Probabilistic Assessment of the Durability of Reinforced Concrete Piles under Chloride Aggression

I I Ovchinnikov¹, O V Snezhkina², I G Ovchinnikov¹³
¹Tyumen Industrial University, Tyumen, Volodarsky Street, 38, 625000, Russia
²Department of descriptive geometry and graphics, Penza State University of Architecture and Construction, Penza, Herman Titov Street, 28, 440028, Russia
³Perm National Research Polytechnic University, Perm, Komsomolsky prospect, 29, 614990, Russia

E-mail: o.v.snejkina@yandex.ru

Abstract. The article presents a model of the deformation of a reinforced concrete pile, which is subjected to the joint action of the load and chloride corrosion. The model takes into account the probabilistic nature of corrosion processes, the variation of the geometric and strength characteristics of the pile, the probabilistic nature of the load. A method for calculating the strength and durability of the pile, which takes into account the stages of the process of interaction of the pile with chlorides, is given, a calculation analysis is performed. The influence of various parameters on the durability of reinforced concrete piles is analyzed. A correlation dependence of pile durability on compressive load and a durability histogram are constructed. It has been established that the lifetime of a pile with a 95% security is 16 years, with a security of 70% - 52 years, with a security of 50% - 80 years.

1. Introduction
The process of deformation of bridge reinforced concrete structures in time can be considered random: reinforced concrete structures initially have a spread of geometric dimensions, strength and deformative properties; in the process of their installation, instability of technological methods takes place: during operation they are exposed to loads and external influences (temperature, humidity, aggressive media), which are of a random nature. The most common corrosive environment for bridge structures is chloride-containing medium. The problem of deterministic prediction of the behavior of reinforced concrete structures under the joint action of loads and chloride-containing media was considered in [1-9]. The probabilistic approach to predicting the behavior of reinforced concrete bridge structures was actively developed in the works of Frangopol D.M. with staff and students [10-12]. However, in these papers, the random nature of only some of the destruction processes was considered. In this paper (using the example of a reinforced concrete pile), consideration is given to the probabilistic nature of a larger number of factors affecting the processes of destruction of reinforced concrete structures: the variability of the mechanical characteristics of materials and the dimensions of structures; probabilistic nature of power and non-force effects; the influence of the time factor on the random properties of materials and the random nature of the effects of the external environment.
2. Materials and methods of research

The generalized model of deformation of a reinforced concrete structure is considered as a set of models: models of a structural element (rod, beam, plate); material models (including a model of concrete deformation and a model of reinforcement deformation); models of exposure to aggressive environment; loading models; models of the onset of the limiting state of the structure. The following are considered random, taking into account known experimental data: dimensions and cross-sectional area of the structural element, area of reinforcement, thickness of the protective layer. As a model of concrete deformation, the following ratios are taken.

\[
\bar{\sigma} = \begin{cases} 
\bar{A}_p (\bar{C}) \cdot \varepsilon - B_p (\bar{C}) \cdot \varepsilon^3 \\ 
\bar{A}_c (\bar{C}) \cdot \varepsilon - \bar{B}_c (\bar{C}) \cdot \varepsilon^3 
\end{cases}
\]

(1)

where \( \bar{A}_r, \bar{B}_r, \bar{A}_p, \bar{B}_p \) – coefficients of the concrete deformation diagram in the initial state:

\[
\bar{A}_p (\bar{C}) = \bar{A}_p - \bar{k}_pa (\bar{C}), \quad B_p (\bar{C}) = \bar{B}_p - \bar{k}_pb (\bar{C}), \quad \bar{A}_c (\bar{C}) = \bar{A}_c - \bar{k}_ca (\bar{C}), \quad B_c (\bar{C}) = \bar{B}_c - \bar{k}_cb (\bar{C}).
\]

Thus, the coefficients \( A_c, B_c, A_p, B_p \) and the concentration of chloride-containing medium \( C \) is assumed to be random variables. Dependence (1) also takes into account the nonlinearity of deformation and the unequal resistance of concrete to tension and compression.

The diagram of the deformation of the reinforcement, taking into account its random properties, is taken in the form:

\[
\bar{\sigma}_s = \begin{cases} 
\bar{E}_s \cdot \varepsilon, & \sigma < \sigma_T \\
\sigma_T, & \sigma \geq \sigma_T 
\end{cases}
\]

(2)

Here \( E_s \) – the modulus of elasticity of steel, \( \sigma_T \) – yield strength, \( \sigma \) – stress, \( \varepsilon \) – deformation.

The model of exposure to a chloride-containing medium includes: a model of the penetration of a medium into a structural element, the dependence of the mechanical characteristics of concrete on the parameters of the medium in the bulk of the structure, and a model of corrosion of reinforcement. It is assumed that the chloride-containing medium penetrates the structural element with a diffuse front (Fig. 1) and at the instant \( t \) the profile of chloride penetration into the concrete is described by a random function \( C(X_1, ..., X_n, t) \). Corrosion of reinforcement begins when a critical concentration of \( C_{cr} \) is reached on its surface.

The model of corrosive wear of reinforcement is taken in the form (Fig. 2):

\[
\delta = \begin{cases} 
0, & t < t_{inc} \\
k \cdot (t - t_{inc})^n, & t \geq t_{inc}
\end{cases}
\]

(3)

Where \( \delta \) – the depth of corrosion damage,

\( k, n \) – coefficients, which are random variables.

The reinforcement cross-sectional area is a function dependent on random parameters:

\[
\bar{F}_s (t) = \varphi (\bar{d}_0; \bar{k}; \bar{t}_{inc}; t)
\]

(4)

where \( \bar{d}_0 \) – the initial diameter of the valve,

\( \bar{k} \) – parameter of the rate of corrosive wear of steel,

\( \bar{t}_{inc} \) – incubation period determined by the model of chloride-containing medium penetration into concrete.
As a model of the onset of the limiting state, the condition is assumed for the deformations in concrete or reinforcement to reach their limiting values. That is, in this model, the processes of cracking in concrete are not considered yet.

![Figure 1. Profile of chloride penetration into concrete](image1.png)

![Figure 2. Corrosion wear kinetics by model (3).](image2.png)

3. Research results

Using the experimental data, the coefficients of the described models were determined (Table 1), and due to the lack of reliable information, it was assumed that all of them have a normal distribution.

| Parameter  | Unit rev. | Average value | The coefficient of variation | Coefficients correlations |
|------------|-----------|---------------|------------------------------|--------------------------|
| $A_{p0}$   | [Pa]      | $0.810 \cdot 10^{10}$ | 0.13 | $\rho(A_{p0}, B_{p0}) = 1$ |
| $B_{p0}$   | [Pa]      | $10.800 \cdot 10^{15}$ | 0.13 | $\rho(A_{p1}, B_{p1}) = 1$ |
| $A_{p1}$   | [Pa]      | $0.561 \cdot 10^{10}$ | 0.13 | $\rho(A_{p0}, A_{p1}) = 1$ |
| $B_{p1}$   | [Pa]      | $7.480 \cdot 10^{15}$ | 0.13 | $\rho(A_{x0}, B_{x0}) = 1$ |
| $A_{x0}$   | [Pa]      | $4.181 \cdot 10^{10}$ | 0.11 | $\rho(A_{x1}, B_{x1}) = 1$ |
| $B_{x0}$   | [Pa]      | $3.484 \cdot 10^{15}$ | 0.11 | $\rho(A_{x0}, A_{x1}) = 1$ |
| $A_{x1}$   | [Pa]      | $2.855 \cdot 10^{10}$ | 0.11 | $\rho(A_{x0}, B_{x0}) = 1$ |
| $B_{x1}$   | [Pa]      | $2.379 \cdot 10^{15}$ | 0.11 | $\rho(A_{x1}, B_{x1}) = 1$ |
| $D$        | [m$^2$/year] | $3.679 \cdot 10^{4}$ | 0.07 | $r(\sigma_T, E) = 1$ |
| $C_s$      | [kg/m$^3$] | 10.09        | 0.07 | -- |
| $C_{krit}$ | [kg/m$^3$] | 0.83         | 0.125 | -- |
| $E$        | [Pa]      | $214000 \cdot 10^6$ | 0.07 | -- |
| $\sigma_T$ | [Pa]      | $450.0 \cdot 10^6$ | 0.07 | -- |
| $a_3$      | [m]       | 0.03         | 0.10 | -- |
| $k_s$      | [m/year]  | 0.0003       | 0.15 | -- |
| $h$        | [m]       | 0.35         | 0.015 | -- |
| $b$        | [m]       | 0.35         | 0.015 | -- |
| $d_0$      | [mm]      | 16           | 0.03 | -- |
The ultimate deformations of tension and compression $\varepsilon_{b,ult,s}$, $\varepsilon_{b,ult,c}$, have values of $0.5 \cdot 10^{-3}$ and $2 \cdot 10^{-3}$, respectively. Using the above ratios, the calculation of reinforced concrete piles (Fig. 3) was carried out under the joint action of the load and the chloride-containing medium.

The equilibrium equation of the pile has the form

$$N = \int A(C) \cdot \varepsilon - B(C) \cdot \varepsilon^3 dF_b + \int E \cdot \varepsilon dF_s$$

(5)

where $N$ – is the load on the pile, the other parameters are defined earlier.

The pile calculation algorithm is constructed using the method of statistical modeling and allows to take into account the influence of the input random parameters spread and to obtain the statistical characteristics of the output calculated parameters. The algorithm is based on the scheme of deterministic calculation of a reinforced concrete pile. As a result of the calculation, data were obtained on the concentration field of the chlorides at various points in time, the stress field, and the kinetics of the change in strain over time.

The durability of the pile was determined taking into account the random properties of the load, the parameters of concrete and reinforcement, the geometrical dimensions and characteristics of the corrosive environment separately, as well as taking into account all the random parameters at the same time. For illustration in fig. 4 shows a histogram of pile durability.

In fig. 5 shows the dependence of the durability of the pile on the magnitude of the applied load. As you can see, the durability of the pile with a 95% security was 17 years, with a security of 70% - 50 years, from 50% - 78 years. By setting the load value, the service life of the pile can be determined by correlation.
4. Conclusions
A method for calculating the strength and durability of the pile, taking into account the stages of the process of interaction of the pile with chlorides, has been developed; a computational analysis has been performed. The influence of various parameters on the durability of reinforced concrete piles is analyzed. A correlation dependence of pile durability on compressive load and a durability histogram are constructed. It has been established that the lifetime of a pile with a 95% security is 16 years, with a security of 70% – 52 years, with a security of 50% – 80 years.

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