

Reliability analysis of pile foundations: peculiarities of consideration of uncertainties and partial factors

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Abstract. Pile foundations are used to transmit construction loads deep into the ground, thus ensuring the stability of the structure. In this context, there is no question that the calculation of pile bearing capacity is important in the design of economical and safe geotechnical structures. Typically, the axial bearing capacity of piles can be determined using five approaches. At the same time, under real conditions, the effectiveness of these approaches is limited, firstly, by the restrictions inherent in their computational apparatus and, secondly, by the action of a variety of uncertain and random factors. Meanwhile, in geotechnics the uncertainties are largely unknown or very difficult to measure. In view of the above, the aim of the article is to develop a methodology for analyzing the reliability of a pile foundation taking into account uncertainties and partial factors. The methodological basis of the research is a comprehensive approach, which includes the analysis and synthesis of literary data on the topic of work, analytical and experimental research. In the process of research an algorithm based on the Monte-Carlo method and the evolutionary neural network, which allows in the process of calculating the reliability of piles to take into account such uncertainties as: physical, statistical and modeling uncertainties. The conducted tests showed that the model has a high prediction accuracy. The theoretical value of the obtained results consists in the development of the pile foundation reliability evaluation apparatus due to the use of neural network modeling. In practice, the recommendations formulated in the article can be used as a basis for conducting experiments with pile foundations in various soil sciences conditions. Key words: reliability, pile foundations, neural network, prediction, modeling.

1 Introduction

Progressive and continuous progress of positive socio-economic changes, which can be observed today, accelerating every day the pace of the industrial revolution, determine the sustainable development of many industrial sectors, including construction industry, in particular, the development of residential, industrial, energy and road infrastructure [14]. This leads to the fact that regions with unfavorable geological and engineering conditions, where the load-bearing soils are tens of meters below the surface, are gradually developing, which

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necessitates the use of deep indirect foundations, the most popular of which are pile foundations. They are often the only possible option of constructing a building foundation.

Thus, over the past decades, the pile foundations have become widespread in construction, and high-rise buildings, long-span bridge structures and industrial facilities in mountainous areas are built on their basis. The pile foundation has a number of advantages, such as high bearing capacity, low draft, ease of construction, etc. [3, 9].

Taking into account the fact that the foundation plays significant role in the relevant structures, the problems of its reliability and bearing capacity attract much attention in the engineering field, since the safety of the structure and its service life depend on it to a great extent.

When designing a pile foundation, engineers are constantly balancing between creating a foundation with a high level of reliability and using the maximum geotechnical potential of the soil mass. Settlements of buildings based on pile foundations are much lower than the permissible values, which indicates significant overconsumption of resources for the construction of foundations and the formation of unused reserves of bearing capacity in the soil base of such foundations [24].

In this context, it can be noted that the main problems with the reliability of pile foundations and their bearing capacity are caused by the uncertainties existing in the geotechnical environment (namely, randomness, vagueness, and incomplete knowledge). Uncertainties can be classified as inherent variability (uncertainty of material parameters), measurement variability (uncertainty of loads or equipment errors), and transformation uncertainty (uncertainty of hypotheses or mathematical modeling) [20].

Traditionally, geotechnical engineers account for uncertainties in design by using global safety factors (FS) that are based on past experience [19]. However, this approach does not provide a rational basis for understanding the effect of uncertainties on the reliability and bearing capacity of pile foundations. The First Order Second Moment Method (FOSM) is quite effectively used in problems of pile bearing capacity reliability analysis [7, 9]. However, this method is very time-consuming and requires additional effort, especially in the case of multivariable dependences due to the large number of calculations of the performance functions and/or their partial derivatives with respect to the random basis variables. In addition, for performance functions other than the normal distribution, the results tend to be inaccurate. The tangent plane method, the multiplanar surface method, and the response surface method (RSM) [28, 29] improve accuracy, but their applicability is limited to nonlinear convex or concave limit state surfaces.

Thus, the essence of the problem is that standard algorithms of geotechnical programs are not adapted to solve the problem with sequential loading of pile foundation elements, and also do not allow to reliably determine its reliability and safety margin.

Therefore, to date, an important scientific and practical task is to improve the modeling apparatus of the pile foundation, as well as to refine the methods of analysis of its interaction with the soil base in conditions of existing uncertainties and inaccuracies. The relevance and practical importance of solving the task predetermines the choice of the topic of the ongoing research, as well as determines its conceptual basis and scientific tools of knowledge.

2 Literary Review

Polischuk A.I., Chernyavskii D.A. [27], Zhang Jie [17], Basu Prasenjit [2], Zhang Yongli [18], Chen Fengchen [4], Ai Zhi Yong [1] devoted their works to improvement of the method of numerical modeling of interaction of a pile foundation with the base considering sequential static loading of its components.

Nanazawa Toshiaki [12], Oudah Fadi [13], K. Ilamparuthi, R. G. Robinson [5], and Wu Xing Zheng [15] analyzed the reliability of a single pile subjected to horizontal loads. In these

authors' studies, the failure probability of pile bearing capacity under certain functions and the effect of failure probability on the corresponding parameters were determined using the response surface method [RSM].

Study of specifics of influence of geotechnical uncertainties on reliability of vertically loaded pile foundations by means of MCS and FORM, and analysis of sensitivity of reliability to the source of these uncertainties have been done by Kumar Manish [8], Kapustin V.V., Churkin A.A. [23], Plotnikov A.A., Merzlyakov V.P. [26], Li G., Zhang D., Liu C., Liu X. [25].

From the above-mentioned studies, it can be concluded that researchers relatively often use four methods, namely MCS, FORM, RSM and HOMM, to analyze the reliability of pile foundations.

However, in spite of the available developments, it should be emphasized that not all misunderstandings and difficulties with the calculation and prediction of the reliability of pile foundations that geotechnical designers face in practice have been eliminated yet. It is necessary to study separately and conduct a series of calculations that allow us to establish the impact of each source of uncertainty on the probability of failure and failure of piles.

Thus, in view of the above, the purpose of this article is to develop a methodology for analyzing the reliability of a pile foundation, taking into account uncertainties and partial factors.

The objectives of the study include: 1) consideration of the peculiarities of using neural modeling to analyze the reliability of piles, 2) development of an algorithm for conducting calculations of the stress-strain state of a pile foundation under conditions of uncertainty factors.

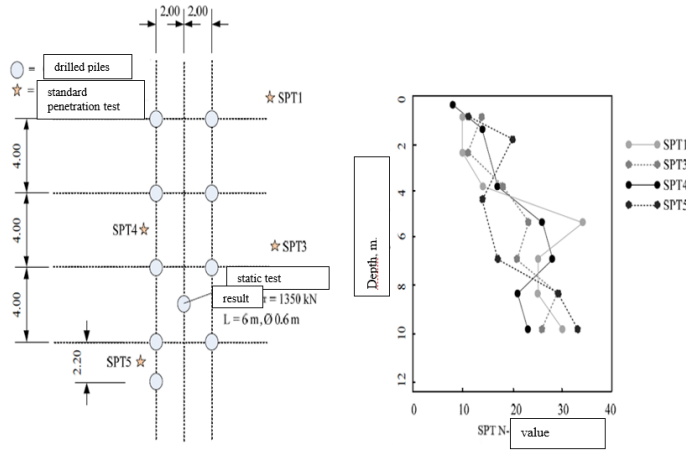
The hypothesis of the study: the use of alternative methods of analysis to traditional approaches, such as fuzzy modeling and neural network, will increase the reliability of the analysis and prediction of the reliability of the pile foundation.

3 Materials and methods

The methodological basis of research is a comprehensive approach, which includes the analysis and synthesis of literary data on the topic of work, analytical and experimental research. As well as methods of neural network modeling, machine learning, the Monte-Carlo method.

4 Results

As an example, presented in this paper, we considered the foundation, consisting of vertically loaded piles from the experimental site in Togliatti (Fig. 1.a). The pile was drilled into the residual soil and has a diameter of 0.6 m and a depth of 6 m. At this experimental site various laboratory and in-situ tests were carried out, but in this paper only standard penetration tests (Fig. 1.b) are considered to assess the bearing capacity of the piles.



a) foundation plan

b) SPT-results

Fig. 1. Experimental site of the pile foundation in Togliatti.

The evolutionary neural network (ENN) and Monte-Carlo method is the basis of the considered analysis methodology.

ENN consists of three layers through which information and data flows, they are the input layer, the hidden layer and the output layer (Fig. 2).

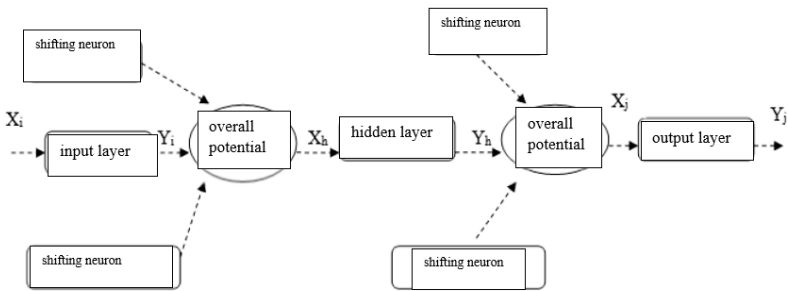


Fig. 2. Typical ENN block diagram during computation with direct data transfer.

The input layer, the hidden layer and the output layer contain i , h and j neurons, respectively. Here X_i and Y_i denote the input and output values of neurons i respectively, so that $X_i = Y_i$. The input and output values of hidden neurons for the hidden layer are denoted by X_h and Y_h respectively, and are related by formula (30):

$$Y_h = \left(\frac{1}{1 - \exp(-X_h)} \right)$$

In addition, the input and output values of hidden neurons for the output layer are denoted by X_j and Y_j respectively, and are related by formula (22):

$$Y_j = \left(\frac{1}{1 - \exp(-X_j)} \right)$$

To investigate the pile foundation and soil under uncertainty and random factors, we propose a methodology that includes 4 steps. Within the framework of this methodology, uncertainties will be introduced at various stages of modeling and design (see Fig. 3).

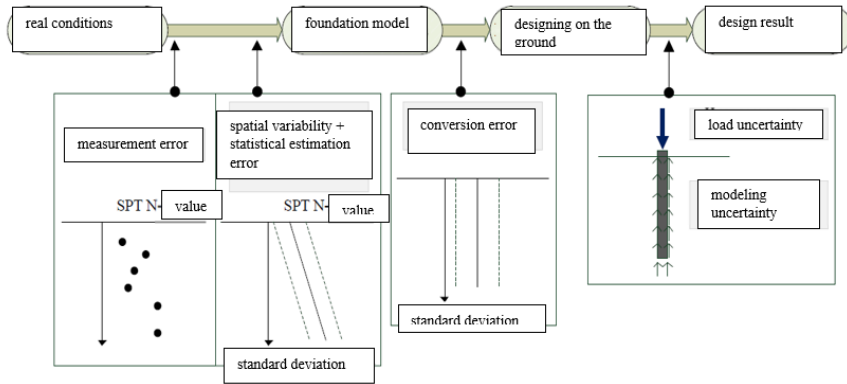


Fig. 3. Algorithm of the reliability assessment of the pile foundation taking into account uncertain and random factors.

Let us consider the proposed algorithm in more detail.

1. Spatial variability and statistical estimation error are studied simultaneously. In many cases, it is very difficult or impossible to separate them. This step includes:

- trend calculation of in-situ or laboratory tests (e.g., SPT - standard penetration test),
- analysis of residual errors, including estimation of autocorrelation distance.

2. The conversion error and modeling uncertainty are estimated - these quantities are calculated from the documentation data.

3. Calculation of resistance (R) and the action of external forces (E), as well as the performance function:

$$M = g(R, E) = R - E$$

Where M is the safety factor,

g - performance function,

R - resistance,

E - action.

It should be noted that the uncertainties of the actions can be derived from studies already conducted.

4. Construction of the neural network model, its training and tuning, and the use of Monte-Carlo method to estimate the probability of failure and calculate the reliability index of problem tasks using the following equation:

$$pf = \sum_1^m I, \quad I = \begin{cases} 0, & \text{if } M \geq 0 \\ 1, & \text{if } M < 0 \end{cases}, \quad \beta = -\Phi^{-1}(pf)$$

Where pf is the probability of failure,

m - number of observed elements,

I - failure indicator,

M - safety margin,

β - reliability index,

Φ - normal cumulative density function with mean 0 and variance 1.

As part of the ongoing study, we will use the following performance function to predict the bearing capacity of the pile:

$$M = (R_{\text{tip}} + R_{\text{side}}) - (G + Q) = (\delta_t \times Q_{\text{tip}} + \delta_f \times F_{\text{side}}) - (\delta_G \times G_k + \delta_Q \times Q_k)$$

Where M is safety margin,

R_{tip} - resistance of the pile tip,

R_{side} - lateral resistance of the pile,

G - constant load,

Q - variable load,

δ_t - model error factor (tip resistance),

Q_{tip} - predicted tip resistance,

δ_f - model error factor (lateral resistance),

F_{side} - predicted lateral resistance,

G_k - constant characteristic load,

Q_k - variable characteristic.

5 Discussion

Uncertainties in the process of evaluating the reliability of a pile foundation can be of different nature and nature of origin, among them we can distinguish: physical uncertainties (uncertainty inherent in parameters), modeling uncertainties (theoretical approaches and predictions), statistical uncertainties (finite size and fluctuations in samples) and human errors (when performing multiple tasks) [11, 6]. Human error is a type of uncertainty that is not generally included in pile reliability analysis [16].

The current study considers the physical uncertainty of actions (constant and variable loads) and the inherent variability in soil, as well as modeling uncertainty (or model error) in empirical SPT-based resistance estimation.

Fig. 4 shows the simulation results of maximum compressive stresses (MCS), maximum tensile stresses (MTS) of the pile foundation using the proposed algorithm.

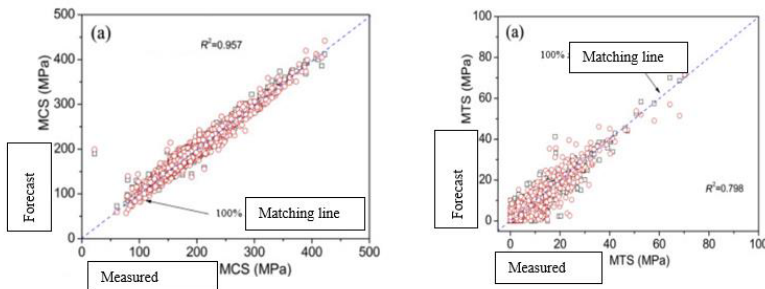


Fig. 4. MCS and MTS prediction for a pile foundation, taking into account random and uncertain factors.

MATLAB software environment was used for modeling. The R-value for all models in the training and testing phases is very close to one, so the models are reliable for predicting the reliability of the pile foundation.

6 Conclusion

This article presents a methodology that allows evaluating and predicting the reliability of a pile foundation, taking into account uncertainties. The Monte- Carlo method and the evolutionary neural network were used for modeling. The uncertainties (actions, ground variability, and model error) were estimated and implemented into the model using a case study. In addition, the models developed are quite easy to interpret. Moreover, because the neural network assumes a clear definition of the input and output data, it allows engineers to have insight and understanding of where significant changes in the data may occur.

The algorithm presented in this article can be considered as a basic one and can be further improved depending on soil and pile types for further foundation reliability analysis.

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