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Effect of distance from the sea on reinforced concrete chloride corrosion probability

Seyedreza Alinaghimaddah[1], Mohsen Ali Shayanfar[2,*] , Mohammad Ghanooni-Bagha[3]

[1] School of Civil Engineering, Iran University of Science and Technology, Narmak, Tehran, Iran,
[2] The Centre of Excellence for Fundamental Studies in Structural Engineering, Iran University of Science and Technology, Narmak, Tehran, Iran
[3] Department of civil Engineering, East Tehran Branch, Islamic Azad University, Tehran, Iran

ABSTRACT: When the discussion is about the destructive effects of salt spray on the coastal structures, the distance between RC structures and the sea is considered as an important parameter. This parameter allows considering the distance influence on structural durability in order to make a proper decision to protect the structure against the corrosive chloride agent. Since probabilistic methods and modeling at the design stage can save the costs of repair and reconstruction of structures, in this paper, through probabilistic modeling and using Monte Carlo simulation, the probability of reinforcement corrosion initiation has been considered at different distances from seawater as a chloride source. Considering a structure in Caspian Sea condition, the effect of surface chloride reduction is investigated with increasing distance from the sea and its effect on corrosion probability is studied. The results of this study show that by increasing the distance from the sea after 200 meters, the chloride concentration will be significantly reduced. It is also observed that, after 2000 meters, the effect of chloride. Also, it can be seen that with increasing distance, chloride corrosion will not have a significant effect on the durability of reinforced concrete structures. However, further studies are needed regarding the change in the rate of reduction of chloride due to distance from the sea.

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1. INTRODUCTION

In recent decades, many studies have been carried out to evaluate the effect of different parameters on chloride diffusion in concrete, corrosion initiation and corrosion propagation in concrete elements[1]. The process of reinforcement's corrosion is a complicated process that depends to a large extent on environmental condition and external factors such as temperature and humidity[2]. The failure of RC structures in marine conditions is an attractive topic for researchers and several papers have been published by far[3], [4]. Products made of corrosion of rebars under spraying conditions can result from the passive layers of the rebar or the surrounding environment. These products are as a result of the reaction between the materials and the environment[5]. Shayanfar et al. using reliability PSO optimization estimated the probability of corrosion initiation[6]. Considering the uncertainty of effective variables in the chloride corrosion process, probabilistic methods are used to investigate concrete structures durability against this destructive process[7], [8]. It is obvious that spraying zone in marine environments could be very destructive for concrete structures. In Iran, a country that has a large coastal area both in the north and south of its total area, marine conditions play an important role in relation to the chloride corrosion of RC structures. The wind blows chlorides from bursting bubbles at sea level over long distances, causing a spraying region. This effect is important when the wind speed exceeds the limit. This limit was reported by a number of researchers in the range of 7 to 11 m/s[9]. On the other hand, some papers and studies acknowledge that the ramp-up of wind speeds of 3 m/s is enough to form this phenomenon[10]. Considering the formation of the spray region, it is observed that with increasing wind speed, the amount of chloride present in these areas also increases[10]. Moreover, regarding to the chloride spray from marine regions, apart from the wind blowing, which leads to the transfer of these ions to distant distances, the effect of gravity is also effective as a preventive factor in the transport of ions in long distances[11]–[13]. In other words, the presence of gravity as an obstacle in the transfer of chlorides causes a reduction in chloride concentration by increasing the distance from the sea[12], [13]. Therefore, RC structures in marine areas should be categorized based on their distance from the sea. It should be noted that the amount of surface chloride at a height of more than 4 m above sea level will not change significantly, so the deck of most bridges will be built at altitudes above the water level[14], [15]. It is noticeable to mention that in this study, the height of the water level is ignored. A large number of research and studies have considered corrosion of reinforced concrete structures in

*Corresponding author's email: shayanfar@iust.ac.ir

saturated or tidal conditions, hence the results of these studies can only be used for structures that are precisely located in such conditions[16]–[20]. Also, probabilistic methods have been used to determine the probability of corrosion initiation in predicting the lifetime of reinforced concrete structures[21]–[25]. Feliu et al. [26] conducted a field test in coastal area at different distances with the aim of obtaining a theoretical model determining the effect of corrosion on RC structures service life in spray zones. They also showed that, as the distance from the sea increases, parameters such as wind conditions, waves and hydrodynamic behavior of the surface water affect the amount of chloride[26]. In contrast to what has been done so far, most of the discussion is about the probability of corrosion initiation for concrete structures located in seawaters, while the probabilistic effect of chloride on concrete structures located in a distance from seawaters not considered so much. This paper, assuming the Caspian Sea conditions, examines the probabilistic effects of chlorides on reinforcement's corrosion initiation process as a function of distance from the sea. In this paper, a probabilistic analysis is used to study the effect of distance from the sea and wind speed on the probability of chloride corrosion. This study compares the responses of various methods proposed determining the amount of surface chloride concentration using the Monte Carlo simulation to estimate the time of corrosion initiation according to Iran's National Concrete Code.

2. REINFORCEMENTS CORROSION PROCESS

Reinforcements are protected by two factors: the physical factor, which is concrete cover on the rebars and the chemical factor. Chemical protection means, the alkalinity of concrete with high PH (about 13-12) causes to form a thin layer on the surface of rebars called passive layer and protect them from being corroded. In this way, corrosion will be prevented even in the presence of moisture and oxygen[27]. If the concrete alkalinity decreases, the passive layer will be lost and the concrete's vulnerability to corrosion will increase. One of the factors that causes reinforcements corrosion is chloride ions.

2-1 Model of chloride corrosion

In the corrosion process, chloride ions act like a catalyst. This means that, chloride ions do not disappear in the corrosion process, but help break down the passive layer on rebars and cause a rapid progress in the process of corrosion. The chloride ion penetration causes local corrosion, also known as pitting corrosion[28]. The amount of chloride concentration at depth x from the concrete surface at time t is obtained from the following equation[29]:

$$C(x,t) = (C_s)[1 - erf(\frac{a}{2\sqrt{D_{app}t}})] \tag{1}$$

In this equation, C(x, t) is the chloride concentration at time t and depth x of concrete cover, t is time, a is cover thickness, C_s is the surface chloride concentration at time t, and D_{app} is the chloride diffusion coefficient in concrete. The erf (.) Function is an error function or Gaussian error function defined as follows:

$$erf(x) = 2\Phi\left(x\sqrt{2}\right) - 1 \tag{2}$$

In the equation above, $\Phi(x)$ is the cumulative probability distribution function and has a standard normal distribution.

3. THE DURABILITY ANALYSIS AGAINST CHLORIDE CORROSION BASED ON RELIABILITY METHOD

The purpose of the reliability analysis is to calculate the probability of failure with respect to a specific failure scenario, which is referred to as a limit state. The first step in evaluating reliability is to determine random variables. In order to determine the randomness, all probability distributions must be determined for all of these parameters. In this study, the probabilistic distributions of each variable is based on confirmed researches by researchers. The next step in this process is to define the desired failure mode and determine the state function of the limit state g(x) for that mode. This function divides the space into a favorable and undesirable region as shown in Fig.1. In general, R and S as capacity and demand, respectively. The limit state function for the failure mode is defined as follows[30]:

$$g(x) = R(X) - S(X) \tag{3}$$

In this study, the limit state function is used to estimate the time of corrosion initiation based on the following equation[25].

$$\mathrm{g(x) = C_{th} - C(x,t)} \tag{4}$$

In this case, C_{th} is the critical chloride content, and if the value of this function is g<0, the system enters undesirable conditions or failure. In this study, undesirable condition is the deterioration of the passive layer on rebars which results in corrosion initiation phase. The probability of failure of Pf is expressed as the probability of a "failure" occurrence as follows:

$$P_f = P\{R < S\} = P\{g(.) < 0\} \tag{5}$$

Generally, the probability of failure can be expressed as the area below the graph of random variable's density function over the failure area (i.e, g (.)<0). To mathematical expression:

$$P_f = \int_{g(.)<0} f_{S,R}(s,r)dsdr \tag{6}$$

The Monte Carlo simulation method, as a numerical simulation method, is an approach that is widely used in reliability issues[32]. This method, which deals with the simulation of limit state function, generates samples of random variables in order to create a set of values for determining the desired and undesirable regions and calculating limit state function. These samples are generated based on the probabilistic distribution of each random variable. The core of

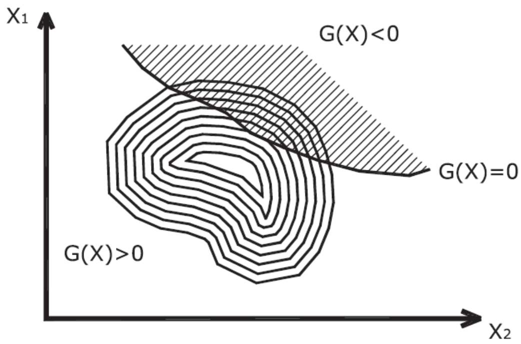

Fig. 1. The division of desirable and undesirable regions for two random variables[31]

this method is to generate a sample set for each of the random variables in the problem. Then, desirable and undesirable regions are determined using the limit state function. The probability of failure or, in other words, the probability of corrosion initiation in the Monte Carlo method is calculated as follows:

$$P_f = \int_{G\le 0} f_x(x_i)dx_i = \int_{G\le 0} I(x_i)f_x(x_i)dx_i = E[I(x_i)] \quad (7)$$

In the equation above, the function $I(x_i)$ can be expressed as follows:

$$\begin{aligned} I(x_i) &= 1 \rightarrow G \le 0 \\ I(x_i) &= 0 \rightarrow G > 0 \end{aligned} \quad (8)$$

By simulating the limit state function for the proper number of samples, the mean value of I (xi) can be an estimation for the probability of corrosion. Therefore:

$$\overline{P}f = E[I(x_i)] = \frac{1}{N}\sum_{i=1}^{N} I(x_i) \quad (9)$$

4. NUMBER OF SAMPLES IN MONTE CARLO SIMULATION

In 1964, Broding suggested that the following equation could be used to predict the number of simulations N for the confidence level C and the probability of failure Pf as follows[33]:

$$N > \frac{-\ln(1-C)}{Pf} \quad (10)$$

In this study, a confidence level of 99% and a probability of failure of 10^{-4} are considered, which requires around 50,000 simulations. It is worth noting that the probability of failure in this regard actually represents the sensitivity of the designer[34]. Since the Monte Carlo simulation involves random values, simulation results are subject to a lot of statistical changes. The more simulations are, the more accurate the final result[35]. By assuming a correct model with an adequate number of simulations, the error rate can be greatly reduced. Therefore, in this study, 200,000 simulations will be used.

5. ANALYSIS METHOD

The modeling of reinforcement's corrosion should be done for two stages, the first stage is chloride penetration into the porous concrete space. At this stage, the chloride concentration increases over time through cover. Then, when the chloride concentration at the reinforcement's surface reaches chloride critical value, the passive layer on the rebar is lost and corrosion begins. At the end of this stage, the rebars will remain undamaged. The second stage is called the propagation stage, which will be accompanied by a reduction in the reinforcements cross-section, which will result in the structural strength reduction[36]. The second stage is much shorter compare to the first stage in the corrosion process. Therefore, it seems more appropriate measuring the time needed to start corrosion to show the durability of the structure[31]. Accordingly, in this paper, corrosion criteria will be reaching to the critical chloride content at the rebars surface. The main parameters related to reliability analysis in this study are as follows:

- The amount of critical chloride in the concrete and steel interface is representative of corrosion initiation, and is here based on Stewart's work[37].
- The amount of surface chloride content, which this parameter is based on previous works and formulated in relation with the effect of distance from the sea and wind speed.
- Concrete release coefficient is also based on Nogueira's work[31].
- Data on the adequate concrete cover thickness is based on Nogueira's assumptions and work[29], [31].

It should be noted that in this study, the primary cracks from concrete and contraction operations and longitudinal cracks are neglected. These phenomena have an effect on the corrosion process, and their modeling can be done accurately using finite element method and boundary element method[7], [8], [38].

Table 1. Geographical coordinates of the studied points

Longitude	Latitude	Distance from the sea (m)
52° 15' 35''	36° 38' 09''	20
52° 15' 42''	36° 38' 06''	200
52° 15' 50''	36° 37' 58''	500
52° 15' 57''	36° 37' 42''	1000
52° 16' 03''	36° 37' 09''	2000

Table 2. Concrete specification

Cement type	Cover thickness (mm)	Minimum cement content (Kg/m^3)	Maximum w/c	Condition
Type 1 & 2	50	325	0.45	Intensive (B)

According to Nogueira's work[31], chloride concentration on the surface of rebars is a function of environmental condition. The probabilistic model allows the probabilistic assessment of the corrosion with respect to the random variables involved in this process. In addition, this model can express the degree of dependency of corrosion initiation to the distance of the RC structures from the sea.

In order to apply this model to the corrosion of a concrete member located at a distance from the sea, it is necessary to define a safety index. Here the index is based on fib-Bulletin 65[39]. Accordingly, the corrosion initiation is the time when the reliability index reaches a value of 1.3. This value is approximately equivalent to the probability of corrosion of 10%. The higher the chloride concentration in concrete cover over a period, the structural reliability index decreases. In this regard, according to the environmental conditions, fib determines a structural reliability index. When the reliability index decreases lower than the specified value, that year is considered as the corrosion initiation.

6. REINFORCEMENT'S CORROSION MODELING

6-1 Environmental specifications

Data on environmental conditions such as temperature, relative humidity, wind speed and direction are based on the information provided by the Iranian Meteorological Organization and the Center for Statistics of Iran for the assumed environmental conditions. In addition, since the benchmark of the study is based on the criteria provided by Iran's national regulations of concrete structures, in order to better illustrate the modeling parameters in Table 1, first, environmental conditions are required in accordance with the definition of this standard. Environmental conditions for structures near the coastal area and exposed to winds containing chloride ions accounts as severe (B). The horizontal distances from the sea, which are considered for the modeling of chloride spraying in this study, are 20, 200, 500, 1000 and 2000 meters, which are presented in the following table according to geographic information. Meanwhile, we have tried to select the areas at a same geographic elevation level above the sea so that the difference of the gravity component in calculations do not be effective on final results. In this paper, all studied points are in the 22-meter above the sea level as presented in Table 1. All data in the following table is based on Google Earth data.

To determine the concrete cover thickness given in Table 2, Iran's National concrete design code provides values based on the element type, where in this paper the elements will be beam and column. In this study, the minimum value for concrete compressive strength, maximum water-cement ratio and cement type considering environmental conditions according to the standard have been extracted and presented in the following table. It should be noted that, the chloride diffusion coefficient in concrete requires knowing the concrete specifications.

6-2 Surface chloride content (Cs)

In coastal areas, chloride spraying from the sea surface (chloride ions transmitted by the wind to the farthest parts of the coastal area) leads to an increase in chloride concentration on the surface of reinforced concrete elements. It is estimated that winds can transport these chlorides to a distance of 3 km or more from the sea[14]. The spray-induced chlorides concentration on concrete element's surface depends on environmental conditions, topography, orientation of the element and the distance from the sea[40]. Based on previous studies, it is assumed that the chloride concentration increases through the time[41], [42]. On the other hand, some other researchers are of the opinion that the amount of chloride is constant over time[43]. In Equation 1, C_s depends on the environmental condition. This section introduces several

Table 3. Maximum wind speed and number of days

Year						Month
2017		2016		2015		
Number of days	Maximum speed (m/s)	Number of days	Maximum speed (m/s)	Number of days	Maximum speed (m/s)	
29	15	26	14	7	8	January
17	14	-	-	21	11	February
19	15	6	7	-	-	March
10	17	3	12	22	12	April
11	15	16	10	1	11	May
1	10	22	8	7	10	June
31	10	3	12	12	9	July
-	-	2	7	17	10	August
12	10	29	16	-	-	September
16	12	16	12	10	18	October
24	12	2	19	14	20	November
7	20	6	17	4	15	December

equations presented by researchers to investigate the effect of distance from the sea on corrosion initiation. Yu-Chen Ou represents a formula calculating the amount of C_s regarding the distance from the sea as follows[44]:

$$C_s = 0.988[1.29r(w_s^{0.386})(d_{s0}^{-0.952})]^{0.379} \quad (11)$$

In the above relation, w_s is the mean wind speed over a period of time in m/s, and d_{s0} is the distance from the intended point to the nearest sea in kilometer. Also r is the ratio of the number of winds per day (from sea to coast) according to Table 3 for one month (30 days).

Another relationship for C_s by Stewart and Melchers for intervals between 0.1 km and 2.84 km is presented below[21]:

$$C_s = 1.15 - 1.81\log_{10}(d) \quad (12)$$

In the formula above, d is the distance from the nearest sea in kilometer.

Also, fib code expresses another relation for calculating the maximum amount of chloride in terms of the weight percent of cement[45]:

$$C_s = 0.465 + 0.051.\ln(x_a + 1) - (0.00065(x_a + 1)^{-0.187})x_h \quad (13)$$

In this case, x_a and x_h are the horizontal and vertical spacing of the target point to the sea level in cm respectively.

First of all, the winds at the intended point in north of Iran and in the south of the Caspian Sea were collected according to the available data from the Iran's meteorological station and after performing the fitness test via Minitab software for data from 2015 to 2017 according to Table 3, the distribution of results for data, the mean and standard deviations are shown as 12.78 and 2.3, respectively. In this study, only the winds has direction from the sea to the land are included. In addition, to maximize the reliability of modeling, the maximum speed of recorded winds is used during each day. Also, in Yu relation the parameter r called the ratio of the duration of the wind blown over a year, which is determined by the following table:

In Table 4 for different distances from the Caspian Sea and based on the relationships provided by[21], [44], [45], the mean value for C_s is expressed. In this paper, by inserting the parameters required in the relations provided by fib and Stewart, the mean values are obtained and shown in Table 4, as well, because the conditions presented according to fib and Stewart are in accordance with the conditions considered in this paper, The statistical distribution type and the values for the deviation coefficient are derived from the values given by fib and Stewart. In relation to the Yu method, to determine the type of distribution, the mean value and the coefficient of deviation of surface chloride concentration in each distance, all the values of the parameters contained in the Yu method are inserted and according to the fitness test performed for the quantities obtained in Minitab, the distribution type is Normal and other values are included in the table below[21], [44], [45].

Table 4. Surface chloride concentration in different distances (Kg/m³)

fib		Stewart et al		Yu et al		Distance (m)
CV	Mean	CV	Mean	CV	Mean	
0.75	1.06	0.5	2.95	0.31	1.27	20
0.75	0.66	0.5	2.42	0.31	0.55	200
0.75	0.5	0.5	1.69	0.36	0.51	500
0.75	0.38	0.5	1.15	0.35	0.37	1000
0.75	0.26	0.5	0.61	0.31	0.24	2000

Table 5. Probabilistic data for chloride corrosive condition

Reference	Statistical distribution	CV	Mean	Random variable
Stewart[37]	Lognormal	0.2	0.9	C_{th} (kg/m³)
Nogueira & Leonel[31]	Lognormal	0.75	14.2	D_{app} (mm²/year)
Nogueira & Leonel[31]	Normal	0.5	50	a (mm)

6-3 Structural condition explanation

The probabilistic model used in this study is intended to express uncertainty and estimate the probability of corrosion initiation for an RC concrete constructed at distances from the sea, subject to spraying. This concrete is made of ordinary Portland cement without use of additives and cement substitutes and also from reinforcements with no epoxy coating. The expected structure is exposed to different values of surface chloride which is shown in Table 4. These values are calculated using relations 11, 12 and 13. Here, because the main purpose is to investigate the effect of distance on corrosion, in Table 5 for the parameters a, D and C_{th}, statistical distributions based on previous studies are presented[21], [31], [46]. It should be noted that since the diffusion coefficient is related to both cement substitute materials and water-cement ratio, and in Nogueira's work, these two factors are similar to this paper's assumption, the amount of this parameter, considering the compatibility with the concrete specification is listed in Table 2. The critical chloride content is also estimated to be 0.9 Kg/m³ for conventional concrete and 20% for coefficient of variation. The proposed values for probabilistic parameters are given in Table 5.

7. RESULTS AND DISCUSSIONS

In the previous sections, probabilistic distributions, mean values and coefficient of deviation were determined for all parameters. Also, in the table above, changes in the amount of surface chloride concentration were shown with increasing distance from the sea. In this section, the probability of corrosion initiation at different distances from the sea was investigated over a 50-year period using the Monte Carlo simulation with 200,000 repetitions. The results are shown in the following diagrams. It should be noted that in this study, the criterion is deterioration of rebar's passive layer.

7-1 Surface chloride change

Assuming that the mean values and coefficient of deviations of the other parameters are kept constant, the amount of surface chloride content in different distances is different according to the three proposed methods. Using the MATLAB software and the Monte Carlo simulation, the following diagram was obtained. As shown in Fig. 2, the three methods confirm that by increasing the distance from the chloride source, the amount of surface chloride over 50 years will decrease by about 80%. Also, it is presented in Fig. 2 that in RC structures, the reduction in the surface chloride concentration is slowed down as a result of increase in the distance from the sea. Considering the conditions considered in this study, the surface chloride concentration in the distant area (spray zone) decreases dramatically after passing 200 meters.

In the diagram above, it can be seen that despite the coherence of the diagrams resulted from Yu and fib methods after 500 meters, in less than 500 meters, the non-uniformity trend is observed in the plot according to the data obtained from the Yu method. This is due to the wind effect in Yu's method which makes the difference compare to Stewart and fib formula.

7-2 The effect of distance on probability of corrosion

As a result of surface chloride reduction as an effective factor in reinforcement's corrosion, the effect of this decrease on the probability of chloride corrosion at different distances from the sea was studied, and the results are presented in the following diagrams. The point to be taken into account is that, as service life of the structure increases, the interaction effect

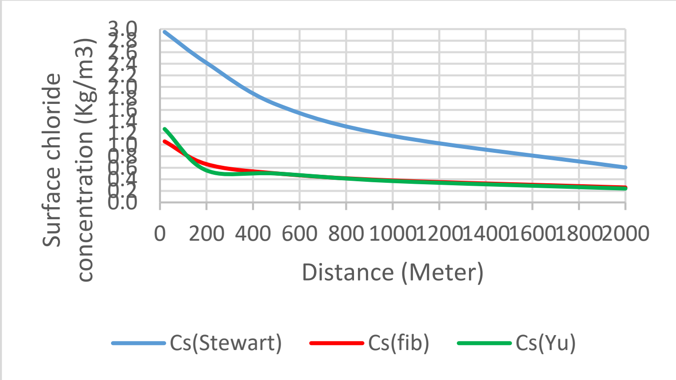

Fig. 2. Different level of surface Chloride concentration at different distances from the sea

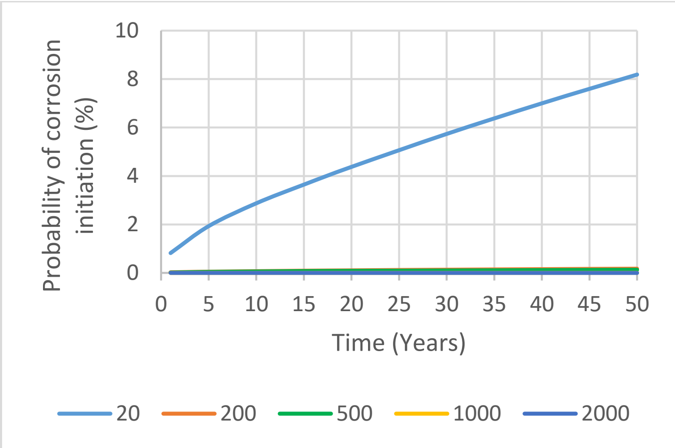

Fig. 3. The changes in probability of corrosion initiation at different distances from the sea in a 50-year period by Yu's method

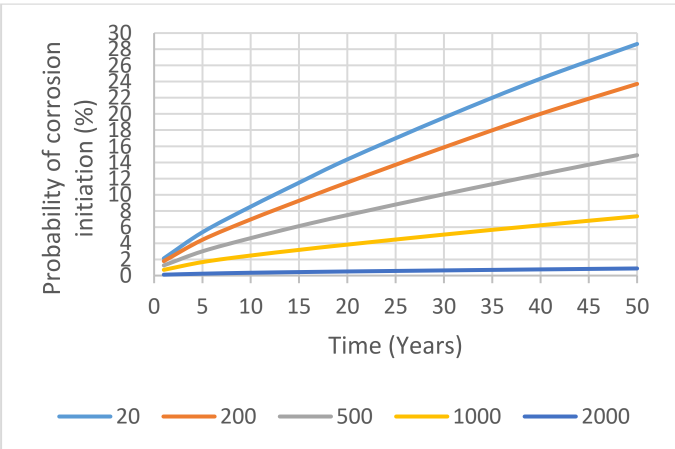

Fig. 4. The changes in probability of corrosion initiation at different distances from the sea in a 50-year period by Stewart's method

will reduce the risk of corrosion by increasing the distance from the chloride source.

According to the diagrams, it is clear that the risk of corrosion in structures located at distances more than 2000 meters almost disappears. Moreover, according to the diagrams, the proximity to the results of the fib and Yu's method and, on the other hand, the difference in these results with that of the Stewart method may indicate that the Stewart method is a higher hand technique or designed for specific conditions. But confirmation the fact that in distances over 2000 meter the probability of corrosion almost disappears is an indication of the proximity of Stewart's approach

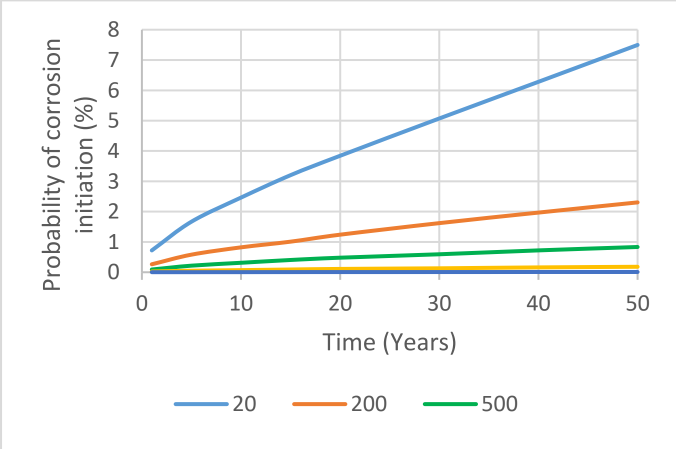

Fig. 5. The changes in probability of corrosion initiation at different distances from the sea in a 50-year period by FIB code

with other two ways. Furthermore, according to fib and Yu diagrams, it is crystal clear that a significant drop in the probability of corrosion initiation happened in distances more than 20 meters. Consequently, if the durability is considered in designing process, it should be noted that the reinforced concrete structures located in spray zones, depending on the distance from the sea, can be exposed to different levels of intrusive chloride agents and this fact should be implemented in designing.

As previously stated, the reliability index according to fib-Bulletin65 is 1.3 or 10%. Based on the diagrams, according to the two methods Yu and fib, the probability of corrosion initiation for structures could be happen only up to 20 meters in about the fifth year, while according to the Stewart method, the probability of corrosion (disappearing of the passive layer on the rebar) at a distance of 20 meters is approximately in twelfth year, 200 meters at about seventeenth and 500 meters in about thirtieth year. Also, based on the charts, the probability of corrosion initiation can be ignored in the distance of more than 1 km from the sea.

8. CONCLUSION

This research mainly focused on the estimation of reinforced concrete structure's corrosion probability located at a distance from the sea. Most of simulations were done based on field tests to estimate the corrosion time, but here the probabilistic nature of the model was investigated due to the randomness of the variables. For this purpose, the Monte Carlo method was used and the effect of distance on the probability of corrosion was investigated. However, for all of the parameters involved, probabilistic distribution is considered, but the random variables involved in the problem are, in particular, the wind speed, the horizontal distance from the chloride source, and the amount of chloride in the surface. The observations from this simulation show that since the possibility of corrosion is reduced by increasing the distance from the sea, designers in considered area in the south of Caspian Sea, can reduce the parameters such as the thickness of the concrete coating as one of the parameters preventing chloride corrosion in accordance with the provisions of the regulations and hence, in order to economize in design. These sum ups are based on observations and controls of the reliability index based on the probability of failure. Therefore, instead of concrete cover thickness, the structural durability can be achieved through other ways such as reducing the water-to-cement ratio and lowering the permeability of the concrete. The results of this study show that with increasing distance from the sea after 200 m, the amount of chloride is significantly reduced. On the other hand, observations indicate that, the probability of corrosion initiation will not change considerably over years in distant distances of about 2 km or more. Using Monte Carlo simulation is an appropriate tool for reliable prediction of structural service life.

REFERENCES

[1] M. Shekarchi, P. Ghods, R. Alizadeh, M. Chini, M. Hoseini, Durapgulf, a local service life model for the durability of concrete structures in the South of Iran, Arabian Journal for Science and Engineering, 33 (2008) 77-88.

[2] A.A. ramezanianpour, T. Parhizgar, A.R. Pourkhorshidi, A.M. Raeesghasemi, Assessment of Concrete Durability With Different Cement and Pozzolans in Persian Gulf Environment, 2006.

[3] P. Sandberg, L. Tang, A. Andersen, Recurrent studies of chloride ingress in uncracked marine concrete at various exposure times and elevations, Cement and Concrete Research, 28(10) (1998) 1489-1503.

[4] A. Costa, J. Appleton, Chloride penetration into concrete in marine environment—Part I: Main parameters affecting chloride penetration, Materials and Structures, 32(4) (1999) 252-259.

[5] M. Morcillo, D. De la Fuente, I. Díaz, H. Cano, Atmospheric corrosion of mild steel, Revista de Metalurgia, 47(5) (2011) 426-444.

[6] M.A. Shayanfar, M.A. Barkhordari, M. Ghanooni-Bagha, Estimation of Corrosion Occurrence in RC Structure Using Reliability Based PSO Optimization, Periodica Polytechnica Civil Engineering, 59(4) (2015) 531-542.

[7] E.D. Leonel, W.S. Venturini, Multiple random crack propagation using a boundary element formulation, Engineering Fracture Mechanics, 78(6) (2011) 1077-1090.

[8] E.D. Leonel, W.S. Venturini, A. Chateauneuf, A BEM model applied to failure analysis of multi-fractured structures, Engineering Failure Analysis, 18(6) (2011) 1538-1549.

[9] D.E. Spiel, G.D. Leeuw, Formation and production of sea spray aerosol, Journal of Aerosol Science, 27 (1996) S65-S66.

[10] J.W. Fitzgerald, Marine aerosols: A review, Atmospheric Environment.

Part A. General Topics, 25(3-4) (1991) 533-545.
[11] M.E.R. Gustafsson, L.G. Franzén, Dry deposition and concentration of marine aerosols in a coastal area, SW Sweden, Atmospheric Environment, 30(6) (1996) 977-989.
[12] M.E.R. Gustafsson, L.G. Franzén, Inland transport of marine aerosols in southern Sweden, Atmospheric Environment, 34(2) (2000) 313-325.
[13] M. Morcillo, B. Chico, L. Mariaca, E. Otero, Salinity in marine atmospheric corrosion: its dependence on the wind regime existing in the site, Corrosion Science, 42(1) (2000) 91-104.
[14] A. Neville, Chloride attack of reinforced concrete: an overview, Materials and Structures, 28(2) (1995) 63-70.
[15] L.-O. Nilsson, E. Poulsen, P. Sandberg, H.E. Sørensen, O. Klinghoffer, HETEK, Chloride penetration into concrete, State-of-the-Art. Transport processes, corrosion initiation, test methods and prediction models, in, Danish Road Directorate, 1996.
[16] C.G. Berrocal, K. Lundgren, I. Löfgren, Corrosion of steel bars embedded in fibre reinforced concrete under chloride attack: State of the art, Cement and Concrete Research, 80 (2016) 69-85.
[17] M. Otieno, H. Beushausen, M. Alexander, Chloride-induced corrosion of steel in cracked concrete – Part I: Experimental studies under accelerated and natural marine environments, Cement and Concrete Research, 79 (2016) 373-385.
[18] M. Otieno, H. Beushausen, M. Alexander, Chloride-induced corrosion of steel in cracked concrete—Part II: Corrosion rate prediction models, Cement and Concrete Research, 79 (2016) 386-394.
[19] J. Zuquan, Z. Xia, Z. Tiejun, L. Jianqing, Chloride ions transportation behavior and binding capacity of concrete exposed to different marine corrosion zones, Construction and Building Materials, 177 (2018) 170-183.
[20] D. Li, R. Wei, L. Li, X. Guan, X. Mi, Pitting corrosion of reinforcing steel bars in chloride contaminated concrete, Construction and Building Materials, 199 (2019) 359-368.
[21] K.A.T. Vu, M.G. Stewart, Structural reliability of concrete bridges including improved chloride-induced corrosion models, Structural Safety, 22(4) (2000) 313-333.
[22] E.C. Bentz, Probabilistic Modeling of Service Life for Structures Subjected to Chlorides, ACI Materials Journal, 100(5) (2003) 391-397.
[23] A.A. Ramezanianpou, E. Jahangiri, F. Moodi, B. Ahmadi, Assessment of the Service Life Design Model Proposed by fib for the Persian Gulf Region, JOC, 5(17) (2014) 101-112.
[24] D.V. Val, M.G. Stewart, Reliability Assessment of Ageing Reinforced Concrete Structures—Current Situation and Future Challenges, Structural Engineering International, 19(2) (2009) 211-219.
[25] M. Ghanoonibagha, M.A. Shayanfar, S. Asgarani, M.a. Zabihi Samani, Service-Life Prediction of Reinforced Concrete Structures in Tidal Zone, Journal Of Marine Engineering, 12(24) (2017).
[26] S. Feliu, M. Morcillo, B. Chico, Effect of Distance from Sea on Atmospheric Corrosion Rate, CORROSION, 55(9) (1999) 883-891.
[27] ACI222 - Corrosion of materials in concrete, ACI Committee, USA, 1985.
[28] D.A. Hausmann, Steel corrosion in concrete--How does it occur?, in, Materials protection, 1967.
[29] N.B.R. Office, Iran›s Design and Construction of Steel Structures, 4th Edition ed., Tose›e Iran, Iran, 1392.
[30] M.A. Shayanfar, M. Ghanooni-Bagha, E. Jahani, Reliability Theory of Structures, Iran University of Science and Technology, Iran, 1394.
[31] C.G. Nogueira, E.D. Leonel, Probabilistic models applied to safety assessment of reinforced concrete structures subjected to chloride ingress, Engineering Failure Analysis, 31 (2013) 76-89.
[32] K.R. Collins, A.S. Nowak, Reliability of structures, Michigan, MC Graw, New York, 2000.
[33] R.E. Melchers, Structural reliability: Analysis and prediction, John Wiley \& Sons, Sydney,Australia, 2018.
[34] S.-K. Choi, R.V. Grandhi, R.A. Canfield, Reliability-based structural design, Springer, London, 2007.
[35] M.A. Shayanfar, E. Jahani, Reliability Index in ABA Design Code, Amirkabir Journal of Civil Engineering, 42(01) (2010) 41-46.
[36] K. Tuutti, CORROSION OF STEEL IN CONCRETE, Swedish Cement and Concrete Research Institute Stockholm, Sweden, 1982.
[37] M.G. Stewart, Spatial variability of pitting corrosion and its influence on structural fragility and reliability of RC beams in flexure, Structural Safety, 26(4) (2004) 453-470.
[38] M.A. Shayanfar, M. Ghanooni-Bagha, A Study Of Corrosion Effects Of Reinforcements On The Capacity Of Bridge Piers Via The Nonlinear Finite Element Method, Sharif Journal of Civil Engineering, 28-2(3) (2012) 59-68.
[39] fib Model Code, International Federation for Structural Concrete, Lausanne, Switzerland, 2010.
[40] N. Berke, M. Hicks, Estimating the Life Cycle of Reinforced Concrete Decks and Marine Piles Using Laboratory Diffusion and Corrosion Data, in: V. Chaker (Ed.) Corrosion Forms and Control for Infrastructure, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, 1992, pp. 207-207-225.
[41] K. Takewaka, S. Mastumoto, Quality and Cover Thickness of Concrete Based on the Estimation of Chloride Penetration in Marine Environments, Special Publication, 109 (1988) 381-400.
[42] T. Ohta, Corrosion of Reinforcing Steel in Concrete Exposed to Sea Air, Special Publication, 126 (1991) 459-478.
[43] P. Bamforth, W.F. Price, An international review of chloride ingress into structural concrete, Thomas Telford, 1997.
[44] Y.-C. Ou, H.-D. Fan, N.D. Nguyen, Long-term seismic performance of reinforced concrete bridges under steel reinforcement corrosion due to chloride attack: LONG-TERM SEISMIC PERFORMANCE OF CORRODED RC BRIDGES, Earthquake Engineering & Structural Dynamics, (2013).
[45] Model code for service life design - Bulletin34, Federation International, 2006.
[46] Q. Suo, M.G. Stewart, Corrosion cracking prediction updating of deteriorating RC structures using inspection information, Reliability Engineering & System Safety, 94(8) (2009) 1340-1348

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