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RESEARCH ARTICLE

Estimation of Corrosion Occurrence in RC Structure Using Reliability Based PSO Optimization

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Abstract

In this study, meta-heuristic approach of two types of Particle Swarm Optimization (PSO) method is used to calculate corrosion occurrence probability, due to chloride ions penetration and carbonation. The models' efficiency is verified by comparing with available examples in technical literature and results of Monte Carlo analysis. According to the analyzes performed, using different probabilistic distributions regardless of probabilistic moments based on real distribution, lead to diverse results. In addition, influence of each effective parameter on corrosion occurrence varies by changing other parameters and by time The effect of concrete cover (d) reduces at corrosion initiation and the corrosion threshold (C_{th}) slightly increases over time Almost, the concrete cover is the most important factor, and the corrosion threshold is also the least important factor. The influence of chloride concentration amount at surface (C_s) increases over time, in a way that, it becomes the most important parameter in low-quality concretes after several years. Thus, the precise amount of C_s is of great importance in exact estimation of corrosion and durability design.

Keywords

RC Structure · Chloride Corrosion · Corrosion Initiation · Reliability Index · PSO Optimization

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1 Introduction

Corrosion of Reinforcement is the most important cause of damage and failure in reinforced concrete structures. Neglecting corrosion occurrence and its progress may take the structures out of use before their due date and can lead to loss of construction and maintenance capitals. According to the researches, corrosion happens in two forms: Chloride [1] and Carbonation [2]. Structures in corrosive environments (e.g. coastal areas, areas with hard winters where salt is used for ice melting and generally structures in continuous presence of chloride ions), the reinforcement corrosion happens through chloride ions penetration. Corrosion of structures in polluted areas and cities is due to acid rains and penetration of carbon dioxide into the concrete and is called carbonation kind [1, 2]. Rebars in reinforced concrete structures are protected by a protective layer which is formed due to high alkalinity of concrete around the Reinforcement. Over time and mainly based on two cases of chloride ions penetrations and carbonation, the concrete alkalinity reduces with acid formation and the armatures corrode in the vicinity of moisture and oxygen [3]. Corrosion reduces the area and load bearing of reinforcements, increases volume of steel which causes corrosion, destructs the concrete cover and decreases continuity strength between concrete and steel [4, 5].

There are some researches that study determination of corrosion occurrence probability in reinforcement which have attracted much attention during recent years. Enright and Frangopol [6] analyzed the effect of different parameters variations on corrosion initiation time and bending capacity of bridge beams. They considered all the variables log-normal. Amleh et al. [7] studied the causes of Dickson bridge failure and the governing distribution on probable parameters of corrosion. Papakonstantinou and Shinozuka [8] presented a comprehensive model in actual scale for the process of corrosion occurrence and its progress inside the concrete in large structures. A model for determining corrosion occurrence probability in order to evaluate the concrete structures strength by using FORM with a direct coupling approach was represented by Nogueira and Leonel [9] and they compared it with MCS. Song et al. [10] calculated the corrosion occurrence probability of concrete tunnel-box structure on seabed using Monte Carlo simulation method by determining rate of chloride transport experimentally and choosing other parameters by technical literature study. Although most of the research concentrated on developing models of chloride corrosion occurrence prediction, Bastidas-Arteaga et al. [11] analyzed the effect of CO_2 emissions and temperature/humidity variations on bridges. Stewart et al. performed a similar work as Schoef's to study this phenomenon on Australian buildings [12, 13].

Unlike the analysis of large structures which need heavy trial and error works, and regarding explicit limit state functions in case of corrosion occurrence, and also the power of today's computers in reducing computational cost, meta-heuristic approaches are used in the present study instead of moments approaches (e.g. FORM and SORM) and simulation approaches (e.g. Monte Carlo). Charles Elegbede's [14] research in solving structures reliability problem is one the most important studies about application of meta-heuristic approaches which uses PSO algorithm with specific approach penalty available in technical literature. Probabilistic mathematical problems and structures with explicit limit state function with proper accuracy were solved by adding absolute value of constrained function to the target function and minimizing it.

Previous research on determination of corrosion occurrence probability was performed either by moment methods based on first-order derivatives like FORM, second-order derivatives like SORM or higher order ones like HORM which have lower accuracy in nonlinear limit state function, or by simulation methods which need long solution time.

In this paper, two innovative unconstrained procedures in PSO method are used to solve explicit limit state functions of chloride corrosion, by defining Hasofer and Lind [15, 16].In order to solve the problem of determining corrosion occurrence probability, in first type of unconstrained procedure, one of the variables is chosen according to the easiest case and is calculated in terms of other parameters. Finally, the considered parameter is taken to the normal standard state regarding the probabilistic moments. By doing so and considering that we are moving on the limit state function or constraint, the considered response is accurate based on Hasofer-Lind. More descriptions are presented in the relevant sections As other type of unconstrained procedure for this problem [17] we can determine all parameter first and normalize to unit length vector and then with β times of it in PSO algorithm. Although, in the recent approach, $g(X)$ not exactly equals to zero and reliability index is lower than real amount. Indeed this estimation of probability of failure is conservative.

2 Process of Steel Corrosion Occurrence in Concrete

According to literature review, the PH amount of concrete with Portland cement is close to 13 [3, 18] High alkaline property of concrete forms a protective oxide layer on the steel surface. This is called a passive layer. The dioxide existing in the atmosphere or the chloride in the concrete environment along with the moisture and the oxygen can penetrate via the concrete pores and cracks and can reach the reinforcement surface; then, by reducing concrete alkalinity, they cause reinforcement corrosion inside the concrete by destroying the protective oxide layer on the steel.

2.1 Chloride Corrosion

Chloride ions reach the passive layer according to the explained pattern and they begin to react in the passive layer when the amount of chloride ions go beyond the critical value and cause perforation corrosion [19].The process of chloride ion penetration into the concrete is expressed in terms of Flux fundamental concepts presented by A. E. Fick with the following assumptions: governing conditions of the first law of diffusion, independency of diffusion coefficient relative to time and one-dimensional diffusion. It is represented as [20–22]:

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

- C is the concentration of chloride at the abscissa x [mol/m^3]
- D is the chloride diffusion coefficient [m$^2/s$] (the factor D, which A. E. Fick called: the constant depending on the nature of the substances).

By solving Eq. (1) (second law of diffusion) for the constant surface chloride conditions, chloride ion penetration equation is written in terms of depth (x) over time (t) as:

$$C(x,t) = C_s(1 - erf\frac{x}{2\sqrt{Dt}}) \tag{2}$$

Where, $C(x,t)$ = chloride concentration at depth and time, C_s = surface chloride concentration, D = apparent diffusion coefficient, x = concrete cover depth and erf = statistical error function.

Every effective parameter in the previous equation is a random variable and is defined with its own mean value, standard deviation and probabilistic distribution which will be explained later.

2.2 Life cycle model and determination of destruction probability of the structure

According to section 2, after construction and curing of concrete, it takes time until corrosion starts. In this period, chloride is infiltrated to the concrete from its surface and when chloride level on rebar surface exceeds the critical value, passive layer of the steel is destructed and steel will be ready for corrosion. This period is called initial period and assigned with T_i. Since any damage in the structure has not occurred before this time, calculation of this period is important and is often considered as the end of structure lifetime. In this period, no significant of damage and cracks in the structure has been observed yet. Fig. 1 shows the most important and valid existing model that is represented for corrosion progress and structure damage by Tutti

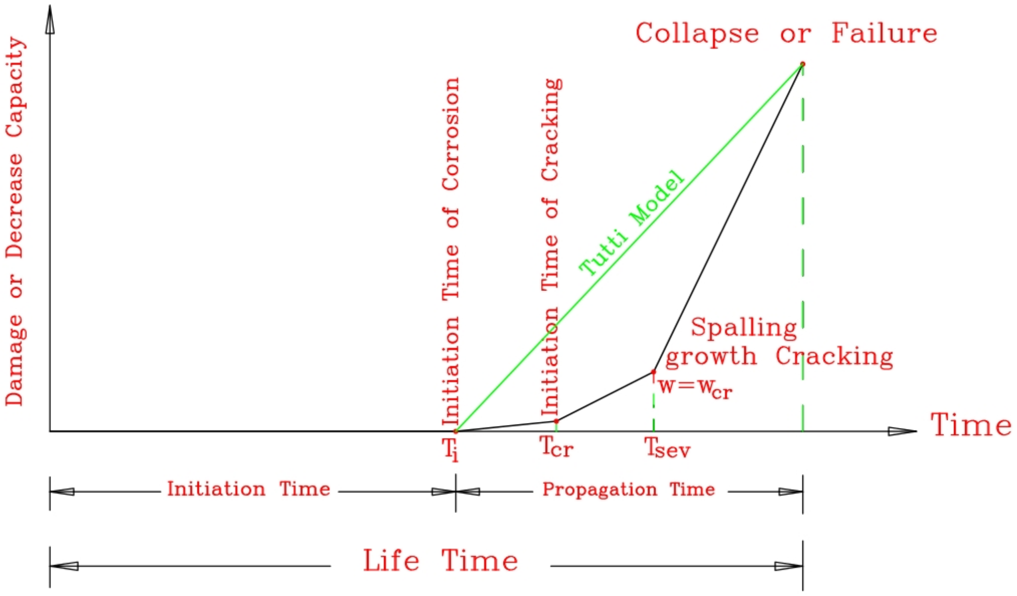

Fig. 1. Modified Service life time model and Tutti model for beginning of corrosion and damage

Tab. 1. Probabilistic moments and governing distribution in some researches done on critical chloride C_{th} (kg/m^3)

Reference	Considerations	Mean	COV	Distribution
Nogueira & Leonel [9]		0.9	0.19	uniform(0.6-1.2)
Duprat (2007) [31]	good concrete	2	0.14	uniform
	ordinary concrete	1.5	0.19	
	poor concrete	1	0.29	
Ferreira [32]		0.06~0.2	0.02	normal
Saassouh & Lounis [33]	bridge deck	0.7	0.2	lognormal

in 1982 [23].After aggressive agents reach to rebar surface, and corrosion starts, since performing rust production, it may take several years for cracks to appear. Of course, length of this period is very shorter than initial period. Beginning of cracking which is from T_i to T_{cr}, first step of corrosion progresses with a slight slope and low velocity. Afterwards, with infiltrating of aggressive agents to concrete cracks and then reaching to rebar surface, destruction rate and corrosion continue faster until the structure is destructed. In Fig. 1 the newest model of corrosion is showed based on damage that is represented by modification of Tutti model and with division of propagation zone of chloride [24, 25]. Development stage is considered a two-stage process by some researchers; the spalling concrete stage is considered before collapse or very low capacity [26]. However, for designing based on structure durability, behavior control of the structure, maintenance prediction and repairing, accurate determination of the first step and time of first cracking is important and essential.

With the same reliability procedure, cracking growth of time and spalling can be calculated by using related formulas with probabilistic presented methods.

According to the [27], time of cracking due to corrosion, t can be obtained from Eq. (3).

$$t = \frac{80C}{dr} \tag{3}$$

Where, C is concrete cover, d is rebar diameter and r is corrosion rate. According to [27] mean value of corrosion rate can be 1 and 16 and coefficient variation of r is 0.5.

3 Probabilistic parameters of corrosion problem

The nature of concrete production is random and porosity is made in the aggregates location. Usually, in ideal conditions, the experimental results of some samples differ slightly. By reviewing the studies done in the field of reinforcements corrosion, it can be seen that the collected data differ significantly and the effective parameters don't have exact and definite amount. The corrosion initiation time is represented in probability percent and the corresponding reliability is calculated since there are a lot of uncertainties in the effective known parameters of reinforcement passive layer failure. Next, some relevant parameters of chloride ion diffusion in concrete and carbonation and also some previous researches done in this field are reviewed.

Chloride threshold (C_{th}):

Minimum density of the required chloride for destroying the passive layer and corrosion initiation is called chloride threshold [29]. Density threshold of chloride ions for corrosion initiation is controversial and depends on many factors including kind of reinforcement, electrochemical environment of the concrete, water to cement ratio, moisture, additives and etc. The amount of *0.04* is suggested for the chloride ion to cement weight ra-

Tab. 2. Probabilistic moments and governing distribution in some researches done on chloride Diffusion

Reference	Considerations	Mean	COV	Distribution
Nogueira & Leonel [9]	w/c=0.4	14.2 mm^2/year	0.75	lognormal
	w/c=0.5	41.0 mm^2/year		
	w/c=0.6	86.4 mm^2/year		
	w/c=0.7	162.7 mm^2/year		
Duprat (2007) [31]	good concrete	1(×10^{-12} m^2/s)	0.7	lognormal
	ordinary	2(×10^{-12} m^2/s)		
	poor	7(×10^{-12} m^2/s)		
Ferreira [32]		1~15(×10^{-12} m^2/s)	2.5	normal
Saassouh & Lounis [33]		40 mm^2/year	0.25	lognormal

Tab. 3. Probabilistic moments and governing distribution in some researches done on the surface chloride C_s (kg/m^3)

Rreference	Considerations	Mean	COV	Distribution
Nogueira & Leonel [9]	C.A. II	1.15	0.5	lognormal
	C.A. III	2.95		
Duprat (2007) [31]		3.5	0.6	normal
Ferreira [32]	DuraConc Software	0.4~1.2	0.3	normal
Saassouh & Lounis [33]	bridge decks	6	0.3	lognormal

tio and is considered as a proper threshold [30]. The results of some available studies in the field of critical chloride are summarized in Table 1. More explanations of this parameter, which represents resistance against chloride corrosion, are previously defined.

Chloride diffusion coefficient (D):

Chloride diffusion (D) in the concrete determines its resistance against chloride ion penetration. Of the most important factors on this parameter and more resistance against chloride ions penetration (smaller D) are selection of a proper dough system and small ratio of water to dough which increases resistance against chloride penetration due to creating low porosity [34]. The results of applied values and the governing distribution on chloride diffusion coefficient in some researches are summarized in Table 2.

Surface chloride concentration (C_s):

The amount of chloride on the concrete surface C_s is a result of regression analysis of the obtained data from concrete chloride penetration and curve fitting of Fick's second law. Surface chloride density is basically the result of environmental conditions in which the concrete presents; however, the concrete quality and structure geometry affects the accumulation and increase of surface chloride density [34]. Applied results in some researches and the governing distribution of surface chloride density (C_s) which is usually considered log-normal is summarized in Table 3.

Concrete cover (d):

The most important factor of variations and errors in cover size of concrete structures depends on the work environment elements such as supervision of engineers, workers and technicians skill. The mean value of cover is determined by measurement and calculations considering the design and standard deviation presented in Table 4.

Carbonation parameters are presented in the previous section and more details are analyzed in section 3-7 examples (numerical examples). Corrosion initiation time corresponds to the log-normal distribution as the researchers findings.

4 Limit state function in corrosion occurrence probability problem

The concept of limit state function or performance function is used for failure determination in reliability analysis. In fact, the limit state function is a boundary between proper and improper performance If this function value is positive ($g(X) > 0$), the region is safe or the performance is appropriate and if it is negative $g(X) < 0$), the performance is inappropriate or is in failure region. The boundary between appropriate and inappropriate region is $g(x) = 0$ and the optimal condition is calculated based on it. Limit state function in design of structures reliability, in the simplest form, is written as:

$$g(X) = R - S \geq 0 \tag{4}$$

Where, S is the loads effect and R is the resistant forces and $G(X)$ is the limit state function. For durability design of concrete structures in the case of chloride corrosion, the amount of critical chloride C_{th} is equal to resistance R and is equal to S in the above equation. Therefore, chloride limit state function is written as:

$$g(X,t) = C_{th} - C_S(1 - erf\frac{x}{2\sqrt{Dt}}) \tag{5}$$

Due to corrosion, limit state function is written based on concrete cover depth (C),reinforcements diameter (d) and corrosion

Tab. 4. Probabilistic moments and governing distribution in some researches done on the concrete cover *d* (mm)

Reference	Consideration	Mean	COV	Distribution
Nogueira & Leonel [9]	C.A. II	30	0.5	normal
	C.A. III	40		
Duprat (2007) [31]		Var	Var	normal
Ferreira [32]	DuraConc Software	Var	Var	normal
Saassouh & Lounis [33]	bridge decks	70	0.2	lognormal

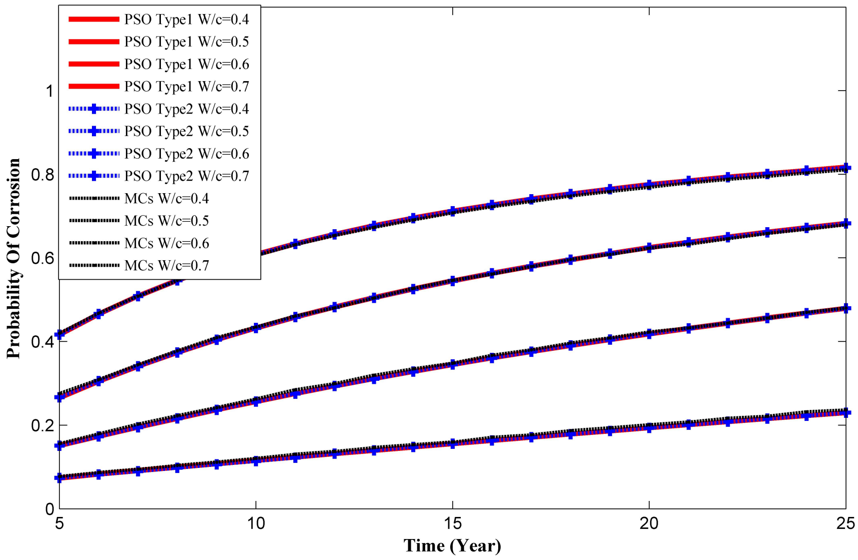

Fig. 2. corrosion probability versus time for proposed algorithms (CIII concrete)

rate (r), according to Eq. (3):

$$g(X) = t_i - t_{crack} = t_i - \frac{80\,C}{d\,r} \tag{6}$$

Where r is corrosion rate (μm/year), d is reinforcements diameter in mm and c indicates cover depth in mm For normal concrete mean and standard deviation of r, are 1 and 0.5 respectively. For Low, Moderate and High Corrosion aggressiveness levels, corrosion rate are 0.5, 2 and 5 respectively [11].For Portland Concrete with w/c ratio = 0.40 and with 45 mm concrete cover using Monte Carlo simulation, Faber et al. [35] considered 3.5 and 1.5 years for mean and standard deviation of time cracking (T_P) after corrosion initiation that follows from log-normal distribution [35]

5 Reliability analysis

Reliability is the probability that a system will perform its function over a specified period of time and under specified service conditions. Failure probability, P_f, is the probability of happening inappropriate performance. Normally, calculation of complement of failure probability is known as reliability analysis. It is done by determining the performance range of limit state function. About calculation of corrosion initiation time, the problem is converted to determination of corrosion probability or inappropriate performance of the limit state function. Exact calculation of failure probability in n-dimensional condition is based on the reliability theory can be written using multi-integration on joint probability density function as [36]:

$$P_f = P\left[G\left(\underline{X}\right) \le 0\right] = \int_{G(\underline{X}) \le 0} f\left(\underline{X}\right)\, d\underline{X} \tag{7}$$

Where, $\underline{X}$ is the random vector which represents random variables and $f(\underline{X})$ is joint probability density function of variables.

Considering the complexity and solution difficulty of the mentioned integral, various methods have been introduced to calculate failure probability and to analyze the reliability. Generally, these methods are classified into three groups: moment methods such as first and second order reliability methods [36, 37], sampling methods like Monte Carlo simulation and importance sampling [37, 38] and advanced optimization methods with using meta-heuristic algorithms [37, 39].

In simple terms, when all of the variables follow the normal distribution and are independent from each other, the failure probability is calculated as:

$$P_f = \Phi(-\beta) \tag{8}$$

Where, $\Phi(\beta)$ is the cumulative distribution function and β is the safety index or reliability index.

Lind and Hasofer [16] defined the reliability index (β) as the shortest distance between space center of the problem and limit state function in standard normal coordinate. Using this defini-

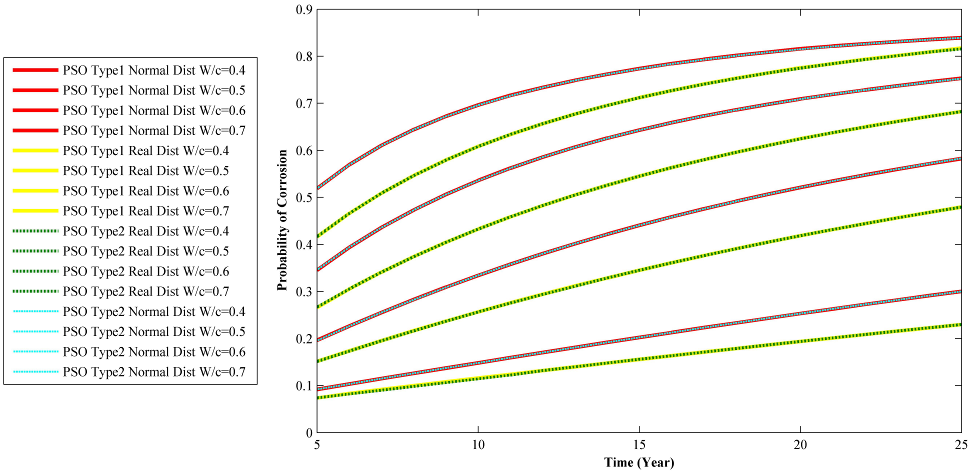

Fig. 3. Effect of different distributions on probability of corrosion occurrence with two PSO algorithms (example 1-CIII)

Tab. 5. design point characteristics in year 25 after CII concrete construction of Example (Eq. (1))

Parameter	w/c =0.4		w/c =0.5		w/c =0.6		w/c =0.7	
	PSO type1	PSO type2	PSO type1	PSO type2	PSO type1	PSO type2	PSO type1	PSO type2
d	-0.9734	-0.9500	-0.5051	-0.5040	-0.2372	-0.2482	-0.1023	-0.1107
D	0.3315	0.3365	0.2648	0.2406	0.1054	0.1427	0.0570	0.0597
C_S	0.6880	0.7295	0.5572	0.5805	0.4444	0.4252	0.2833	0.2833
C_{th}	-0.4240	-0.4056	-0.3433	-0.3220	-0.2418	-0.2428	-0.1788	-0.1719
β	**1.30786**	**1.30860**	**0.86811**	**0.86750**	**0.56863**	**0.56720**	**0.35486**	**0.35440**
P_f	**0.09546**	**0.09533**	**0.19267**	**0.19283**	**0.28480**	**0.28529**	**0.36135**	**0.36152**

tion, a first order approximation of failure probability can be obtained. Nataf [40] and Rosenblatt [41] and linear conversion include three conversions enabled to convert X vector in physical variables space to U vector in standard normal space. Therefore, the problem is converted from a reliability index to an optimization problem. This optimization problem can be written based on Lind and Hasofer:

$$\begin{cases} \text{Minimize} & \beta = \sum\limits_{i=1}^{n} u_i^2 \\ \text{Subject to:} & G\left(T^{-1}(u)\right) = 0 \end{cases} \tag{9}$$

This optimization problem can be solved by different optimization methods. Charles Elegbede [14] solved this problem considering standard normal variables with PSO algorithm. Penalty method is also used to solve this constrained problem [42, 43]. Penalty function and penalty coefficient are fundamental parts of constrained optimization problems. But, determination of penalty function and penalty coefficient is time consuming and difficult The optimization problem solution is equal to the following equation:

$$\underset{u}{Minimize} \sum_{i=1}^{n} u_i^2 + \lambda\xi(G(T^{-1}(u))) \tag{10}$$

Where λ and ξ are penalty coefficient and penalty function respectively, u^* is the equation solution called design point, and the according reliability index is obtained from $\beta = \|u^*\|$ equation.

Selection of penalty function and penalty coefficient in above equations is very important in convergence of search process to solutions of these equations. For overcoming to this deficiency, corrosion problem is solved by converting it to an unconstrained optimization problem. Non-normal parameters must be converting to the normal equivalent in this procedure. Rackwitz and Fiessler method is used to convert un-normal variables into normal ones [44].

6 Optimization Procedure

In this study, Particle Swarm Optimization (PSO) method is used to find design and calculation point of reliability index. PSO method is a population based meta-heuristic algorithm was invented by Eberhart and Kennedy in 1995 [45]. In many aspects, PSO is similar to other evolutionary calculation methods such as genetic algorithm. The system begins with an initial population of random solutions, and then it searches for the optimal value by updating the generations. Of course, unlike genetic algorithm, PSO does not include evolutionary operations such as reproduction and mutation. In PSO, some particles are distributed in search space and each of them evaluates the objective function in their current position (p_i). Then each particle modifies its movement in search space using combination of the best position experienced by the particle ($pbest_i$), the best position of all particles ($pbest_g$) and some random turbulence. Next generation is produced after all the particles finished their move-

Tab. 6. design point characteristics in year 25 after CIII concrete construction of Example (Eq. (1))

Parameter	w/c =0.4		w/c =0.5		w/c =0.6		w/c =0.7	
	PSO type1	PSO type2	PSO type1	PSO type2	PSO type1	PSO type2	PSO type1	PSO type2
C_{th}	-0.1223	-0.1550	-0.0133	-0.0131	0.1097	0.1292	0.2507	0.3017
D	0.3081	0.2640	0.0240	0.0250	-0.2570	-0.2159	-0.3828	-0.3840
C_S	0.2520	0.2381	0.0236	0.0226	-0.2523	-0.2785	-0.5180	-0.6138
d	-0.6111	-0.6293	-0.0366	-0.0367	0.2922	0.2900	0.5969	0.4386
β	**0.73945**	**0.73920**	**0.05157**	**0.05150**	**0.47663**	**0.47430**	**0.91321**	**0.89870**
P_f	**0.22982**	**0.22989**	**0.47943**	**0.47946**	**0.68319**	**0.68236**	**0.81943**	**0.81559**

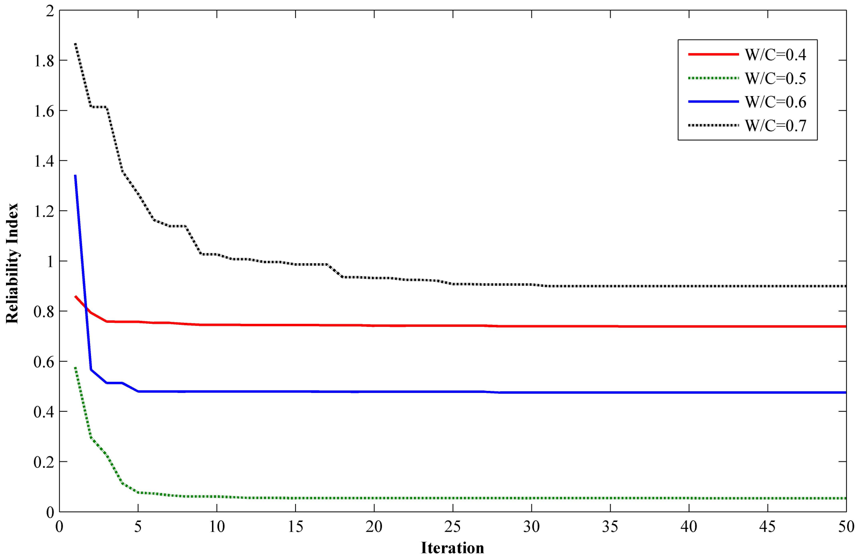

Fig. 4. Convergence history of PSO type 1 for concrete CIII in example 1

ment. Each member has 3-dimentional vectors in particle sets, in other words, these are search space dimensions. These dimensions include: current position x_i, best historical position p_i and velocity vector v_i. Current position x_i, is a set of coordinates for a point in the space. In each iteration of the algorithm, current position is evaluated as a problem solution. Algorithm is operated by adjusting v_i where it is step length. New points are obtained by adding v_i to the coordinate of x_i based on the following equations:

$$\begin{aligned} v_{i+1} &= v_i + u(0,\varphi_1) \times (p_i - x_i) + u(0,\varphi_2) \times \left(p_g - x_i\right) \\ x_{i+1} &= x_i + v_{i+1} \end{aligned} \tag{11}$$

In PSO process, velocity of each particle is modified alternatively, such that particles are placed statistically around p_i and p_g positions. PSO process is repeated until the algorithm approach convergence or reach to a determined iteration number. In this study, in order to remove the optimization constraints (removing coefficient and penalty function), two methods were used by changing PSO optimization rather than space points.

In the first PSO method, the constrained optimization problem is produced with a less parameter and these parameters are transferred to the original coordinates; then, the other parameter is obtained based on the other variables. Finally, this parameter is converted to normal standard space based on its moments. This has two advantages for the solution of reliability problem. First, we are sure that the obtained design point is located on the limit state function ($G(X) = 0$). Second, the constrained optimization problem is converted to the unconstrained optimization problem. In the second method, the variables are produced all together and after normalizing to unit length in standard normal space, until approach to a limit function and pass it, the variables become larger with sectional increase.

$$u^* = \beta\alpha^* \tag{12}$$

$\alpha^*$is normalized coordinate of the final produced vector that represents sensitivity of each parameter. According to the fact that design point and the obtained reliability of this method are smaller than the accurate values on destruction surface ($G(X) \geq 0$ but $G(X) \approx 0$), the solution of this method is slightly conservative. Ultimately, in both methods, according to the definition of Hesofer and Lind [15, 16], the distance between center of the standard normal coordinate and the limiting state function is the reliability index. Therefore, a reliability index for each particle can be calculated corresponding to the representing path displacement of that particle. The difference between two methods is almost zero for the corrosion problem, and it can be perceptible for problems with ultra-small damage probabilities. Although, the second method has the capability of solving

Tab. 7. Variation of importance of every parameter duration of time(year) for w/c =**0.4,0.5,0.6,0.7 – CIII**

w/c =0.4						
Time	P_f	β	d	D	C_S	C_{th}
5	0.07493	1.44	0.9606	0.1931	0.1720	0.1017
10	0.11600	1.1952	0.9245	0.2772	0.2299	0.1246
15	0.15575	1.0121	0.8888	0.3362	0.2698	0.1559
20	0.19382	0.8639	0.8605	0.3535	0.3176	0.1835
25	0.22998	0.7389	0.8269	0.4046	0.3378	0.1962

w/c =0.5						
Time	P_f	β	d	D	C_S	C_{th}
5	0.15118	1.0314	0.9089	0.2992	0.2426	0.1600
10	0.25659	0.6539	0.8219	0.3849	0.3633	0.2105
15	0.34513	0.3985	0.7722	0.4273	0.4137	0.2235
20	0.41847	0.2058	0.7259	0.4500	0.4361	0.2836
25	0.47946	0.0515	0.7083	0.4711	0.4455	0.2791

w/c =0.6						
Time	P_f	β	d	D	C_S	C_{th}
5	0.26691	0.6222	0.8239	0.4066	0.3481	0.1863
10	0.43254	0.1699	0.7473	0.4442	0.4319	0.2400
15	0.54510	0.1133	0.6773	0.4698	0.4896	0.2843
20	0.37566	0.3169	0.6459	0.4652	0.5233	0.3042
25	0.68239	0.4744	0.6214	0.4311	0.5662	0.3277

w/c =0.7						
Time	P_f	β	d	D	C_S	C_{th}
5	0.41637	0.2112	0.7290	0.4640	0.4290	0.2629
10	0.60807	0.2743	0.6498	0.4807	0.5126	0.2896
15	0.71189	0.5589	0.5824	0.4717	0.5913	0.2978
20	0.77467	0.7543	0.5533	0.4470	0.6376	0.2958
25	0.81554	0.8985	0.5024	0.4091	0.6844	0.3343

discrete problems, the first method can be only used for continuous problems which the studied problems are of this type.

7 Numerical examples

Some examples of technical literatures are used in order to show the model efficiency and to study chloride and carbonation corrosion. During the calculations, notes and results from the analysis were examined.

First example: probability determination of chloride corrosion of this study is obtained from CIII concrete of Nogueira and Lionel [9]. Utilized parameters in the performed analyses are the first rows of Tables 1 to 4. Used limit state functions in this and the next examples are Eqs. (7) and (8). In Fig. 2, the corrosion probability is calculated and presented using two methods of PSO and Monte Carlo simulation with *10000* simulations. It can be seen from responses comparison that the calculated response of PSO method analysis exhibits more conservative behavior in the Monte Carlo simulation.

In Fig. 3, the effect of distribution kind on the structure response (corrosion occurrence probability) of the first example is being analyzed. In the first case, real distribution of the parameters is used so that C_{th} has uniform distribution, D and C_s have log-normal distribution and d (concrete cover) follows normal distribution. In the second case, all the parameters are considered normal. Analysis results of the first case are presented in Fig. 2.

For the ratios of w/c from *0.4* to *0.7*, corrosion occurrence probability with real distribution by using PSO method values are *0.2299*, *0.4795 0.6826* and *0.8155*, respectively By using the PSO method with assumption of normal parameters they have *10-3%* difference with the first case analysis In the first years for concrete with good quality (lower w/c) and in the last years for concrete with bad quality (higher w/c) the least difference between two cases was observed (normal and real distribution of parameters) In other time and concrete types difference between two analyzed cases is large. Comparison for case 1 and case 2 results is shown in Fig. 3.

Moreover, the PSO's response with normal distribution has significant difference with Monte Carlo's using normal distribution due to the considerable probabilistic distributions. However, it seems that the main reason for difference is that the used mean and standard deviation values in the analyses are obtained for the main distribution (the real distribution of that parameter in the analyzed conditions) and their usage in normal distribution is not right. If the first moments values are calculated for normal distribution, the responses are closer to reality and then we can have better judgment of values difference One of

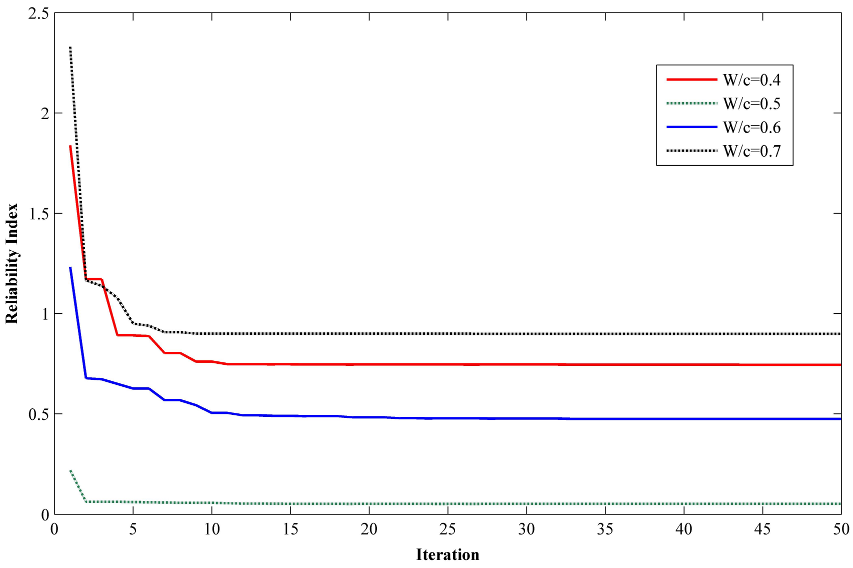

Fig. 5. Convergence history of PSO type 2 for concrete CIII in example 1

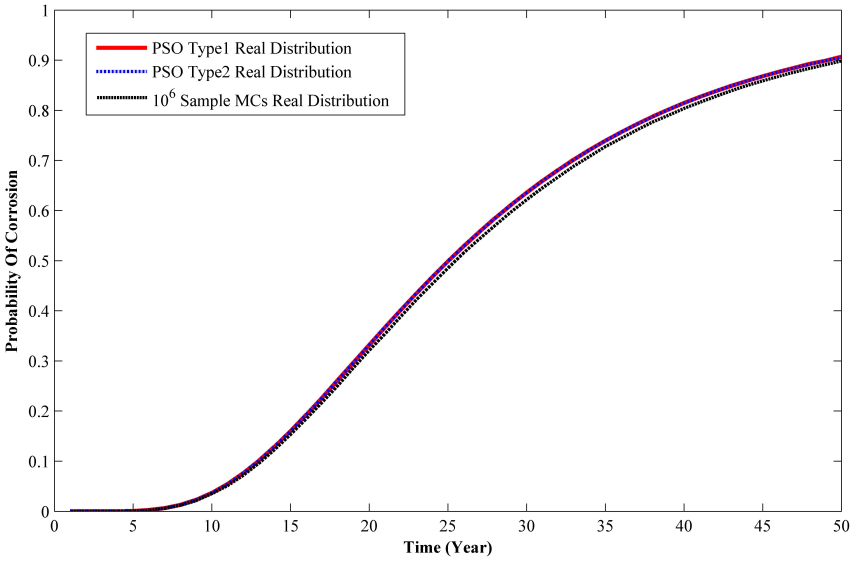

Fig. 6. Comparison of accuracy and efficiency of PSO and MCS in predicting corrosion probability (example 2)

the advantages of this method is that the design point can be obtained in any arbitrary time which cannot be done in Monte Carlo simulation. These values determine the effectiveness of any parameter on the whole response; namely, sensitivity of every parameter to the calculation response is determined. Sample design point characteristics in year *25* after the construction of four types of water to cement ratios in CII concrete are presented in Table 5.

The values of obtained design points for four kinds of water to cement ratios (w/c) are presented in Table 6 for CIII type concrete in year *25* after the construction. According to the calculated values, the importance and effectiveness of every parameter can be discussed.

By dividing each parameter in Table 6 into the vector length (β), the dimensionless design values are obtained which demonstrate the importance of each. As can be seen in Table 7, the concrete cover is the most important factor, and the corrosion threshold is also the least important factor. The concrete cover is the most crucial parameter especially in high-quality concretes, but its importance gradually reduces over time.

In addition to the fact that, the effect of concrete cover is the most important parameter, reduces with decreasing of concrete quality (i.e., increase of water to cement ratio or D) and over time. Additionally, the influence of chloride concentration amount at surface (C_s) increases over time, in a way that, it becomes the most important parameter in low-quality concretes after several years. Thus, the precise amount of $C_s$is of great importance in exact estimation of corrosion and durability design. The effect and importance of D increase over time at lower values of diffusion coefficients (i.e., high-quality con-

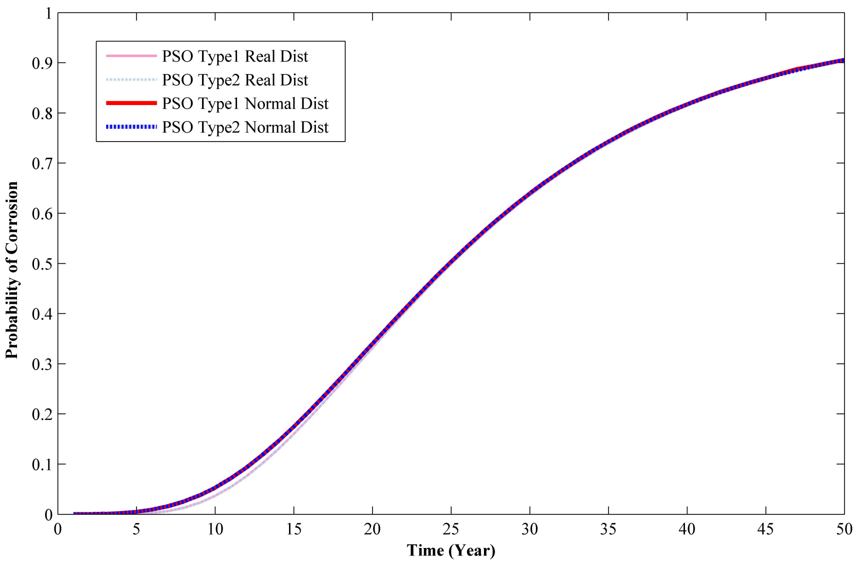

Fig. 7. Comparison of distribution type effect in predicting corrosion probability (Example 2)

cretes). But, it is almost constant or fluctuates slightly for low-quality or medium-quality concretes over time.

Convergence history of the calculation response is represented for every concrete in year *25*. Convergence history of the calculation response (reliability index) in PSO Type 1 method is illustrated for CIII type concrete in year *25* for the given parameters values of Tables 1 to 4 which shows the algorithm's powerfulness in solving optimization problems. This case can be obtained like design point for every arbitrary time.

Example two: determination of corrosion occurrence probability due to chloride from Sossash and Lounis [33] in which all the effective parameters on corrosion occurrence are considered log-normal. This example is about predicting chloride ion penetration and corrosion occurrence in deck of a concrete bridge with *0.3%* longitudinal reinforcement in two directions; the concrete is normal and salt is used in winter to prevent glaciation. Mean and standard deviation values of the applied parameters in analyses are used from the last rows of Tables 1 to (Eq. (4)). Results of the analysis with optimization method and the Monte Carlo analysis with *1*million simulations for corrosion occurrence calculation are presented in Table 5. According to the Fig. 6, the results are so close and show high accuracy of this method.

Fig. 6 exhibits the effect of assuming two conditions for all the effective parameters in determination of corrosion occurrence probability: normal and log-normal. Here, it seems that-if all parameter follow the lognormal distribution- conversion to normal distribution does not affect much the responses by considering log-normal assumption for all the parameters. However, in the obtained responses in the first 20 years -that probability of failure is almost low, the values of corrosion probability with normal distribution are slightly larger than corrosion probability with log-normal distribution.

8 Conclusions

In this study, two new modified meta-heuristic approaches of PSO were used to calculate corrosion occurrence probability or corrosion initiation time due to chloride ions penetration. Analysis of the examples and results of research work in literature demonstrated efficiency and accuracy of the used method. Accuracy of the calculated results was studied in comparison to the Monte Carlo method. The main conclusions are as follows:

- One of the useful features of the presented solution is the fast convergence of the responses in low iteration numbers which shows the solution accuracy in finding the minimum point in optimization problems. The PSO type 1 showed the better performance.
- Short solution time and accessing design point (for calculation of importance of each parameter) at any time are features of presented methods in comparison to Monte Carlo method.
- The analysis results showed that using different distribution type for problem parameters without changing the probabilistic moments, proportion with distribution type is effective in calculation results. Also, there is no reason that log-normal variables calculate conservatively the failure probability or corrosion occurrence.
- Influence of each effective parameter on corrosion occurrence varies by changing other parameters and by time
- Almost, the concrete cover (d) is the most important factor, but effect of it reduces overtime and increases with w/c ratio (decrease of D parameter).
- The influence of Chloride diffusion (D), for lower w/c ratio (0.4, 0.5) (amount of higher of D), increases over time and it is the second importance parameter in these types of concretes. But for low-quality concretes (higher w/c ratio), de-

spite of fluctuations, its importance almost remains constant over time, and therefore it is the third important parameter.

- The influence of chloride concentration amount at surface (C_s) increases over time and by decrease of D, in a way that, it becomes the most important parameter in low-quality concretes after several years. Thus, the precise amount of C_s is of great importance in exact estimation of corrosion and durability design.
- Almost, the corrosion threshold (C_{th}) is the least important factor, but effect of it slightly increases overtime and with increase of w/c ratio (decrease of D parameter)

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