Centrum
Rzeczoznawstwa
Budowlanego

**Inżynieria Bezpieczeństwa**
**Obiektów Antropogenicznych 4 (2023) 35-45**
https://inzynieriabezpieczenstwa.com.pl/

Inżynieria Bezpieczeństwa
Obiektów Antropogenicznych

# Modeling of chloride-induced corrosion in concrete bridge using the simplified and full probabilistic methods

Izabela SKRZYPCZAK[1*], Anna HALICKA[2], Marta SŁOWIK[2]

[1] *Rzeszow University of Technology, Faculty of Civil and Environmental Engineering and Architecture, Powstańców Warszawy 12 Av., 35-959 Rzeszow, Poland*
[2] *Lublin University of Technology, Faculty of Civil Engineering and Architecture, Lublin, Poland*

## Abstract

Concrete and reinforced concrete structures are subjected to chloride corrosion, which can shorten their service life and safety of use. Reliability and safety prediction of concrete structures is a crucial task for optimizing their life cycle design and maintenance and for minimizing their life cycle costs. In the paper a probabilistic analysis of concrete durability in structural members is presented. Two methods: simplified-probabilistic and full-probabilistic have been applied for modelling chloride-induced corrosion in concrete structures. 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 have been analyzed. A case study of a reinforced concrete bridge has been used to illustrate the capability and efficiency of these probabilistic methods in modeling the uncertainty and predicting the time-dependent probability of corrosion. FREeT-D and ProCAAT software have been used for the analysis.

**Keywords:** durability limit states, chlorides, probabilistic analysis, reinforced concrete structures

## 1 Introduction

The main cause of degradation of concrete in structures such as pavements, bridges, marine structures, parking lots and garages results from chloride-induced corrosion of reinforcing steel. The main source of chlorides is the external environment. This applies to the use of de-icing salts or seawater. The rate of chloride entry or penetration

---

* **Corresponding author:** E-mail address: (izas@prz.edu.pl) Izabela SKRZYPCZAK

https://dx.doi.org/10.37105/iboa.194
Received 15 November 2023
Available online 5 December 2023
ISSN 2450-1859, eISSN 2450-8721
Published by Centrum Rzeczoznawstwa Budowlanego

depends primarily on the quality of the concrete, in particular the ratio of water to cement in the concrete mixture, the presence of cement additives (e.g. silica, fly ash or slag). There are various physical mechanisms of chlorides entering concrete: diffusion, capillary absorption, electrical migration, presence of cracks and penetration under the influence of hydraulic pressure (Kropp, 1995 Saassouh and Lounis, 2012). Furthermore, the penetration process is also influenced by chemical reactions such as chloride binding. Corrosion of steel reinforcement leads to cracking of concrete through cracking, delamination and spalling of the concrete cover, reduction of both the cross-sections of the concrete and the reinforcement, loss of bond between the reinforcement and concrete, and a reduction in the concrete strength. As a result of chloride corrosion, the usefulness functional properties, strength, safety and service life of concrete structures are reduced.

Chloride-induced corrosion has been and is is constantly being widely studied (Tuutti, 1982; Rosenberg et al., 1989; Cady and Weyers, 1983), particularly as a result of the high costs of repairing and maintaining communications infrastructure resulting from the effects of chloride-induced corrosion and degradation. Most studies and analyzes concern the diffusion process, predicting changes over time, predicting the chloride content in concrete, and determining the chloride threshold to determine the chloride corrosion resistance of reinforcing steel. Despite many studies, the design of concrete structures in terms of their durability is still based on determining the minimum cover thickness (depending on environmental exposure), the maximum water to cement ratio (in order to obtain a low chloride content), the use of more corrosion-resistant reinforcing steel (e.g. .stainless steel) and the use of security systems. However, a significant level of uncertainty may be associated with one or more of the above parameters (due to Alonso et al., 2000):

- the heterogeneity and aging of concrete together with its temporal and spatial variability in terms of chloride diffusivity;
- variability of the depth of concrete cover, which depends on the quality of workmanship and type of structure;
- variability of surface chloride concentrations, depending on the degree of environmental exposure, precipitation, and leaching of structures;
- uncertainty regarding the chloride threshold level, which depends on the type of reinforcing steel, type of cementitious materials, test methods.

The combination of these uncertainties leads to significant uncertainty in the computational model, i.e. time to corrosion initiation or service life. Uncertainty in both: the model and the input parameters to the model can lead to significant consequences like inappropriate concrete mix design, inspection and maintenance planning, which in turn can reduce the service life of the structure and increase life cycle costs (Zhang and Lounis, 2009; Cusson et al., 2010). Therefore, analyzes using simplified and fully probabilistic methods related to modeling chloride corrosion in concrete structures seem to be effective tools to ensure the required level of durability and minimize maintenance costs.

The aims of this paper is to analyze the durability to life cycle based on mechanistic models for chloride ingress into concrete and onset of steel reinforcement corrosion. The simplified probabilistic method (FORM) and in-full probabilistic method (Monte Carlo Simulation - MCS) were used for analyses. The methods take into account the uncertainty and variability of parameters in order to predict the time-dependent probability of chloride contamination of concrete cover and probability of corrosion of steel reinforcement for concrete bridge deck. The analyzes were performed using two kinds of software: ProCAAT (FORM method) and FREeT-D (FORM method and SMC method). It enables to quantify the impact of the different parameters on probability of corrosion and service life, which can be used to develop effective management strategies of bridges. The probability of failure is an important indicator in design or assessment of concrete structures. Attention is focused on chlorides corrosion as it is one of the most usual deterioration mechanisms attacking reinforced concrete bridges.

## 2 Reliability and Durability of Concrete Structures

Durability and reliability rank amongst the most decisive structural performance characteristics. The reliability analysis is significant for assessment of structures service life, inspection and maintenance planning, decisions about making repairs and life cycle costing. The time-dependent limit state approach is recommended probabilistic approaches to the assessment of structures for durability in codes (ISO 13823:2008; Model Code:2012; ISO 2394:1998).. Probabilistic reliability assessment and durability assessment of structure can be applied to life cycle costing (LCC), life cycle assessment (LCA) and life cycle management (LCM) [Frangopol et al., 2012; Thoft-

Christensen, 2012). The general definition of structural reliability can be found in codes as well (ISO 2394:1998; Model Code:2012). The verification of a structure with respect to its reliability to a particular limit state, is carried out via estimation of the probability of the occurrence of failure in a specified reference period. The aim of reliability analysis is an estimation of unreliability using a probability measure called the failure probability $P_f$, defined as (1):

$$P_f = P\ (R \leq S\ ) < P_{fd}$$

where: $S$ is the effect of an action and $R$ is the resistance; both are random variables and $P_d$ is the design (acceptable, target) probability value.

The equation (1) expresses the limit state for the ultimate limit states (ULS) and serviceability limit states (SLS). Alternatively the target value of the index of reliability $\beta_d$ can be utilized instead of $P_f$ in practice. In this case, the target reliability level refers to an acceptable failure probability corresponding to a specified reference period. The reliability target refers to the acceptable probability of failure corresponding to a specified reference period. The definition of structural reliability is presented in (ISO 2394:1998; Model Code:2012). If $R$ and $S$ are independent normal random variables then $g= R\text{-}S$ is also a normal random variable and in this case, equation (1) transforms into equations (2) and (3) (4):

$$P_f = P(g=R-S<0)=\Phi[(0-\mu_g)/\sigma_g]$$

$$P_f = \Phi(-\mu_g/\sigma_g) = \Phi(-\beta)$$

where Φ(.) is the standard function of the normal probability distribution.

The structure can be considered reliable when the calculated value of the reliability index according to formula (3) is not less than the target value (5):

$$\beta > \beta_{\lim}$$

Annex B in the PN-EN 1990:2004 provides the recommended minimum (target) values of the reliability index for ULS structures of various reliability classes and for reference periods $T_0$ = 1 year and 50 years (Table 1 and Table 2).

| **Reliability classes** | $\beta_{\lim}$ / $P_{fd}$ **for** $T_0$ **= 1 year** | $\beta_{\lim}$ / $P_{fd}$ **for** $T_0$ **= 50 years** |
|---|---|---|
| RC3 | 5.2 / 9.96E-08 | 4.3 / 8.54E-06 |
| RC2 | 4.7 / 1.30E-06 | 3.8 / 7.23E-05 |
| RC1 | 4.2 / 1.33E-05 | 3.3 / 4.83E-04 |

**Table 1.** *Minimum values of the reliability index* $\beta_{lim}$ *according to* PN-EN 1990:2004

| **Limit States** | $\beta_{\lim}$ **for** $T_0$ **= 1 year** | $\beta_{\lim}$ **for** $T_0$ **= 50 years** |
|---|---|---|
| Ultimate Limit States | 4.7 | 3.8 |
| Serviceability Limit States |  | 1.5 to 3.8 |
| Fatigue Limit States | 2.9 | 1.5 |

**Table 1.** *The target reliability index* $\beta_{lim}$ *for the considered Limit States according to* PN-EN 1990:2004

In general, $S$ and $R$ can change over time and therefore $P_f$ and $\beta$ are time dependent. This is important for durability analysis (ISO 13823:2008; Model Code:012). Therefore, probabilistic methods should be used to assess the reliability of both new designed and existing structures. The randomness and uncertainty of parameters regarding durability analysis, including corrosion caused by chlorides, force the use of this methods. Significant uncertainties regarding, parameters affecting the destruction processes of concrete and reinforced concrete structures highlight the need to use this approach.

## 3 Ingress of Chloride Ions

Corrosion of reinforcement is certainly one of the most limiting factors for the service life of reinforced concrete structures. Steel bars are passive, as far as corrosion in the presence of oxygen and moisture is concerned, thanks to a microscopically thin oxide layer which forms on their surface due to the alkalinity of the surrounding concrete. Protective layer is dissolved if the alkalinity of the concrete is lost due to carbonation. This layer, in marine and coastal environments, or in the presence of deicing salt ($NaCl$), it can be destroyed by chloride ions dissolved in pore water. The chloride level at the reinforcement surface which results in a significant corrosion rate leading to reinforcement corrosion in concrete may be called the critical chloride concentration (the chloride threshold concentration). Corrosion rates exceeding values of $1\text{-}2\ \mu A/cm^2$ are often regarded as being significant on reinforcing steel (Glass and Buenfeld, 1997).

The chloride threshold concentration is preferably presented by means of the total amount of chloride by weight of cement, amount of a free chloride, a concentration ratio of free chloride ions to hydroxyl ions or ratio of acid soluble chloride content and the acid neutralization capacity (the content of acid needed to reduce the pH of concrete and cement paste suspended in water up to particular value) (Ann and Song, 2007). On basis of the research (Glass and Buenfeld, 1997; Ann and Song, 2007), the total chloride content related to the cement weight is considered as the best parameter of analysis of chloride ingress. That conducted to the reduction in the range of determined values of the critical chloride concentration and represents the total potential aggressive ion content expressed relatively to the total potential inhibitor content (Ann and Song, 2007; Duprat, 2007; Glass and Buenfeld, 1995; Glass and Buenfeld, 1997).

One reason for the lack of agreement among the measured values of the critical chloride concentration is the influence of several factors such as chloride binding, chloride mobility, steel interface (voidage, pre-rusting), cementitious binder (type of binder, C3A content, pH), concrete barrier (cement type, amount of cement, w/c ratio, curing, concrete cover), and environmental factors (relative humidity, temperature, chloride type). The key factor was found to be a physical condition of the steel-concrete interface (Ann and Song, 2007; Glass and Buenfeld, 1995). Another reason is the difference among the methods of measurement of the chloride threshold concentration, the chloride content at the steel surface and the time of onset of corrosion. The onset of corrosion may be detected by measuring half-cell potential, monitoring the macrocell current between an anode and a cathode, monitoring the corrosion rate measured by the polarisation technique or AC impedance method, or visual inspection.

## 4 Durable Limit-State Functions of Ingress of Chloride Ions

For the modelling of chloride induced corrosion in uncracked concrete a model has been developed within the DURACRETE research project, funded by the European Union. In this research, only de-icing salt effects and chloride contaminated aggregates or water are considered (no marine or costal environments). The formula for $C(x = a, t)$ is presented in [fib TG 5.6, 2007; fib Bulletin:2006) (6):

$$\mathrm{C}(x=a,t) = \psi\left(C_0 + (C_{S,\Delta x} - C_0)\cdot\left[1 - \mathrm{erf}\frac{a-\Delta x}{2\cdot\sqrt{D_{app,C}(t)\cdot t}}\right]\right)$$

Where:

$C(x\text{-}a, t)$ - content of chlorides in the concrete at depth x (structure surface: x = 0 mm) and at an arbitrary time of exposure $t$ (or target design service life $t_D$) [wt.-%/cement]

$C_0$ - initial chloride content of the concrete [wt.-%/cement]

$C_{S,\Delta x}$ - chloride content at depth $\Delta x$ and a certain point of time $t$ or $t_D$ [wt.-%/cement]

$x$ - depth [mm] with a corresponding content of chlorides $C(x, t)$

$a$ - concrete cover [mm]

$\Delta x$ - depth of the convection zone (the concrete layer, up to which the process of chloride penetration differs from Fick's 2nd law of diffusion) [mm]

$D_{app,C}(t)$ - apparent diffusion coefficient of chloride through concrete [$m^2/s$]

$t$ - an arbitrary time of exposure or target design service life ($t_D$) [years]

$erf(\cdot)$ - error function

$\psi$ - uncertainty factor of the model [-]

*To* - create a limit state function the $t = t_D$ has to be used, $t_D$ being the specified target service life. Indicative values for the target design service life $t_D$ are given in Table 2

| Target design service life $t_D$ [years] | Examples |
|---|---|
| 10 | temporary structures<br>(structures or parts of structures that can be dismantled with a view to being re-used should not be considered as temporary) |
| 10-25 | replaceable structural parts, e.g. gantry girders, bearings |
| 25-30 | agricultural and similar structures |
| 50 | building structures and other common structures |
| 100 | monumental building structures, bridges, and other civil engineering structures |

**Table 1.** *Minimum values of the reliability index $\beta_{lim}$ according to* (fib TG 5.6: 2007).

## 5 Case study

It appears that predictive probabilistic models should be applied to estimate how resistance, loads and safety levels will change over time. The software packages FReeT-D (FREeT-D, 2017) and ProCAAT (ProCAAT:2017), have been used efficiently. Models e.g. chloride ingress are accessible. Some applications are described e.g. in (Vořechovská et al., 2009). A parametric study based on the following limit state condition has been extracted from (Teplý and Vořechovská, 2012).

The actual ingress of chloride ions over time is computed according to an analytical model implemented in FREeT-D and ProCAAT (ProCAAT:2017). In this example, time $t_D$ represents the propagation period only; to perform a service life prediction, the appropriate initiation period must be added. All input information is listed in Table 1. Note that the adopted concrete is approximately of class C30/37, which is relevant e.g. to exposition class XF4 according to (PN-EN 1992-1-:2003).

The proposed probabilistic approach for the uncertainty modeling and prediction of chloride concentration of concrete corrosion is illustrated on an example a reinforced concrete bridge deck structure that is subjected to the application of deicing salts during winter.

The example is used to show the applicability, accuracy and efficiency of probabilistic method to model the uncertainty in the parameters governing the probability of corrosion of reinforced concrete structures subjected to chloride attack.

The parameters values are based on data taken from field data and literature (Lounis, 2004; Lounis and Mirza, 2001; ProCAAT, 2017; FREeT-D, 2017)) and are presented in Table 3.

| **Description/ Parameter/ [Units]** | **Distribution function** | **Mean (μ)** | **Standard deviation (σ)** | **Coeff. of variation (c.o.v)** |
|---|---|---|---|---|
| Ccrit/ Critical chloride content [wt.-%/c] | Beta | 0.60 | 0.15 | |
| $C_o$/ Initial chloride content [wt.-%/c] | Determinstic | 0.10 | | |
| $C_s$ or $C_{s.\Delta x}$ / Chloride content at surface or at substitute surface at depth Δx [wt.-%/c] | Lognormal | 1.00 | 0.50 | 0.50 |
| a/ Concrete cover [mm] | Normal | 35 | 6.00 | 0.12 |
| Δx/ Transfer function - Splash conditions (XS3) [mm] | Beta | 10.0 | 5.00 | |
| $D_{RCM.0}$ / Chloride migration coefficient [E-12 m2/s] | Normal | 7.567 | 1.513 | 0.20 |
| $k_t$ / Transfer parameter [-] | Constant | 1.0 | | |
| $b_e$ / Regression variable [K] | Normal | 4800 | 700 | 0.15 |
| $T_{ref}$ / Standard test temperaturę [K] | Deterministic | 293 | | |
| $T_{real}$ / Temperature of the structural element or the ambient air [°F] | Normal | 32.0 | 15.7 | 0.49 |
| $t_o$ / Reference point of time [years] | Deterministic | 0.0767 | | |
| α /Ageing exponent-Portland cement concrete [-] | Beta | 0.30 | 0.12 | |
| $t_{SL}$ / Design service life [years] | Deterministic | 100 | | |
| B / Target reliability index [-] | Deterministic | 1.30 | | |

**Table 3.** *Data for analysis*

The first stage of analysis was performed in ProCAAT software (ProCAAT:2017). the second stage - sensitivity analysis in FREeT-D software (FREeT-D. 2017).

Figures 1-4 were obtained from the ProCAAT software. Figure 1 shows variation of probability of failure over time and of reliability index over time. The limit value of β = 1.3 for 100 years prescribed typically for SLS (according to Model Code) is also shown in the figure.  It appears that e.g. for $t_D$ = 20 years the cover should be greater than 35 mm to satisfy the serviceability requirements; for $t_D$ = 15 years. 30 mm of cover would be satisfactory.

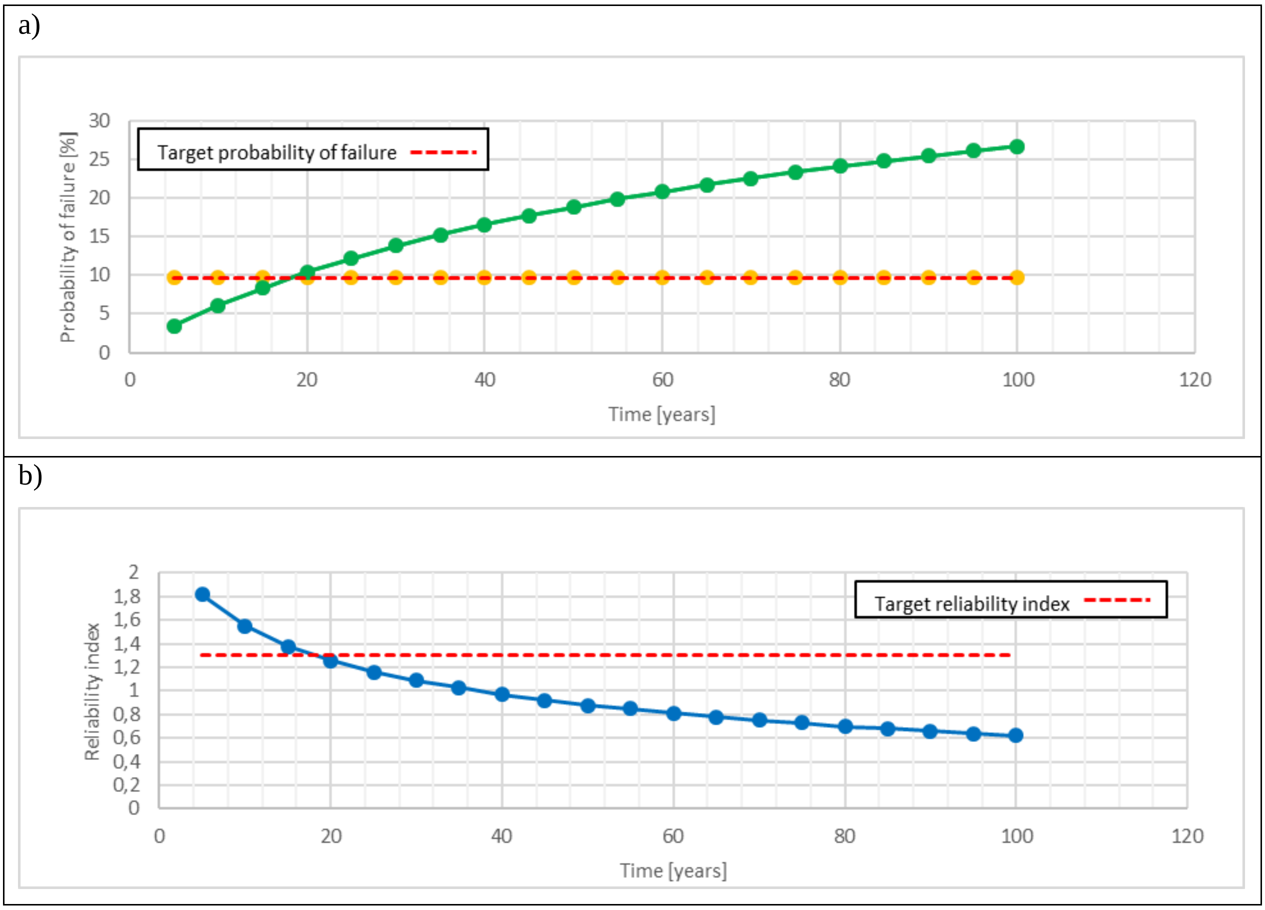
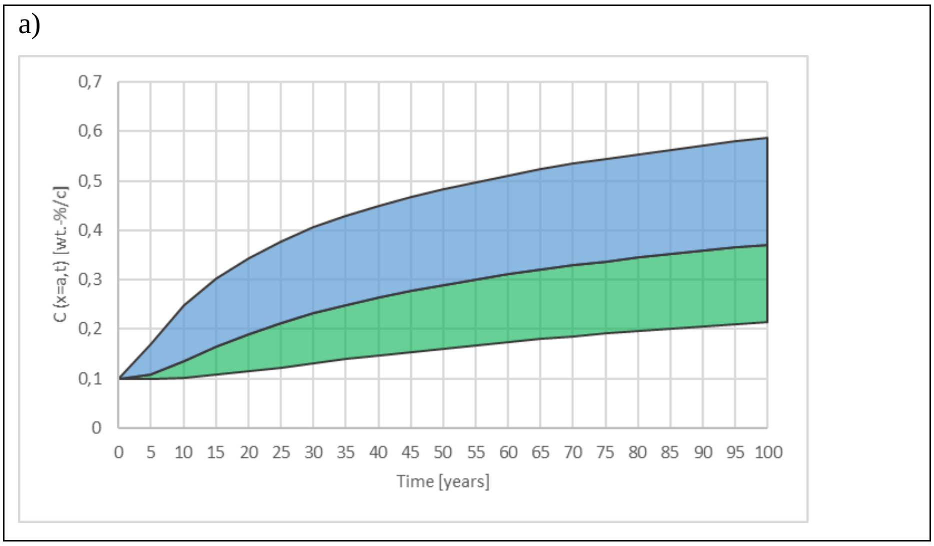


**Figure 1.** *Variation of probability of: a) of failure over time ; b) reliability index over time*

Figure 2 shows variation of chloride content at the reinforcement depth over timea and variation of the depth of critical chloride content over time.



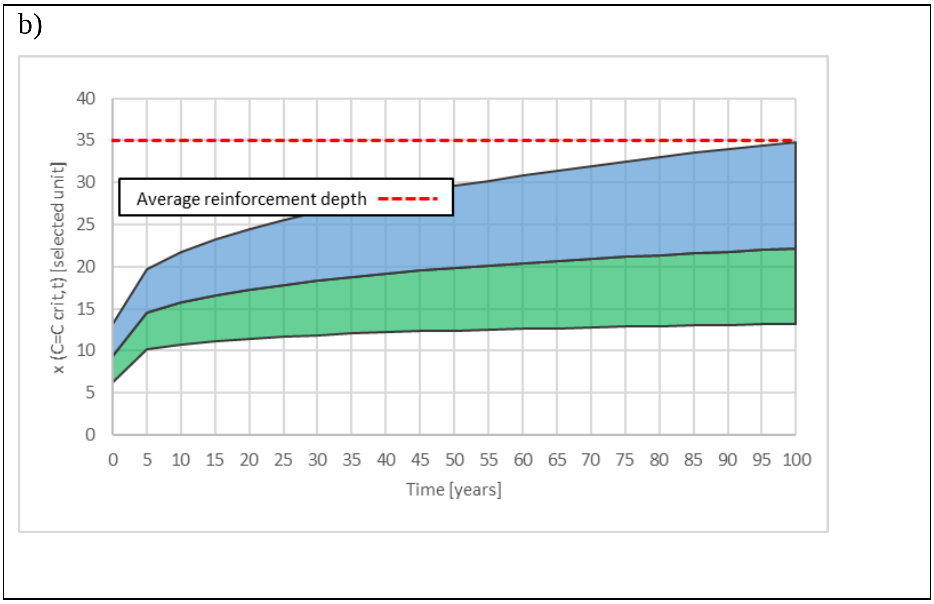


**Figure 2.** *Variation of: a) chloride content at the reinforcement depth over time; b) depht of critical chloride content over time*

A change in the variation coefficient of the chloride threshold has a much lower impact on the probability of corrosion than that of the cover depth. The same range of variation was noticed for the diffusion coefficient (*D*) and surface chloride concentration (*Cs*) (Figure 2-4).

The probability of corrosion is affected marginally by a change in the variation coefficient of the three parameters *Cs* . *D* and $C_{th;}$ its range of variation does not exceed the 5%; however exceeds 20% in case of change in the cover depth variation coefficient.

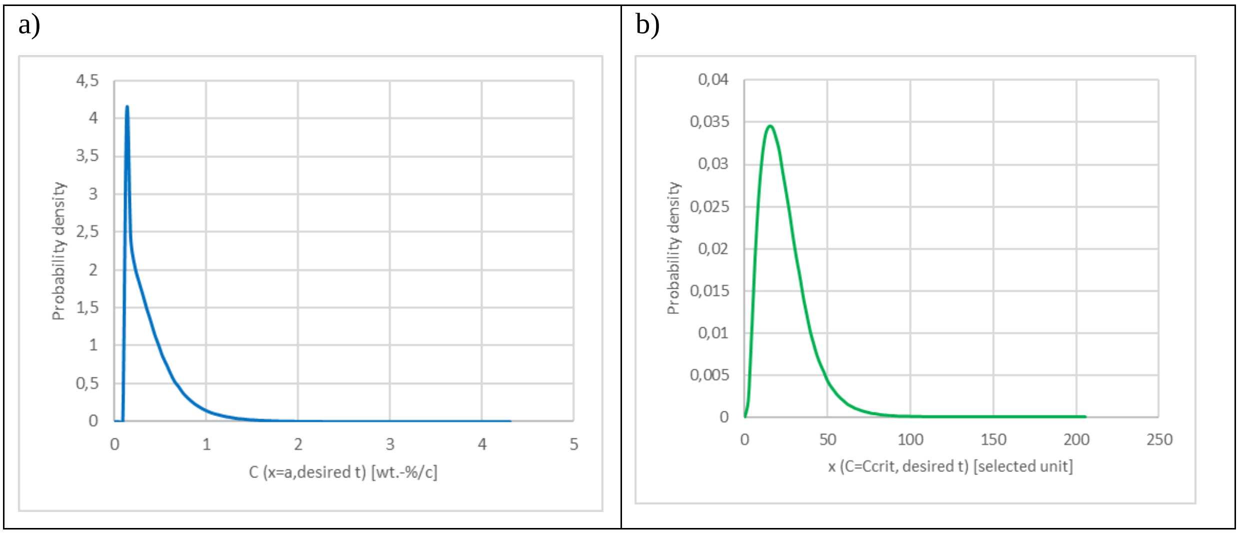


**Figure 3.** *Probability distribution of: a) chloride content at the reinforcement depth at desired time; b) depth of critical chloride content at desired time*

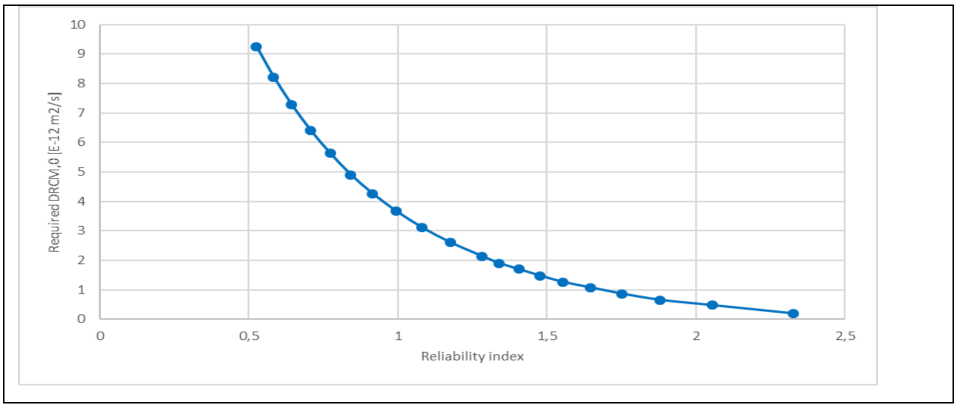


**Figure 3.** *Required chloride migration $D_{RCM.0}$ for the target reliability index β*

The Limit State Function graph was obtained from the FREeT-D software (Fig. 6).

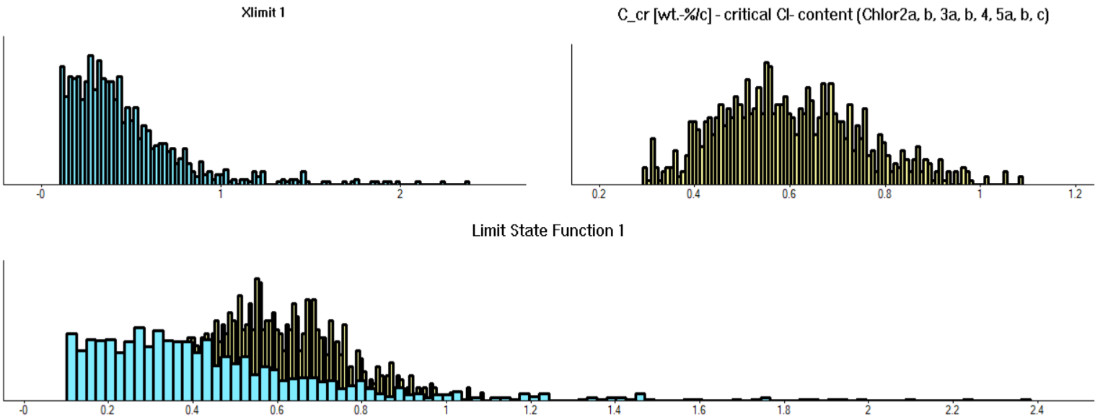


**Figure 6.** *The graph for the defined limit state function*

Sensitivity analysis was performed in FREeT-D software (FREeT-D. 2017). Based on the sensitivity analysis. it is possible to assess the importance of the parameters and their impact on the probability of corrosion and. above all their impact on the value of the reliability index. Assuming that the parameter values are the same as in Table 3 and taking into account sensivity analysis. it can be concluded that: the probability of corrosion is significantly influenced the three parameters $C_s$. or $C_{th}$; $k_t$; *a* and marginally regression variable (Table 4).

| Description/ Parameter/ | Value of sensivity coefficients |
|---|---|
| $C_s$ or $C_{s.\Delta x}$ / Chloride content at surface or at substitute surface at depth Δx | 0.59526 |
| a/ Concrete cover | -0.48479 |
| $k_t$ / Transfer parameter | -0.40874 |
| Δx/ Transfer function - Splash conditions | 0.26674 |
| $D_{RCM.0}$/ Chloride migration coefficient | 0.13914 |
| $b_e$ / Regression variable | -0.057333 |

**Table 4.** *Values of sensitivity coefficients for selected parameters*

In terms of the efficiency of FORM vs. MCS. the results are comparable. For such adopted parameters (Table 3) and the analysis performed (Figure 1-3). the considered bridge slab has unsatisfactory reliability.

## 5 Summary

This paper presented two probabilistic methods for reliability analysis (FORM and MCSM) to model the uncertainty of the parameters that govern the chloride ingress into concrete and onset of corrosion of reinforcing steel in reinforced concrete structures subjected to chlorides from deicing salts. A case study illustrated the main capability and efficiency of the presented methods for the life cycle based design a of reinforced concrete structures.

These models can be used by designers to quantify how changes to the structural design and maintenance will affect its probability of corrosion and service life.

The proposed methods enables also to study the sensitivity of the corrosion probability to different parameters. including their mean values and coefficients of variation. It is found that in order to achieve a low corrosion probability and durable design. the concrete cover depth is the most influencing parameter. More specifically. the variability of the cover depth makes it very important vs. the other parameters.

## Acknowledgment

The research leading to these results has received funding from the commissioned task entitled “VIA CARPATIA Universities of Technology Network named after the President of the Republic of Poland Lech Kaczyński” contract no. MEiN/2022/DPI/2578, action entitled “In the neighborhood—inter-university research internships and study visits”.

The authors would like to thank Paolo Bocchini. Professor and Director of the Catastrophe Modeling Center at Lehigh University for making ProCAAT software available in the performed research.

## Bibliography

1. Alonso C. Andrade C. Castello M. Castro P.(2000). Chloride threshold values to depassivate reinforcing bars embedded in a standardized opc mortar. *Cem Concr Res; 30*. pp.1047–55.
2. Ann. K.Y.. Song. H.W. (2007) Chloride threshold level for corrosion of steel in concrete. *Corrosion Science. 49.* pp. 4113–4133.
3. Cady P. Weyers R. (1983). Chloride penetration and deterioration of concrete bridge decks. *Cem Concr Aggreg. 5(2)*. pp. 81–97.
4. Cusson D. Lounis Z. Daigle L. (2010). Benefits of internal curing on service life and lifecycle cost of high-performance concrete bridge decks – a case study. *Cem Concr Compos;32(5)*. pp.339–500.
5. Duprat. F. (2007) Reliability of RC beams under chloride-ingress. *Construction and Building Materials. 21.* pp. 1605–1616.
6. fib TG 5.6 (2007) fib Model Code for Service Life Design. Proposal for future fib Model Code. 2007.
7. FIB. fib Final Model Code. fib Bulletins No. 65 and 66. Lausanne. Switzerland. 2012
8. FREeT-D:2017 (2017). FReET-D PROGRAM DOCUMENTATION Revision 01/2017. FReET Deterioration Module version 1.4
9. Frangopol. D.M.. Saydam. D.. Kim. S.. (2012). Maintenance. management. life-cycle design and performance of structures and infrastructure: a brief review. *Structure and Infrastructure Engineering. 8.* pp. 1– 25
10. *fib* Bulletin 34:2006 (2006). *Model Code for Service Life Design*. fib Bulletin 34. International Federation for Structural Concrete (fib). Lausanne. Switzerland.

11. Glass. G.K.. Buenfeld. N. R. (1995) Chloride threshold levels for corrosion induced deterioration of steel in concrete. In Proc. of the Proc. of the International Workshop Chloride penetration into concrete. Nilsson O. and Ollivier J.P. (eds.). RILEM Publications. Vol.1. St. Rmyles-Cheuvreuse. France. 429–439.
12. Glass. G.K.. Buenfeld. N. R. (1997) The presentation of the chloride threshold level for corrosion of steel in concrete. *Corrosion Science. 39(5).* pp. 1001–1013.
13. ISO 13823. General Principles in the Design of Structures for Durability. ISO. 2008
14. ISO 2394. General principles on reliability for structures. ISO. 1998
15. Kropp J.(1995) *Chlorides in concrete. In: Performance criteria for concrete durability*. RILEM Report 12 E& FN SPON; 1995 .pp. 138–64.)
16. Li. C.Q.. Melchers. R.E.. Zheng. J.J. (2006). An analytical model for corrosion induced crack width in reinforced concrete structures. *ACI Structural Journal. 103*. pp. 479– 482.
17. Lounis Z. Mirza M. (2001). Reliability-based service life prediction of deteriorating concrete structures. *Concrete under severe conditions*. pp. 965–72.
18. Lounis Z. (2004). Uncertainty modeling of chloride contamination and corrosion of concrete bridge. In: Ayyub B. Attoh-Okine NO. editors. Applied research in uncertainty modeling and analysis. Springer. pp. 491–511 (Chapter 22).
19. PN-EN 1990:2004 Eurokod 0 -Postawy Projektowania Konstrukcji
20. PN-EN 1992-1-1 Design of concrete structures. Part 1-1. Eurocode 2. 2003
21. ProCAAT (2017). *Tutorial for probabilistic chloride attack analysis tool procaat full-probabilistic design tool*. Developed by Amirali Shojaeian Paolo Bocchini. Ph.D.. Clay Naito. Ph.D.. P.E.. April 2017. ProCAATtutorial.pdf (lehigh.edu)
22. Rosenberg A. Hansson C. Andrade C. (1989). *Mechanisms of corrosion of steel in concrete*. In: Paskalny J. editor. Materials science of concrete I. Westerville. OH: The American Ceramic Society. Inc.; 1989. p. 285–313.
23. Saassouh. B.. Lounis. Z. (2012) Probabilistic modeling of chloride-induced corrosion in concrete structures using first- and second-order reliability methods. *Cement & Concrete Composites 34.* pp. 1082–1093. http://dx.doi.org/10.1016/j.cemconcomp.2012.05.001).
24. Teplý. B.. Vořechovská D. (2012). Reinforcement corrosion: Limit states. reliability and modelling. *Journal of Advanced Concrete Technology. 10*. pp. 353– 362.
25. Thoft-Christensen. P. (2012). Infrastructure and life-cycle cost-benefit analysis. *Structure and Infrastructure Engineering. 8.* pp. 507– 516.
26. Tuutti K. (1982) Corrosion of steel in concrete. *Cement and Concrete Research Institute*. Stockholm. Swedish.
27. Vořechovská. D.. Chromá. M.. Podroužek. J.. Rovnaníková. P.. Teplý. B. (2009). Modelling of Chloride Concentration Effect on Reinforcement Corrosion. *Computer-Aided Civil and Infrastructure Engineering. 24*. pp. 446– 458.
28. Zhang J. Lounis Z. (2009). Nonlinear relationships between parameters of simplified diffusion-based model for service life design of concrete structures exposed to chlorides. *Cem Concr Compos.. 31(8).* pp. 591–600.