approach to durability or life cycle design based on mechanistic models for chloride ingress into concrete and onset of steel reinforcement corrosion; (ii) present simplified semi-analytical probabilistic models based on first-order and second-order reliability methods (FORM/SORM) that take into account the uncertainty and variability in the governing parameters and propagate it to predict the time-dependent probability of chloride contamination of concrete cover and probability of corrosion of steel reinforcement; and (iii) to assess the efficiency of the simplified analytical FORM and SORM methods by comparing their predictions to those obtained by using Monte Carlo simulation (MCS) with a large number of simulations on a typical highway concrete bridge deck exposed to deicing salts during winter.

2. Overview of mechanisms of chloride ingress into concrete structures

Since concrete is a porous medium, chlorides can penetrate concrete through a number of mechanisms. First, if the concrete is not fully saturated, the salt solution is absorbed into the unfilled spaces by capillary action [19]. As the chlorides migrate into the concrete, some chlorides are absorbed onto concrete and react with the cement hydrates [38], which slows down the rate of chloride migration [31]. When the surface dries, the salt crystallizes. With successive cycles, there may be a progressive build-up of salts at the surface and in the near surface layers until, after few cycles, a limiting value is reached [36]. The time it takes to achieve a stable surface level will, however, depend on the severity of exposure. In addition to this early absorption, the chloride ions migrate further into the concrete by diffusion through the pore water that is driven by the concentration gradient between the surface and the sub-surface layers. As the chlorides migrate further, so the process of “binding” continues to remove chlorides from the pore solution [2]. In concrete, which is permanently submerged and saturated, this diffusion process is the only means of transport after the initial wetting. However, even without drying there may be a build-up of chlorides in the pores water to a level above that of the surrounding saline solution, due to a process defined as chloride “condensation” [35]. This is may be due to the physical adsorption of chlorides onto the pore surfaces by the electric double layer in cement and can result in chloride concentrations, which can be two to four times those of the solutions to which the concrete is exposed. These are commonly referred to as loosely-bound chlorides.

Therefore, in the absence of shrinkage phenomena, the main transport mechanisms of chlorides into concrete are diffusion and adsorption [25]. 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 [44], so beyond this adsorption zone, the diffusion process will dominate [44,14].

Otherwise, if the concrete cover presents a considerable amount of cracking, two modeling options might be proposed:

- In a cracked concrete cover with relatively few and small cracks, the effect of cracks on the chloride ingress can be considered, by using the same diffusion model with a modified “apparent” diffusion coefficient that takes into account the effect of cracks on the diffusion as in [12,17,16,6].

- In a cracked concrete cover with several and large cracks, diffusion may not be the governing mechanism and the effect of cracks may lead to “permeability” as a mechanism for chloride transport that, by itself, needs to be modeled. This article does not take into account this case.

The chloride diffusion phenomena 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 [10]. 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 be used to predict the time variation of chloride concentration for one-dimensional flow. This law can be expressed as a relationship between the diffusion coefficient and the gradients of concentration, by direct analogy with the equations of heat conduction [10], as follows:

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

where $C_{x,t}$ is the concentration of chlorides at depth x and time t ; D is the diffusion coefficient of chlorides, which is assumed to have a constant value, called “apparent” (or “effective”) diffusion coefficient [2].

In fact, at early age, the diffusion coefficient presents a wide range of scatter (especially with respect to the 28-day value); however this scatter becomes less significant, especially after 5 years. All types of remaining uncertainties, such as time and space variation are supposed to be captured by the probabilistic model proposed. Therefore, the diffusion coefficient used is taken as a random variable having its characteristics based on, an “effective” time-invariant mean value, which is a good fit in the diffusion model, and varies in a narrow range of standard deviation to take into account the remaining uncertainties, that are induced by the effects of chloride binding and concrete aging.

Under the assumptions of a constant diffusion coefficient, a constant surface chloride concentration C_s as the boundary condition, and the initial condition specified as $C_{x,t} = 0$ for $x > 0$, $t = 0$, Crank’s solution yields [10]:

$$C_{x,t} = C_s \left(1 - \operatorname{erf} \frac{x}{2\sqrt{Dt}} \right) \quad (2)$$

where $\operatorname{erf}(\cdot)$ is the error function or Gauss error function, which is very similar to the standard normal (or Gaussian) cumulative distribution function $[\Phi(\cdot)]$. $\operatorname{erf}(\cdot)$ and $\Phi(\cdot)$ differ only by scaling and translation as follows:

$$\operatorname{erf}(x) = 2\Phi(x\sqrt{2}) - 1 \quad (3)$$

In modeling the chloride ingress as a Fickian process, the following assumptions are made:

- Some phenomena (e.g. capillary flow, chloride binding, etc.) are not explicitly considered.
- Crank’ solution for a plane sheet assumes dealing with plane isotropic concrete structures, i.e. one dimensional diffusion.
- The diffusion coefficient and surface chloride concentration are assumed time-invariant.
- Initial concentration of chlorides in the concrete is negligible.
- Interaction with other ions and with electrical double layer is ignored [9].

These conditions are not necessarily satisfied, for many reasons. For example, the diffusion coefficient is not constant because it is influenced by the following factors [25]: (i) concrete is not

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