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Analysis of corrosion risk due to chloride diffusion for concrete structures in marine environment

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The chloride-induced steel corrosion is one of the main causes of deterioration for reinforced concrete structures exposed to marine environments. The chloride ingress into reinforced con-crete structures is even more complex since it depends on random parameters linked to transport and chemical properties of materials, which results in variability of corrosion initiation. This variation raises the need of statistical approaches to evaluate the risk of corrosion initiation due to chloride ingress. To address this issue, we use sensitivity analysis to identify the influence of input parameters on critical length of time before corrosion initiation predicted by our chloride diffusion model. Exceedance probabilities of corrosion initiation time given that input parameters exceed certain thresholds were also calculated. Results showed that the corrosion initiation time was most sensitive to: chloride effective diffusion coefficient D_e in concrete, that is a parameter controllable by relevant stakeholders; surface chloride concentration C_s, a non-controllable parameter depending on surrounding conditions. Reducing the chloride diffusion coefficient enables us to postpone the maintenance of structures. However, the interaction between controllable parameters and non-controllable surrounding conditions was revealed influential on the reliability of results. For instance, the probability that corrosion initiation time exceeds 15 years given an effective diffusion coefficient (D_e) equal to 0.1×10^{-12} m^2·s-1 can vary from 19 to 41% according to stochastic variations of chloride concentrations (C_s) values. Postponing the corrosion initiation time was combined with a decreasing probability of its occurrence.

1. Introduction

Corrosion of steel reinforcement due to chloride ingress is one of the major causes of degradation of Reinforced Concrete (RC) structures [1]. According to Tuutti diagram [2], the corrosion can be divided into two stages: corrosion initiation and corrosion propagation. The corrosion initiation corresponds to the process of chloride ingress into concrete until the chloride concentration has reached the steel rebar and exceeds a threshold value. Then steel is de-passivated and the corrosion propagates into the reinforcement. We define the service life as the period of penetration of chloride into the concrete cover until the chloride content exceeds a threshold

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value at the position of the reinforced steel bar. Indeed, at the end of that period, maintenance operations are required: most current maintenance operations consist in removing the chloride contaminated concrete and replacing it by a new one [3], thus inducing additional costs mainly caused by concrete production. There is thus a balance to ensure both long service life and minimum costs. In a broader perspective, we can also consider that there should also be a balance for environmental impacts because cement concrete is an important contributor to climate change [4]. Consequently, it is important to improve service life predictions, but also to determine influent parameters and to evaluate levels of potential risk in order to provide recommendations for longer service life to engineering designers when designing concrete structure exposed to chloride.

Current studies are increasingly interested in reliability assessment of results on corrosion initiation from chloride ingress modelling. For instance, a probabilistic approach to assess chloride ingress into concrete was performed by analyzing a model of chloride penetration into a stochastic framework [5]. More precisely, this last study applied Monte Carlo simulations and Latin hypercube sampling to consider propagation of uncertainties related to material properties and surrounding conditions. Likewise, a probabilistic analysis of corrosion initiation time was performed by focusing on the initiation phase of chloride induced reinforcement corrosion, when assessing five concrete durability options [6]. Recently, probabilistic de-passivation time for RC structures exposed to chloride ingress was also estimated according to three simple diffusion models, based on experimental data from a concrete structure exposed to the atmospheric marine environment [7]. Meanwhile, probabilistic risk analyses were also conducted for other causes of corrosion of concrete structures, such as corrosion risk due to carbonation [8]. However, in these and other studies, the individual influence of model's input parameters and the influence of their interactions on chloride ingress phenomenon were not investigated. This is required to be deeply investigated, in addition to probabilistic analysis of corrosion initiation time.

Our research aims at combining service life prediction models in order to give recommendations to the design engineers for extending service life. This kind of approach was already developed and applied to a RC structure located in Madrid and submitted to carbonation [9]. In complement to this previous work, the present study focuses on probabilistic assessment of corrosion risk due to chloride ingress into RC structures exposed to marine environment. First, a model for chloride ingress into concrete is chosen based on appropriate simplification in order to use it as decision tool for design engineers. Several studies focused on modeling chloride ingress by exclusively considering the diffusion process or by considering diffusion and convection [10]. Our approach requires a simplified durability model based on parameters (i.e. concrete mix design, construction parameters) that are available and controllable by the engineering designer, and including as well as relevant (i.e. influent) non controllable parameters (meteorology, salinity, …). Second, a probabilistic analysis to corrosion risk due to chloride ingress is performed. That includes a sensitivity analysis (SA) to identify individual influences of model's parameters and of their interaction on service life of marine RC structures.

Various SA studies have already been conducted on chloride ingress inside cement concrete. For example, Boddy et al. [11] applied a *one at a time* (OAT) technique for sensitivity investigation of a chloride transport model to the variations of the parameters controlling the rate of diffusion, temperature of exposure, critical chloride level, diffusion coefficient, permeability coefficient, surface chloride concentration and position of steel rebar. Likewise, Kirkpatrick et al. [12] studied a probabilistic model to predict chloride corrosion initiation depending on the position of steel rebar, surface chloride concentration and apparent diffusion coefficient. A deeper deterministic SA than the two previous studies was conducted by undertaking a differential analysis technique on corrosion model depending on four governing parameters: apparent chloride diffusion coefficient, position of steel rebar, surface chloride concentration, chloride threshold [13]. A global SA using Sobol method was used to study the sensitivity of the probability of failure to the assumed coefficients of variation of properties of the pre-stressed concrete [14]. Likewise, the Sobol method was applied to investigate independent and cooperative effects of the material parameters on masonry compressive strength [15]. In addition to SA, exceedance probabilities of model output are calculated given that input parameters exceed certain thresholds, for reliability assessment of service life improvement.

Our study proposes to apply successively Morris [16] and Sobol [17] approaches as complementary methods for SA of diffusion-based chlorides model. The originality of our work is to go beyond the recent studies in literature on uncertainties in the models describing the degradation of reinforced concrete structures, by considering the individual influence of available input parameters as well as the influence of their interaction on model output. A nonlinear chloride transport model easy to implement is used to enable us to investigate the potential interaction between input parameters, for which few experimental results are available in the literature. SA methods are applied to better understand the phenomena involved in chloride model and identifying input parameters (i.e. action levers) that sector's actors can control to improve service life behavior of concrete structures. These controllable (or technological) parameters are the action levers that will result in the proposition of possible pathways for structure owners to extend the length of time before corrosion initiation. Furthermore, the probabilistic analyses of the critical length of time to corrosion initiation given the most influent parameters are calculated to provide information on the reliability of results.

2. Material and methods

2.1. Chloride transport model

Various approaches were developed to model the chloride ingress through cement based materials. The main difference between models concern the fact that they considered concrete exposed in saturated and/or unsaturated conditions.

For saturated conditions, the diffusion process obeying the Fick's second law is generally sufficient to model the chloride ingress [18]. Likewise, the time-dependence of the apparent diffusion coefficient is considered as well as the chloride concentration of the exposed surface [19,20] by using empirical laws to establish time dependency functions.

For models accounting for unsaturated conditions, some studies have modeled chloride transport by taking into account both

diffusion and convection [21–27]. These models used semi-empirical laws found by fitting experimental data to get the moisture diffusivity and the chloride diffusion coefficient. These models can be mono-species (only chloride is considered) or multi-species (ions contained in the pore solution are also considered). They are considered as sophisticated models because they take into account some physical or chemical phenomena occurring into concrete such as chemical binding, electrical double layer, activity of pore solution.

However, models suitable for unsaturated conditions require many input parameters that are not currently measured for concrete design because they are expensive or time-demanding to collect and they are not required by the standards [28,29]. Moreover, reinforced concrete material in marine environment can generally be considered as saturated. Indeed, when casted on site, concrete is initially saturated and persistently exposed to high Relative Humidity (RH) that, for instance, stands superior to 80% on the French Atlantic coast [30]. In the case of maritime structures it is thus obvious to consider the chloride displacement into concrete by a diffusion equation as it was done by some studies to analyze chloride profiles obtained from reinforced concrete structures in unsaturated conditions [30–34]. From an engineer point of view, the Fick's second law is simple and the orders of magnitude of diffusion coefficient (or chloride profile), which we can obtain with this law, are correct and acceptable [35]. In addition, numerical implementation of this law is not time consuming in order to conduct statistical investigation.

Thus, according to our objective, our choice goes to a simple model suitable for saturated conditions. This model is resumed in Fig. 1. Equations are justified below.

Fick's second law of diffusion is written as:

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

where $C(x,t)$ ($kg \cdot m^{-3}$of concrete) is the chloride concentration at position x (m) at time t (s).

The previous equation can be solved by considering finite or semi-infinite boundary conditions. The last case is often considered for computing diffusion coefficient or chloride concentration, because the unsteady state is not time consuming. By assuming a time-invariant chloride concentration C_s at the concrete surface and a time-invariant diffusion coefficient D, Crank's solution of second Fick's law is given by Crank [36]:

$$C(x,t) = C_s erfc\left(\frac{x}{2\sqrt{D_a t}}\right), \tag{2}$$

under the initial condition $C = 0$ for $x > 0$ and$t = 0$. In equation (2), C_s ($kg \cdot m^{-3}$ *of solution*) is the chloride concentration at the concrete surface, D_a ($m^2 \cdot s^{-1}$) is the apparent diffusion coefficient and erfc() is the complementary error function.

Input parameters C_s and D_a are not time-dependent in this paper, as it was done by Ref. [31–33]. Moreover it was shown that the chloride diffusion coefficient decreases particularly in the first few months before being stabilized even with admixtures as slag [37].

The apparent diffusion coefficient D_a previously mentioned is given as [1]:

$$D_a = \frac{D_e}{1 + \frac{1}{p}\frac{\partial C_b^{'}}{\partial C_f}} \tag{3}$$

where D_e ($m^2 \cdot s^{-1}$) is the effective diffusion coefficient, p is the porosity and, $C_b^{'}$ ($kg.m^{-3}$of concrete) and C_f ($kg.m^{-3}$of pore solution) are the concentrations of bound and free chlorides, respectively [38].

In order to easily use the statistical study, we have to note that as first step, we considered the diffusion coefficient as intrinsic

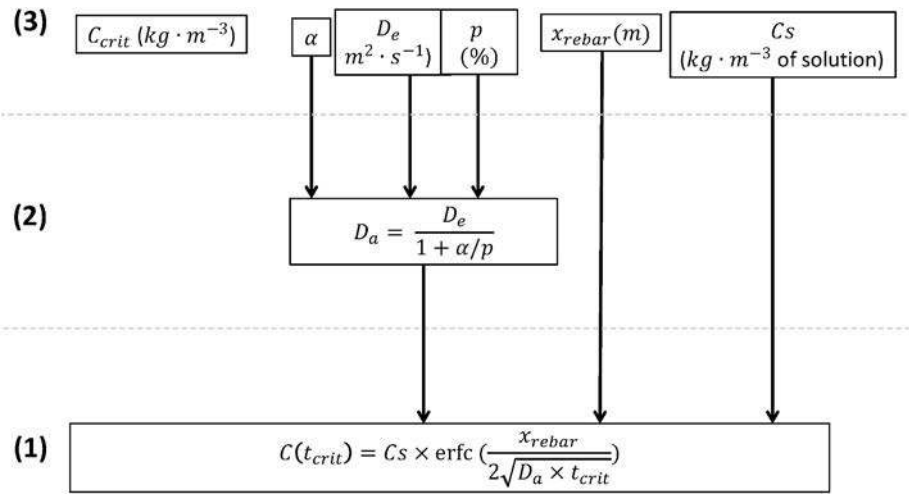

Fig. 1. Representation of chloride diffusion model: (1) model output, (2) intermediary model, (3) input parameters.

property of the material so "constant". Taking into account the time dependency of the diffusion coefficient by introducing the ageing factor [39,40] is a possible and interesting step not done in this paper.

Chloride binding isotherm is the relationship between free and bound chloride ions at a given temperature such that the partial derivative $\partial C_b/\partial C'_f$ can be determined. The chloride binding capability of concrete is a very complex phenomena describing by thermodynamic equilibrium, kinetic control and surface complexation [41] and the effects of different types of chloride binding (physically and chemically bound chloride) can be taken into account to describe the chloride ingress [42]. Usually to evaluate the relationship $\partial C_b^{'}/\partial C_f$, three types of binding isotherms (linear, Langmuir, Freundlich) have been proposed by fitting isotherm models with measurements [43]. In order to experimentally determine this isotherm, researchers usually use powder or thin disc extracted from concrete cores. In that way the best fitting with experimental data was obtained with the Freundlich isotherm in many cases [37, 44]. However, this experimental procedure did not match the observations on reinforced concrete in a natural maritime environment. So, to establish the relationship between free and bound chloride, it is necessary to expose concrete specimens under marine environment for a long time [45,46]. For the different concrete compositions, which were tested in these studies, the obtained chloride binding capacity fitted very well with the linear relationship. So, the linear isotherm is used as:

$$C_b^{'} = \alpha C_f. \tag{4}$$

That results in the apparent diffusion coefficient given as follows:

$$D_a = \frac{D_e}{1 + \frac{\alpha}{p}}. \tag{5}$$

In summary, the chloride diffusion model is presented in Fig. 1 with the main input parameters involved in chloride ingress into RC structures. We are interested in determining the critical time $t = t_{crit}$ that corresponds to the period of time during which chlorides penetrate the concrete but no damage is observed [2]:

$$C(x_{rebar}, t_{crit}) = C_{crit} \;\; for \;\; x_{rebar} = \text{steel rebar position}, \tag{6}$$

where the critical chloride concentration C_{crit} ($kg \cdot m^{-3}$ of concrete) is the chloride concentration threshold above which passivation of steel is destroyed [47].

The critical chloride concentration involved in equation (6) can take three forms [10]: the concentration of total chlorides [48], the concentration of free chlorides [49], and the $[Cl]/[OH]$ ratio [50]. These levels are highly variable because they depend on particular surrounding conditions, such as concrete mix design, experimental procedures [51], as well as rebar surface conditions [52,53]. The concentration of total chlorides was shown to be more relevant than the concentration of free chlorides alone or than the $[Cl]/[OH]$ ratio [54,55], thus we choose the total chloride content as our critical chloride concentration for the threshold value.

The critical length of time t_{crit} to corrosion initiation is defined as the time at which the chloride concentration at the position of steel rebar x_{rebar} exceeds the critical value. The time t_{crit} can be analytically expressed as:

$$t_{crit} = \frac{{x_{rebar}}^2}{4D_a erfc^{-1}\left(\frac{C_{crit}}{C_s}\right)}. \tag{7}$$

2.2. Risk analysis study

According to our objective, to obtain best service life values, a risk analysis study induced by chloride ingress phenomenon is conducted in three steps: 1) to perform SA to evaluate the influence of our model's various input parameters on its output parameters [17], 2) to calculate conditional probabilities of critical length time to corrosion initiation, and 3) to analyze favorable and unfavorable scenarios to corrosion initiation.

2.2.1. Sensitivity analysis

At the first step, Morris and Sobol SA methods are applied to the model. The method of Morris [16] provides sensitivity information (influential, sense of variation) about input parameters on the interval range of interest. As a complement to the former, the method of Sobol [17] evaluates the contribution of the variation of each input parameter to the total variation of model output via quantitative indices. Sobol indices also quantify the contribution of the interaction between input parameters. Morris and Sobol methods are successively conducted based on the same methodology originated from Andrianandraina et al. [56]. More precisely, in this methodology, the model is first defined with used intermediary models, constants and input parameters. All input parameters are then characterized with their pdf and are grouped in two categories according to the actor's action possibility: *technological* that are controllable by the engineering designer and corresponding to potential action levers, and *surrounding* parameters that are not controllable by the engineering designer. Morris and Sobol methods are successively applied using variation range and pdf of parameters. More details on these two SA methods are provided in Supplementary Material (Section B).

2.2.2. Conditional probability of critical length of time to corrosion initiation

At the second step, conditional distributions of critical length of time t_{crit} to corrosion initiation are calculated given the most influential input parameters. More precisely, that consists in evaluating exceedance probabilities of t_{crit} given that input parameters X_1

andX_2 exceed certain thresholds x_1 andx_2, respectively, by setting other input parameters at their default or mean value, such as:

$$Prob(t_{crit} \geq t | X_1 \geq x_1, X_2 \geq x_2) = \frac{Prob(t_{crit} \geq t, X_1 \geq x_1, X_2 \geq x_2)}{Prob(X_1 \geq x_1, X_2 \geq x_2)} \quad (8)$$

We will practically considered input parameters X_1 andX_2 having the most important contribution on variations of critical length of time t_{crit}.

2.2.3. Comparisons of simulated scenarios

At the third step, unfavorable, favorable and medium scenarios are simulated and compared. The first scenario called "unfavorable" aims at simulating the degradation of service life that the engineering designer can obtain by choosing values of parameters that decrease service life. Thus all influential *technological* parameters are set at their most unfavorable for the shortest service life and all *surrounding* parameters at their default or mean value [56]. The second scenario called "favorable" aims at simulating the reliability of the possible improvement of service life that the engineering designer can obtain by choosing values of parameters that increase service life. Thus all influential *technological* parameters are set at their most favorable for the longest service life and all *surrounding* parameters at their default or mean value [56]. The last scenario, called "medium" aims at obtaining an average scenario, for which values of parameters are not known and thus all set to their mean values. Probability distributions of simulated critical length of time t_{crit} are then plotted according to the three previous scenarios. The comparison among probability distributions of $t_{crit}$and their descriptive statistics (mean and standard deviation) will provide information about uncertainty and potential variation (extension or reduction) of the corrosion initiation time in each simulated scenario.

All calculations (SA indices, conditional probabilities, various scenarios) were realized over 5000 repetitions by Monte Carlo simulations. This number of repetitions was sufficient to reach stable and relevant results, with a reasonable computation time. Input parameters are assumed to be independent, as required in the methodology of the two SA methods applied.

2.3. Characterization of input parameters

According to our objective, we investigate the individual influence of input parameters D_e, x_{rebar}, C_s,C_{crit}, p and α, as well as the influence of their interaction on the corrosion initiation time t_{crit}.

Technological parameters are the position of steel rebar in concrete since it is governed by the European normalization (*EN 1992-1-1* [29]*)*, the effective diffusion coefficient D_e, the porosity p because the engineering designer can control them through other factors such as the Water/Binder ratio. *Surrounding* parameters are the chloride concentration at the concrete surface, the linear isotherm α, as well as the critical chloride content which it is sensitive to chemical characteristics of concrete components (binder and type of aggregates).

Probability density functions (pdf) of input parameters considered in this study are shown in Table 1 and we explain below how they were obtained.

Descriptive statistics of parameters related to properties of the materials (chloride diffusion, porosity) were calculated from a literature review of experimental studies performed on 13 references with 52 different concrete mixtures and different types of binders [37,57–67]. The references were selected because they determine the effective diffusion coefficient D_e in concrete from accelerated steady state migration tests with a method closed to the French standard XP-P-18461. The distributions of observed values of effective diffusion coefficient D_e and porosity p obtained from our literature review were assumed lognormal and normal, respectively (Fig. S 1 in Supplementary Material). The influence of water/Binder ratios and incorporation of mineral admixtures, on porosity and diffusion coefficient, are described by Fig. S2 in Supplementary Material.

Concerning the surface chloride concentration C_s, the values corresponding to moderate and severe corrosive exposures were

Table 1
Input parameters for chloride diffusion model and their descriptive statistics. Column headings: parameter, unit, variable classification, mean, coefficient of variation (COV), probability density function (pdf), variation range, sources.

Parameter	Unit	Class	Mean	COV (standard deviation)	Pdf	Variation range	Sources
Porosity (p)	%	Tech	12.85	0.16 (2)	Normal	8.1–17.3	Fig. S 1
Effective diffusion coefficient (D_e)	$10^{-12}m^2 \cdot s^{-1}$	Tech	0.66	1.24 (0.82)	Log-normal	0.1–6.0	
Position of steel rebar (x_{rebar})	Mm	Tech	50	0.25 (12.5)	Normal (truncated at lower bound = 10 mm)	10–75	[69]
Linear isotherm (α)	n.u.	Surr	–	–	Uniform	0.01-0,1	[45,46]
Surface Chloride Concentration (C_s)	$kg \cdot m^{-3}$of pore solution	Surr	9.75	0.51 (4.97)	Normal (truncated at lower bound = 1.67 $kg \cdot m^{-3}$)	1.67–17	[68] [a]
Critical chloride concentration (C_{crit})	$kg \cdot m^{-3}$ of concrete	Surr	0.9	0.19	Uniform	0.6–1.2	[68] [b]

n.u = no unit; Tech: technological (controllable); Surr: surrounding conditions (not controllable).
[a] Table 2a in Ref. [68] (page 1607) presents descriptive statistics of surface concentration for structures exposed to marine breeze.
[b] Table 3 in Ref. [68] (page 1608) presents descriptive statistics of critical chloride concentration.

considered for testing corrosion initiation and a normal distribution is assumed in this study [13,68]. More precisely, any conclusions were drawn about statistical distributions of C_s for structures exposed to marine breeze [68]. In our work, we considered a normal distribution of C_s truncated at the minimum value of its variation range.

The linear isotherm parameter α is experimental and it does not have a known pdf in literature. Some α values that were calculated in one study varied from 0.01452 to 0.06195 [45]. In that study, the concrete specimens were exposed to marine environment for 10–30 years before samples were collected to determine total and free chlorides content. The Water/Binder ratios varied from 0.45 to 0.55 and different binders were studied: ordinary Portland cement, slag cement and fly ash cement. Concrete specimens with Water/Binder ratios varying from 0.45 to 0.65 were also used with different binders (cement types CEMI, CEMV, as well as binders with fly ash replacing Portland cement type CEMI) [46]. In that study, the concrete specimens were exposed to seawater for seven years before determining total and free chloride content. The α values calculated from these data varied from 0.01584 to 0.0423. From these two references we assume that the α parameter can vary inside the [0.01; 0.1] interval. As we only have a minimum and maximum value, but no information on its pdf, we assume a uniform probability distribution.

The critical chloride concentration inducing the end of the de-passivation state [2], chosen as the concentration of total chlorides [54,55] as previously explained, depends on many parameters such as the type of steel or electrochemical environment in concrete [68]. Its pdf being unknown, we also assume a uniform probability distribution.

At last, the position of steel rebar is assumed to follow a normal distribution truncated at a lower bound equal to 10 mm [69].

3. Results and discussion

3.1. Sensitivity analysis

Results of SA concerning the influence of input parameters D_e, x_{rebar}, C_s, C_{crit}, p and α of the studied model are given in Table 2.

3.1.1. Individual influences

According to the algebraic sign of Morris index μ, the time t_{crit} may be reduced ($\mu < 0$) by an increase of D_e, p and C_s. Conversely, the time t_{crit} may be extended ($\mu > 0$) by an increase of C_{crit}, x_{rebar} and α. These trends for D_e, p and α are expected from the analytical expression of apparent diffusion coefficient D_a in equation (5). Increasing α decreases the apparent diffusion D_a, while increasing p increases D_a. Then, looking at the individual effect of parameters (S_i) as well as the total effect (ST_i), the time t_{crit} is found most sensitive to variations of D_e(S_i. = 29.90%). That emphasizes the key role of diffusion phenomenon in the chloride ingress process in comparison with binding capacity and porosity of the concrete, as experimentally found by Pradelle et al. [70]. Our results were affected by bias calculations particularly for estimated Sobol indices close to 0.

A comparison can be established with deterministic [13] and probabilistic SA [71] performed on diffusion-based corrosion initiation model by considering four governing parameters: apparent chloride diffusion, position of steel rebar, surface chloride concentration, critical chloride concentration. An approximation of the considered model was developed by applying analytical differential techniques based on a Taylor series that do not take into account pdf of parameters [13]. Their results are in agreement with ours, on

Table 2
Sensitivity analysis (Sobol and Morris indices) for input parameters involved in chloride transport model. Mean value of Sobol first order indices are highlighted in grey.

	Sobol indices							***Morris indices***	
	Indices of first order S_i (%) and second order S_{ij} (%)						***Total order indices ST_i (%)***	***Algebraic sign of μ***	***Ratio σ_i/μ_i^****
Parameters	D_e	C_s	x_{rebar}	α	C_{crit}	p			
D_e	29.90	15.38	11.63	-0.18	-0.39	-0.61	70.45	-	2.02
C_s		13.03	1.12	1.78	2.42	-0.35	50.17	-	1.83
x_{rebar}			7.88	-0.29	-0.40	-0.38	28.58	+	1.86
α				0.59	-0.44	-0.41	4.13	+	1.89
C_{crit}					0.50	-0.36	21.41	+	2.66
p						0.06	0.29	-	2.29

- sign (+) denoted increasing trend; sign (-) denotes decreasing trend
- Negative values of Sobol indices were due to bias in the estimated values of indices close to 0

the positive trend of t_{crit} to x_{rebar} and C_{crit} and the negative trend of t_{crit} to C_s and D_e. However, the individual effects of parameters differ between the two studies. Different types of steels (conventional black carbon steel and corrosion resistant steels) and exposure conditions (light, moderate, high and severe) were considered in Ref. [13] such that the ranking of parameter importance varied between these different cases. In one case, the time t_{crit} with regards to chloride diffusion was most sensitive to variations of x_{rebar} then D_e; in other case, it was most sensitive to C_s and C_{crit}. Importance factors of governing parameters were calculated in Ref. [71] by using their statistical distributions assumed to be lognormal. These factors were both influenced by time within the design life of the structure and coefficient of variation of parameters. According to these importance factors, the input parameter x_{rebar} was ranked first, followed byD_e, C_s and C_{crit}.

These results of SA cannot be entirely compared with ours since SA results must be interpreted with regards to variation range and statistical distributions considered for input parameters as well as the type of concrete structures studied. Furthermore, one of the main advantages of the approach applied in this work is the quantification of the influence of interaction between input parameters, which was not done by previous studies.

3.1.2. *Influences of interactions*

Possible interactions between parameters were indicated by the value of the ratio σ_i/μ_i^* superior to 0.5 for all parameters in Table 2. Interactions detected by the Morris method are confirmed by the Sobol method. Results show that the influence of interactions between input parameters are the most important forD_e and C_s (via the calculations of the difference $ST_i - S_i \geq$30%) and non-negligible for x_{rebar} ($ST_i - S_i \geq$20%). The strongest interactions is observed between D_e and C_s with $S_{ij} = 15.38\%$ then D_e and x_{rebar} with $S_{ij} = 11.63\%$. Furthermore, significant interactions of third order (between three parameters) were also revealed by calculating $ST_i - S_i - \sum_j S_{ij}$ shown to be superior to 10% for D_e, C_s and C_{crit}.

Various bivariate graphs are shown below to highlight interactions. For sake of visibility, 1000 points were plotted in Figs. 2 and 3, over the 5000 sample size used for simulation. As the parameter $D_e$is found the most influential with a strong interaction with other parameters (Table 2), we investigated bivariate plots of D_e as function of parameters such as C_s(Fig. 2), $C_{crit}$and α (Fig. 3). For instance, the time t_{crit}(described by the size of points in Fig. 2) varies simultaneously according to D_e and C_s, which emphasizes the strong interaction between these two parameters. In addition, around the mean value of $C_s = 9.75\text{kg} \cdot m^{-3}$, D_e ranges from 0.3×10^{-12} to $5 \times 10^{-12}\ m^2 \cdot s^{-1}$ (Fig. 2b) with various t_{crit}values. Note that C_s not only depends on the surrounding conditions but also on the concrete mix design reflected by the chloride binding capacity of the binder which in turn depends on its free chloride content and so on its diffusivity. This dependency between both parameters D_e and C_s was experimentally found by Othmen et al. [30] for total chloride profiles determined from 30 cores extracted at the same level above the sea from a reinforced concrete beam exposed to Atlantic ocean. The authors observed an increase of about 10 times in the diffusion coefficient for the mean chloride surface concentration (compared with about 16 times in Fig. 2b).

No interaction between D_e and C_s, as well as between D_e and α (Table 2) are found, and the time t_{crit} only varies according to D_e as shown in Fig. 3a and b. This trend is in accordance with the results obtained by Pradelle et al. on experimental data [70]. The weak effect of correlations between chloride diffusion coefficient, linear isotherm, and critical chloride content was globally highlighted through a sensitivity analysis: introducing correlations in the study will not modify the relative influence of each input data.

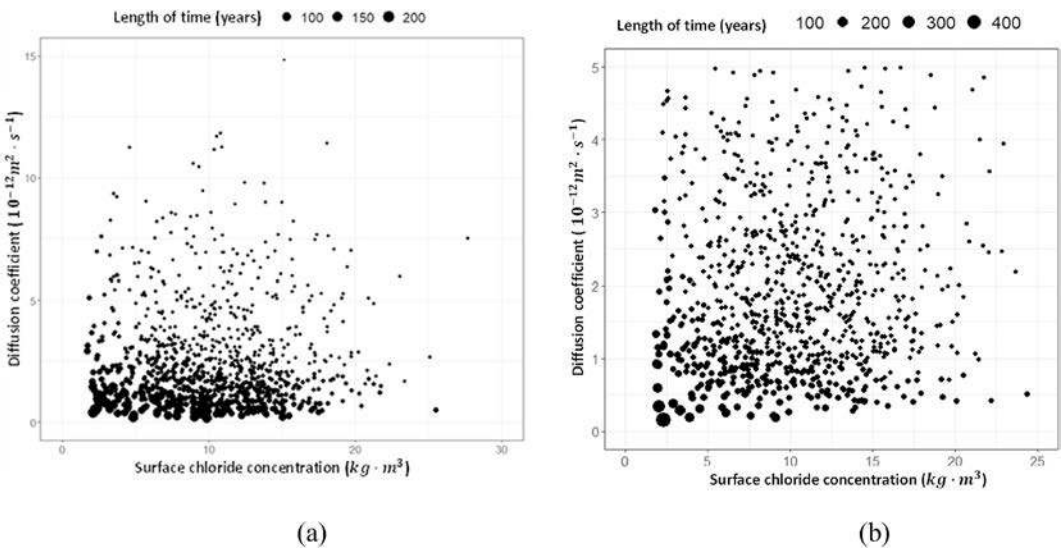

Fig. 2. Bivariate plot of (a) effective diffusion coefficient D_e ($10^{-12}\ m^2 \cdot s^{-1}$) as function of surface chloride concentration C_s ($kg \cdot m^{-3}$) over 1000 simulated points, with (b) a zoom on interval ranges D_e in [0;5] ($10^{-12}\ m^2 \cdot s^{-1}$) and C_s in [0;25]($kg \cdot m^{-3}$) over 883 simulated points.

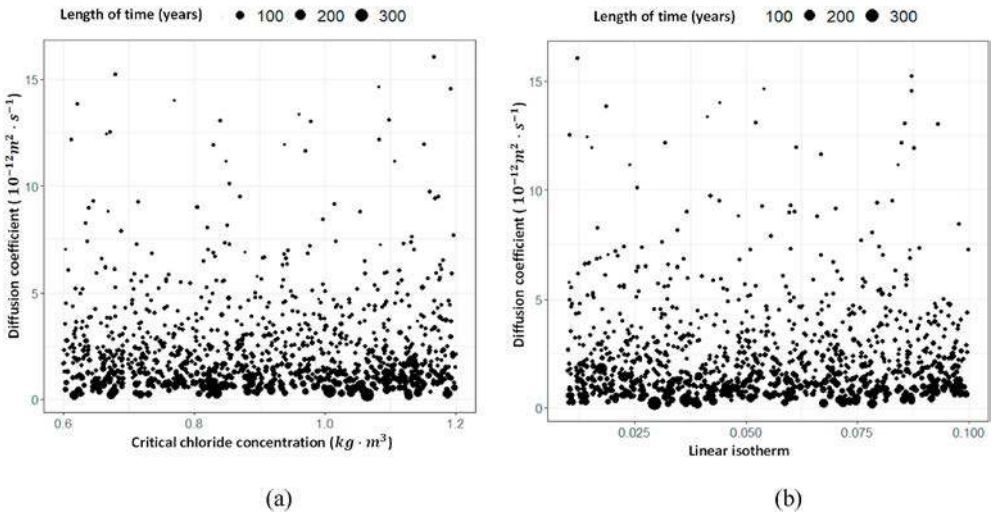

Fig. 3. Bivariate plot of effective diffusion coefficient ($10^{-12}\ m^2 \cdot s^{-1}$) as function of (a) critical chloride content ($kg \cdot m^{-3}$) and (b) linear isotherm over 1000 simulated points.

3.2. Conditional probabilities of critical length of time given effective diffusion coefficient and surface chloride concentration

For the influence of D_e and C_s pointed out from the analysis presented so far, the probabilistic analysis of t_{crit} regarding co-occurrence of D_e and C_s was investigated by applying equation (8) given by

$$Prob(t_{crit} \geq t | D_e \geq \mathrm{d}, C_s \geq \mathrm{c}) = \frac{Prob(t_{crit} \geq t, D_e \geq \mathrm{d}, C_s \geq \mathrm{c})}{Prob(D_e \geq \mathrm{c}, C_s \geq \mathrm{c})}, \tag{9}$$

where d and c are predefined values of D_e and C_s, respectively. According to the methodology described in Sub-section 2.2.2, conditional probabilities of t_{crit} were calculated given the co-occurrence of both D_e and C_s by fixing other parameters x_{rebar}, C_{crit}, p and α at their mean value. For instance, considering the case in which one hundred C_s values (generated according to their pdf) were associated with one minimum $D_e = 0.1 \times 10^{-12}\ \mathrm{m}^2 \cdot s^{-1}$, the probability of t_{crit} exceeding 15 years given D_e and each C_s was about 19–41% (Fig. 4a, c and Table 3). That probability logically decreased when C_s increased. Likewise, considering one hundred D_e values (generated according to their pdf) associated with the mean value of $C_s = 9.75\ \mathrm{kg} \cdot \mathrm{m}^{-3}$, the probability of t_{crit} exceeding 15 years was lied between 0 and 38% (Fig. 4b,d and Table 3). Therefore, to achieve an extension of t_{crit} exceeding 15 years was more reliable with $D_e = 0.1 \times 10^{-12}\ \mathrm{m}^2 \cdot s^{-1}$ and various C_s than with $C_s = 9.75\ \mathrm{kg} \cdot \mathrm{m}^{-3}$ and various D_e. In addition, the conditional probabilities of t_{crit}decreased more quickly as D_e increased than as C_s increased. Thus, the extension of t_{crit} was combined with a decreasing probability of its occurrence.

3.3. Comparisons of simulated scenarios

To deeply investigate the time t_{crit}as function of D_e from conditional probabilities calculated so far, three scenarios were simulated: a medium scenario in which D_e was set to its mean value, and a favorable and unfavorable scenarios in whichD_e was set to its minimum and maximum values, respectively. In the three scenarios, technological parametersx_{rebar}, p and α were set at their mean value and surrounding parameters C_s and C_{crit} according to their pdf. Probability distributions of simulated critical length of time to corrosion initiation values were plotted in Fig. 5 and Table 4 presents mean and standard deviation of the simulated values of t_{crit} for the three scenarios. The comparison between favorable and medium scenarios indicates that the corrosion initiation time can be extended by 12 through a decrease ofD_e. However, this improvement is coupled with a large increase of the uncertainty affecting the reliability of the service life extension of t_{crit} in the favorable scenario. That is consistent with conditional probabilities of t_{crit} previously showed in Fig. 4. Conversely, the comparison between unfavorable and medium scenarios indicates that initiation corrosion time is 3 times reduced by an increase of D_e coupled with a reduction of the uncertainty. This means a better reliability of the average length of time to corrosion initiation in the unfavorable scenario. In addition, a scenario corresponding to an average value of t_{crit}close to 100 years (95 years in mean with a standard deviation of 60.6 years) associated with a $D_e = 0.25 \times 10^{-12}\ \mathrm{m}^2 \cdot s^{-1}$ was presented as a reference for service life behavior of structures for sector's actor.

4. Concluding remarks

This study has pointed out the influential role of both parameters related to material properties and surrounding conditions, and their interactions, on the reliability of results from a chloride transport model. Sensitivity Analysis (SA) and conditional probabilities of

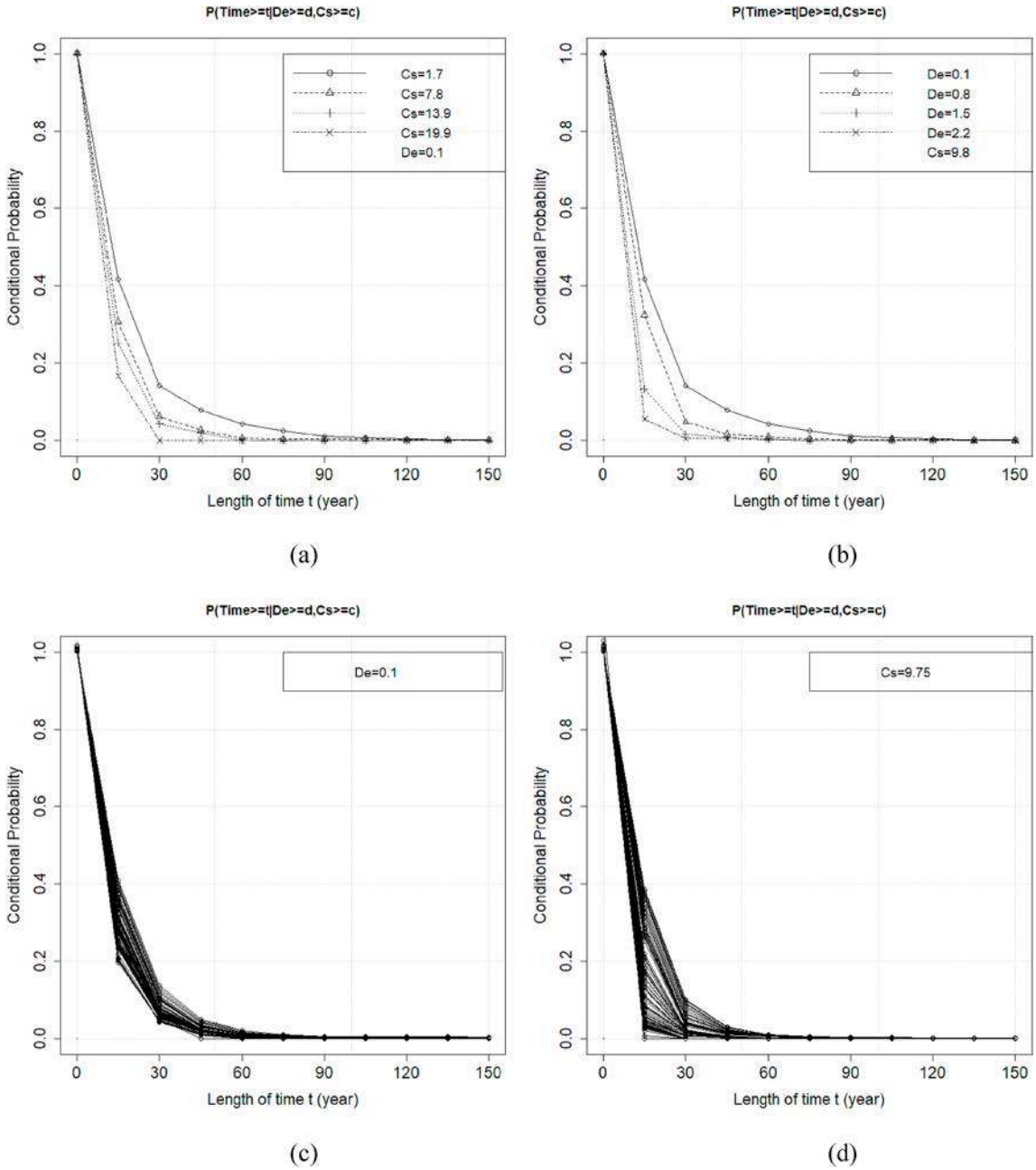

Fig. 4. Conditional probabilities of the critical length of time t (year) to corrosion initiation given the co-occurrence of effective diffusion coefficient $D_e = 0.1 \times 10^{-12}\ m^2 \cdot s^{-1}$ and (a) four and (c) one hundred values of surface chloride concentration (C_s, $kg \cdot m^{-3}$), and given the co-occurrence of $C_s = 9.75 kg \cdot m^{-3}$ and (b) four and (d) one hundred values of D_e.

length of time to corrosion initiation have been used in a probabilistic approach to investigate the corrosion risk due to chloride ingress into RC structures.

The SA has shown that the key input data for predicting time to corrosion initiation are clearly the chloride diffusion coefficient, the surface chloride concentration and the position of steel rebar. The only controllable parameters are the effective diffusion coefficient and concrete cover thickness. It is crucial to define with enough accuracy the mean value and the coefficient of variation of the pdf of these input data. The diffusion chloride coefficient is particularly an action lever that enables relevant stakeholders to influence the service life behavior of structures, in comparison to binding capacity and porosity of the concrete. That finally allows limiting expensive and time consuming experimental tests, necessary to determine input data to predict service life of reinforced concrete structures in marine environment. In a further work, it would be interesting to take into account the time dependency of the diffusion

Table 3
Variation ranges of conditional probability of the critical length of time t_{crit} to corrosion initiation given (a) the co-occurrence of effective diffusion coefficient $D_e = 0.1 \times 10^{-12}$ $m^2 \cdot s^{-1}$ and one hundred values of surface chloride concentration C_s ($kg \cdot m^{-3}$), and (b) the co-occurrence of $C_s = 9.75 kg \cdot m^{-3}$ and one hundred values of D_e.

Length of time t (year)	Variation range of conditional probability of t_{crit} (%)	
	(a):Prob($t_{crit} \geq t \mid D_e \geq 0.1,\ C_s \geq c$)	(b):Prob($t_{crit} \geq t \mid D_e \geq d,\ C_s \geq 9.75$)
10	[20; 65]	[0; 64]
15	[19; 41]	[0; 38]
30	[4; 14]	[0; 10]
38	[0; 10]	[0; 8]
45	[0; 5]	[0; 3]
60	[0; 2]	[0,1]

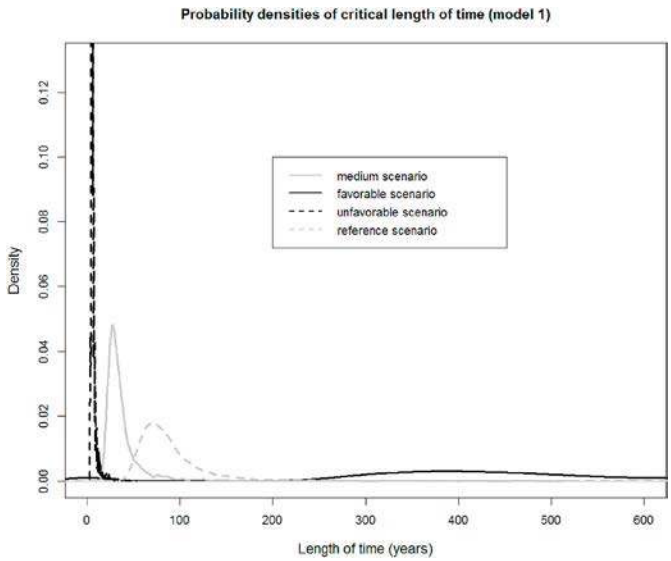

Fig. 5. Pdf of the critical length of time (year) to corrosion initiation for 4 scenarios: unfavorable (with $D_e = 6.0 \times 10^{-12}$ $m^2 \cdot s^{-1}$), medium (with $D_e = 0.66 \times 10^{-12}$ $m^2 \cdot s^{-1}$), reference (with $D_e = 0.25 \times 10^{-12}$ $m^2 \cdot s^{-1}$) and favorable (with $D_e = 0.1 \times 10^{-12}$ $m^2 \cdot s^{-1}$).

Table 4
Descriptive statistics (mean and standard deviation) of pdf of the critical length of time to corrosion initiation for various scenarios.

Scenarios with $x_{rebar} = 50$mm and $p = 12.85\%$	D_e (10^{-12} $m^2 \cdot s^{-1}$)	Mean (years)	Standard deviation (years)
Unfavorable: maximum D_e	6	10	6.1
Medium: mean D_e	0.66	38	27.1
Reference: D_e calculated to obtain the critical length of time 100 years	0.25	100	60.6
Favorable: minimum D_e	0.1	439	184.8

coefficient by introducing an ageing factor.

An emphasis is also shown on the effect of interaction between parametersD_e and C_s. By acting on controllable parameter D_e to extend the time at which chloride concentration achieve a critical level requires to consider possible variations in surrounding parameters, such as chloride concentration at the concrete surface. These interactions emphasize the fact that length of time to corrosion initiation results from complex phenomena concerning the sea water and concrete structures and not only from individual influence of transport and chemical properties of concrete materials. SA methods that focus on combined influences of groups (triplets, …) of input parameters should be deeper investigated.

The results of conditional probabilities of length of time t_{crit} to corrosion initiation in regard to the influence from the co-occurrence of D_e and C_s have contributed to the reliability assessment of extension of t_{crit}. The sector's actor faces the choice either of extending the service life of structures but with a lower reliability of t_{crit}'s extension or of getting a lowest quality of service life but with a higher reliability of t_{crit}'s reduction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marstruc.2020.102804.

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