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Calculation of the Reliability of Pile Foundations

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Annotation: The article analyzes the existing probabilistic methods for assessing the bearing capacity of single piles and pile foundations (taking into account mutual influence). It is noted that in the beginning there were attempts to somehow assess reliability (safety) through the coefficient of uniformity, similar to for soil samples, which often led to erroneous decisions.

It is emphasized that most of the available proposals for the probabilistic calculation of piles and pile foundations are devoted to certain particular issues; for example, determining the required (minimum) amount of testing of piles with a trial static load, in other cases they have very conditional assumptions, and the mathematical apparatus is very complex, which makes it difficult to use it in practice.

The analysis of the above data indicates that they do not take into account such important issues as the reliability of input parameters, on which the reliability of pile foundations directly depends (for example, the mutual influence of piles in the foundation, the variability and nature of load transfer, etc.), and which are key to quantifying their reliability.

Keywords: Probability, reliability, piles, pile foundation, uniformity coefficient, reliability coefficient, reliability assessment. To date, due to the complexity of the problem, there are only a limited number of works devoted to the probabilistic calculation of pile foundations.

The available proposals for the probabilistic calculation of pile foundations are characterized by two approaches. In the first, individual parameters of the variability of the bearing capacity (ground conditions) are studied to determine the design load on piles at different confidence probabilities [1, 2, 3, 4]. The second, being more general, examines the reliability (operability) of pile foundations [5, 6, 7, 8, 9].

The following works can be attributed to the first direction.

In 1968, B.I.Dalmatov, L.S.Lapidus and F.K.Lapshin [2] established the uniformity coefficient for the Leningrad region by statistical processing of the results of static tests of 138 full-scale piles.

$$K = 1 - \frac{\sigma}{\overline{P}}, \qquad (1)$$

Where $\overline{P}$ - average (normative) pile resistance:

σ - the average square deviation of the normative resistance of piles.

Considering the bearing capacity of a bush as the sum of the bearing capacity of single piles, the mean square deviation independent of the number of piles, the authors presented an expression for the uniformity coefficient of a pile bush in the form

$$K_{\kappa} = 1 - \frac{1-K}{\sqrt{n}}, \quad (2)$$

Where n -number of piles in the bush According to equation (2), the greater the number of piles in the bush, the more the coefficient of uniformity K_{κ} approaches unity, which logically correctly describes the probabilistic meaning of this coefficient. However, the probabilistic nature of the uniformity coefficient is not disclosed by the authors. At the same time, it is concluded that the bearing capacity of a pile bush can be assumed to be greater than the sum of the bearing capacities of single piles.

In 1975, B.V.Bakholdin, I.Z.Goldfeld and B.A.Faience [1] proposed a method for probabilistic and statistical processing of static test results in determining the design load on piles. It discusses questions about the criteria for the bearing capacity of the pile, the required number of tests and the normalization of the confidence probability, taking into account the capital class of the object and the design stage. However, the values of the pile bearing capacity criterion and confidence probabilities recommended by the authors of the work cannot be considered sufficiently justified.

The authors' recommendations on excluding individual pile test results during processing as “misses” are also questionable. This also applies to the recommendations of the SNIP [10, 11] on accounting for the variability of the bearing capacity of piles by a statistical method developed for soil characteristics [12, 13]. In particular, for the test results of full-scale piles, which have immeasurably larger sizes compared to soil samples, there can be no “misses". Individual special cases, for example, destruction of pile material during testing, should not be considered as statistical information. It should also be noted that the variability of the bearing capacity of the pile cannot be neglected when the number of experiments is less than six, while taking, according to [10, 11], the reliability coefficient on the ground equal to I. There is no guarantee that single tests for a specific site can reveal the minimum value of the bearing capacity of piles.

In accordance with the rules of statistics, with an increase in the number of experiments, the error of the average, the confidence interval and the characteristics of soil variability decrease, which is accompanied by an increase in the calculated bearing capacity of piles, consequently, a decrease in the cost of foundations.

Based on this, it is possible to make a target cost function, finding the minimum of which gives the optimal number of tests. Based on this approach, Yu.S.Mirenburg and L.N.Khrustalev [4] proposed a method for determining the optimal number of static tests of piles in frozen soils, based on the assumption that the bearing capacity of piles obeys the normal law and meets the minimum expected costs for testing piles and erecting foundations, taking into account the volume of construction.

O.I.Ignatova [14] also developed a methodology for determining the optimal volume of soil testing by sounding on the example of the construction of residential buildings on stilts.

The work of V.B.Koval, A.K.Operstein, L.E.Khariton and V.B.Shvets is devoted to determining the rational volume of static tests in the design of pile foundations [3]. Based on statistical processing of the results of static tests of piles in sandy and pulverized clay soils, they obtained data that do not contradict the hypothesis of the normal distribution law of the bearing capacity of piles. Based on this, it is recommended to determine the required number of tests n, using the expression known from probability theory

$$n = \frac{V^2 * U_{\beta}^2}{a_a}, \quad (3)$$

Where V – expected value of the coefficient of variation;

U_β – quantile (0,1) of the normal distribution $(\beta = \frac{1+\alpha}{a})$;

a_α – the maximum allowable relative error, depending on the confidence probability a.

Based on the analysis of the results of 17 sites where static tests of full-scale piles were carried out in parallel with the sounding, the authors concluded that the coefficient of variation established by the results of the sounding characterizes the variability of soil conditions with a sufficient degree of accuracy. Based on this, it is recommended to set the coefficient of variation of the bearing capacity of piles based on the results of probing, and then use a specially compiled table to determine the minimum number of experimental piles for given confidence probabilities.

It should be noted the work of J. Key [15], in which, by setting the reliability index according to the table compiled on the basis of the Base distribution and using the results of successive tests, the required load-bearing capacity is determined each time. At the same time, the legality of applying the Base distribution to the bearing capacity of piles is not discussed.

The second direction includes the works of L.N.Khrustalev and G.P.Pustovoit [8]. Using the theory of random processes applied to the calculation of the bearing capacity of piles in permafrost soils, the authors established the values of the reliability coefficient that provide the specified levels of reliability, taking into account the operating time of buildings and structures.

The works of A.D. Slobodyan and Yu.I.Solovyov are devoted to the probabilistic calculation of pile foundations for an arbitrary combination of loads [7]. When assessing the stress –strain state of the base, the pile bush was considered as a flat frame with an absolutely rigid crossbar – grillage in an elastic-plastic medium. The statistical heterogeneity of the base was characterized by the bed coefficient, which was determined by the results of static sounding of soils and described using the theory of random functions.

The probability of the calculated parameter staying in the permissible range was taken as a measure of reliability, and its numerical value was determined by the Monte Carlo method under the conditions of limiting the horizontal and vertical displacements of the grillage. The proposed technique was implemented for a 4-pile bush in loess subsidence soils.

The conventionality of the authors' approach is that the pile bush is considered as a flat frame and the mutual influence of piles in the bush is not taken into account. In addition, this technique is difficult to implement for practical purposes, because in each specific case of changing any parameter, it is necessary to repeat the entire far from simple calculation procedure.

The works of G.B.Kulchitsky [5] are devoted to the reliability of pile foundations in the regional soil conditions of Western Siberia. In them, pile foundations are considered as a complex functional, non-repairable system, the reliability of which is assessed by the probability of failure, determined using structural analysis methods.

Failure of piles, as an element of the “pile foundation - foundation” system, can occur either as a result of a violation of the normal functioning of the pile connections with the grillage (sudden failure), or with the ground (gradual failure).

Denoting the failure of the connection of piles with the grillage through with the soil through , the probability of failure of piles S as a complex event, according to [16], is expressed as.

$$q(s) = q(R) + q(G) - q(R)q(G). \qquad (4)$$

The probability of a sudden failure of the connection of piles with the grillage is determined from the probability of joint and dependent events – failure of reinforcement A and (or) concrete B, i.e.

$$q(R) = q(A) + q(Б) - 2q(A)q(Б) \quad (5)$$

When calculating the probability of a gradual failure of the connection of piles with the ground, $q(G)$ the parametric theory of reliability is used [17], and G.B.Kulchitsky recommends determining the bearing capacity of the pile either by the results of static tests of piles (for buildings and structures of the I class of responsibility), or by the results of static sounding of soils (N and W class of responsibility).

In the absence of field test results, the bearing capacity of piles can be determined by regional tables of calculated soil resistances under the lower end of the pile and on the side surface, compiled according to the results of static sounding [5].

The reliability of pile foundations (the probability of trouble-free operation), taking the normal law of the distribution of external load and bearing capacity of piles, he determines using the structural scheme of the reliability of the system (SSN) known in the theory of reliability [18].

According to G.B.Kulchitsky, it turns out that the failure of one pile leads to the failure of a three–pile bush, two piles - to the failure of a four-pile bush and a ribbon foundation, if the two piles that failed are nearby. It is impossible to agree with this, because the achievement of a separate maximum load as part of the foundation cannot be interpreted as a failure in the literal sense of the word. The pile withstands this maximum load during subsequent loads, and does not redistribute it to neighboring ones. Only the excess load over the limit on this pile is redistributed to them. This will naturally lead to a decrease in the level of reliability of the pile foundation, but not to its failure. At the same time, the probability of failure should be the greater, the smaller the number of piles in the foundation. At the same time, according to the method of G.B.Kulchitsky, all other things being equal, the probability of failure with an increase in the number of piles in some cases increases, and in other cases decreases. This contradicts probabilistic logic and is a consequence of the fact that the structural scheme of the reliability of the system is used by them without due consideration of the specifics of the working conditions of pile foundations. A more general approach to predicting the reliability of pile foundations, taking into account all possible random variables, is proposed by B.M.Mazo and V.B.Shvets [6]. However, their proposals have not yet been brought to the possibilities of practical implementation. The issues of reliability of pile structures of offshore hydraulic structures, taking into account the time factor, were investigated by A.V.Shkola, Diaby Abubakar Sidiki [9]. The durability of pile foundations is predicted by them based on the wear of the pile material in an aggressive marine environment.

From the above review of the available proposals for the probabilistic calculation of piles and pile foundations, it follows that most of the works are devoted to certain particular issues, in some cases there are very conditional assumptions in them, and the mathematical apparatus is very complex, which makes it difficult to use it in practice. In some cases, there are results that contradict the logic and physical nature of the interaction of pile foundations with the foundation soils. In addition, such important issues as the reliability of input parameters, on which the reliability of pile foundations directly depends, fall out of consideration in the above works: the bearing capacity of single piles and the bearing capacity of a pile bush, taking into account the mutual influence of piles, especially with an inhomogeneous foundation, the variability and nature of the transfer of loads to the foundation. These issues are key from the perspective of the probabilistic approach and require special study to develop a method for quantifying the reliability of pile foundations.

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