The Uncertainty of Geological Systems in Geotechnical Calculations

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The uncertainty of geological systems in geotechnical calculations

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Abstract. Modeling processes of a very different nature as a rule is concerned with the problem of approximation, inaccuracy and incompleteness of data on the simulated system, with its uncertainty. The concept of uncertainty is closely related to the concepts of heterogeneity and variability. In this study the measure of uncertainty is the correlation distance, which is defined as the length, within which the soil mass is assumed to be homogeneous. The study and analysis of uncertainty is reduced to two tasks: the construction of the uncertainty design model with a quantitative description of various aspects and the subsequent consideration of this model in stochastic calculations. To solve these problems a random limiting equilibrium method (RLEM) was used on the example of the dam stability assessment. An analysis of the results showed that under conditions of uncertainty of geotechnical system safety factor (Fs) is not a reliable parameter characterizing the dam slopes stability. With an increase in the heterogeneity of the soils composing the dam body Fs does not change, however, the probability of destruction increases. Also, the effect of heterogeneity on the slope stability is established in this work. With an increase in heterogeneity the Fs doesn't change, but the reliability of the dam decreases.

Keywords: uncertainty, heterogeneity, stability of the slopes of the dam, the random method of limiting equilibrium, reliability.

Introduction

The lack of completeness of information about composition, structure and properties of soils, about the laws of the ongoing processes, often makes questions in the design and construction of facilities. The collection, accumulation and analysis of data as a rule is accompanied by measurement errors that distort the limited information about the engineering-geological conditions. This problem is aggravated by the spatial-temporal random nature of geological processes affecting geotechnical systems. These and many other factors are the result of uncertainty in the study of the condition and prognosis of the lithotechnical systems behaviour (Kurguzov at al 2020). Working with uncertainty is therefore an essential apect of geoteclmical engi-neering - the larger the uncertainty and the closer to critical, the greater the need for evaluating its effect(s) on the results. The geoteclmical engineer tries to deal with the uncertainties by choosing reasonably conservative parameters for the deterministic stability evaluation. This approach, however, fails to address the problem of properly and consistently dealing with uncertainties [1].

There are many factors that contribute to the uncertainty of geotechnical systems. It is not possible to cover even a small part of these factors in one article.

In this study, the probabilistic nature of soil properties and the correlation distance are the measure of uncertainty. The study and analysis of uncertainty comes to two tasks: the construction of the uncertainty computational model with a quantitative description of various aspects and the subsequent consideration of this model in stochastic calculations.

Currently there are four main models that describe the distribution of soil properties in mathematical modeling in engineering geology and geotechnics.

1. Deterministic model

Density, specific cohesion, angle of internal friction are the initial parameters with scalar values of soil properties defined for each lithological layer:

The result of the solution is to determine the safety factor minimum value (also a scalar value) and to find the position of the corresponding sliding surface.

2. Interpolation model

In this case the initial parameters are the numerical arrays defined for each lithological layer, including soil properties (density, specific cohesion, angle of internal friction) and coordinates of the sampling point. Based on this information, using interpolation methods for each layer, a property distribution field is constructed.

The result of the solution, as in the case of the deterministic model, is to determine the safety factor minimum value and to find the position of the corresponding sliding surface. However, it should be noted that the result depends both on the choice of the interpolation method and on the soil properties distribution nature within the lithological layer.

3. Probabilistic model

Comparing with the models described above, the initial parameters in this case are not scalar values, but functions of the soil properties probability distribution.

The main problem in constructing a probabilistic model is to determine the law of distribution of random variables. In the case of a normal distribution, two parameters are required to construct a probability function - the mathematical expectation, the variance.

The result of the solution in this case is the probability distribution function of Fs, based on which the probability of a landslide process can be determined.

4. Variational model

Spatial variability of soil properties can be modeled using random field theory. The spatial correlation of soil properties is determined based on the autocorrelation function, which can be estimated from the results of measurements of the parameter at various points from the results of field or laboratory tests.

Thus, the necessary initial parameters for the variability model in addition to the soil properties probability distribution function are the values of the correlation distance.

The result of the solution in this case is the probable model of the distribution of soil properties for a given correlation distance and the distribution function of Fs.

This study is devoted to the approbation of the properties distribution variational model when modeling dam stability using the random limit equilibrium method (RLEM).

1 Materials and Methods

A dam in the flooding protection system of the city of Hanoi along the Hanga (Red) River was chosen as the object of study. A typical engineering-geological structure of the riverine territory of the Hanoi city in the vicinity of the dam (Fig. 1) is represented by the interbedding of sandy loams, sands, loams, clays and gravel [Ding T.H., at al 2018].

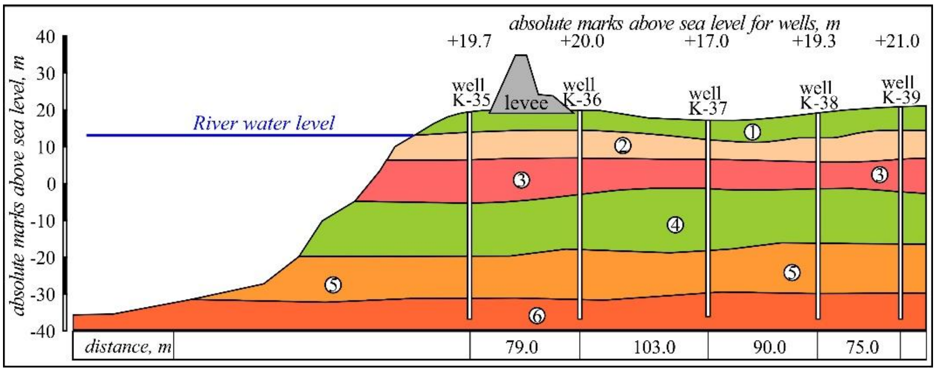

Fig. 1. Schematic engineering-geological section of the riverine territory of Hanoi in the vicinity of the dam. Engineering-geological elements (numbers in white circles): 1-loam, 2-sandy loam, 3-sand, 4-clay, 5-sand, 6-gravel.

The Red River Dam has a complex and long history growing and expanding over hundreds of years. At present it is in an unstable state in many sites due to the absence of justification for decisions during its reconstruction. Thus, the body and base of the dam are subject to the risks of destruction during extreme floods, the main purpose of its construction [24].

Filtration deformations in the soils of the dam foundation are one of the main reasons leading to its destruction. Possible mechanisms of the dam stability loss as a result of changes in the hydrogeological situation due to the hydraulic gradient increasing in time during the flood were considered earlier [17, 24].

One of the approaches to reduce the risks is to consider the uncertainty of the soil properties that make up the dam body when assessing its stability during a flood.

The problem was solved in a flat formulation, the stability assessment was carried out on the basis of the Morgenstern-Price method [25], which belongs to the class of methods of limiting equilibrium, where the general equilibrium of moments and forces is satisfied [23]. In the calculations, the Coulomb-Mohr soil behavior model

was used, which combines elastic-ideal plastic deformation and a linear material strength criterion.
The final geomechanical scheme used to assess the stability of the dam considering the filtration process is shown in Fig. 2.

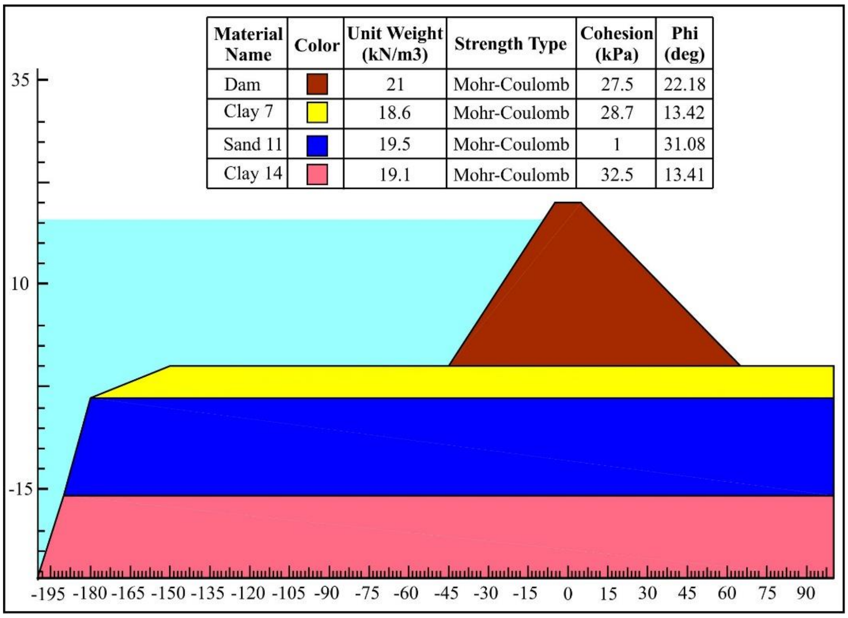

Fig. 2. The geomechanical scheme for assessing dam stability.

The water discharge in the Krasnaya River during the flood peak is quite large, on average about 30 000 - 35,000 cubic meters per second, with a maximum - 48,000 m3/s. The duration of extreme floods is usually 15-20 days. At the peak of the flood the river level rises to 15 - 20 meters [Dinh T.H., at al 2018].
In 2005 as part of the VNK05 program a serious reassessment of the flood protection equipment safety of in the face of a changing climate was made. Several in-vestment projects were aimed at the study of existing dam systems in accordance with the principle of risk reduction. One approach to mitigate risks is to consider the uncertainty of the dam geotechnical system when assessing its sustainability during the flood period.
To study the effect of spatial variability of the soil strength parameters on the probability of the dam slopes destruction a random method of limit equilibrium (RLEM) was used.
Here are some works devoted to the use of RLEM in assessing the stability of slopes: Fenton, G.A., and Griffiths, D.V. (2008), Li and Lumb (1987), Li et al. (2014), El-Ramly et al. (2001), Low (2003), Babu and Mukesh (2004), Cho (2007 and 2010), Hong and Roh (2008), Wang et al. (2011), Ji et al. (2012), Tabbaroki et al. (2013), Javankhoshdel and Bathurst (2014) and Javankhoshdel et al. (2017).

In the RLEM, a random field is first generated using the local average subdivision (LAS) method developed by Fenton and Vanmarcke (1990) and then mapped onto a grid of elements (mesh). Each mesh element in the random field has different values of soil properties, and cells close to one another have values that are closer in magnitude, based on the value of the spatial correlation length. In each realization, a search is carried out to find the mesh elements intersected by the slip surface. The random soil property values are assigned to the slices whose base mid-point falls within that element. A limit equilibrium approach (Morgen-stern-Price Method) is then used to calculate factor of safety (FS) for each realization. The probability of failure is calculated as the ratio of the number of simulations resulting in FS < 1 to the total number of simulations.

The non-circular RLEM used in this study is a combination of Cuckoo search and the LEM (Morgenstern-Price method). When calculating the dam slopes stability, the strength properties spatial variability of the soils composing the dam body was considered.

When calculating the dam slopes stability, the spatial variability of the strength properties of the soils composing the dam body was considered.

Spatial variability of soil properties can be modeled using theory of random fields [20]. In the theory of random fields at any location within a soil layer the soil parameter is an uncertain quantity or a random variable which is characterized by a probability distribution and is correlated with the random variables at adjacent locations [21]. The values of a soil parameter are correlated at different points of a field. The spatial correlation of soil parameter is considered by auto-correlation function. The autocorrelation function of a given soil parameter can be estimated from the measured data of the parameter at different locations [22].

As the Mohr-Coulomb strength criterion [19] was used in the calculations, the spatial variability of adhesion and the angle of internal friction were considered.

Theoretically the correlation structures of the underlying Gaussian random field can be determined using the Markov correlation coefficient function Eq.1.

$$R(\tau_x,\tau_y) = exp\left\{-\sqrt{\left(\frac{2\tau_x}{\theta x}\right)^2 + \left(\frac{2\tau_y}{\theta y}\right)^2}\right\} \quad (1)$$

where, R (τ_x, τ_y) is the autocorrelation coefficient, τ_x and τ_y are the absolute distances between two points in horizontal and vertical directions, respectively. θx and θy are the spatial correlation lengths in horizontal and vertical directions, respectively [13].

To assess the influence of heterogeneity on the probability of the dam slope damaging, five cases were considered during the calculations with different values of the correlation distance in the horizontal direction of 1.0, 3.25, 5.5, 7.75 and 10 m. In the vertical direction, the correlation distance for all cases was 1 m.

The probabilistic properties of soils used in the simulation are given in table 1.

Table 1. The probabilistic properties of the soils of the dam body.

Material Name	Color	Property	Distribution	Mean	Std. Dev.
Dam		Cohesion (kPa)	Normal	27.5	2

		Phi (deg)	Normal	22.18	2

2. Results and discussion.

Fig. 3 a and b and 4 give an example of constructing design models of uncertainty results (for the correlation distance in the horizontal direction equal to 1 m with a minimum Fs).

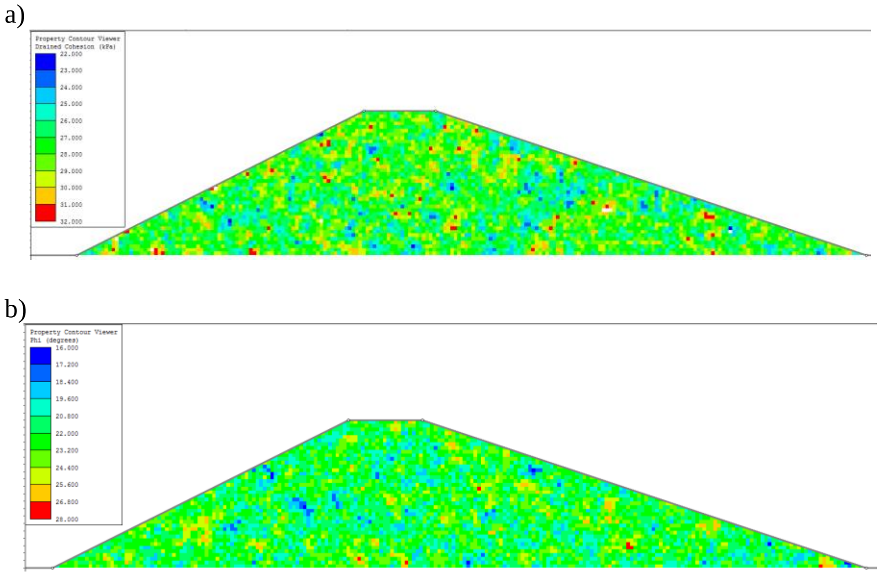

Fig. 3. The distribution of cohesion (a) and the angle of internal friction (b) in the soils of the dam body with a horizontal correlation distance of 1 m, Fs-0.88.

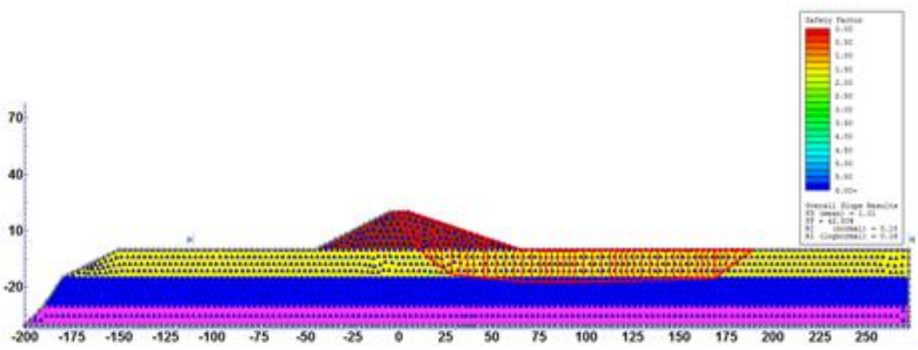

Fig. 4. Result of calculating the slope stability at a correlation distance of 1 m (in the horizontal direction).

Analysis of the calculation results for the various cases described above has shown that the value of the correlation distance does not affect the Fs (for all cases, the Fs value is 1.01). However, the standard deviation (σ) Fs changes with a change in the value of the correlation distance, while, with an increase in the correlation distance, σ decreases. The same trends are described in the work of Cami B. at al [26] and Cho, S.E. [8].

The above mentioned allows us to conclude that Fs is not a reliable parameter characterizing the stability of the dam slopes. Considering the uncertainty and variability of soil properties, it is preferable to use the reliability index (β) [23], defined as following:

$$\beta = \frac{Fs - 1{,}0}{\sigma_{Fs}} \quad (2),$$

where the σ_{Fs} is the safety factor standard deviation.

The fig. 4 shows the relation between the safety factor and the correlation distance.

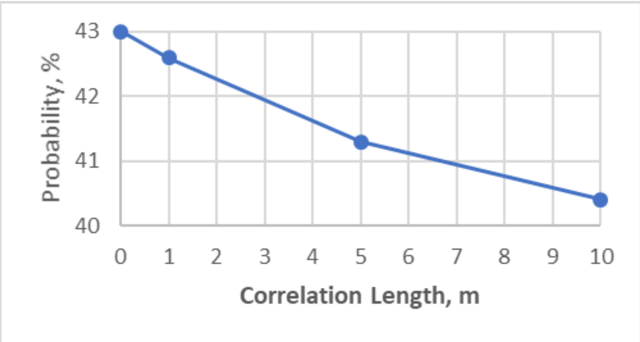

Fig. 5. The graph of the collapse probability dependence on the correlation distance.

The analysis of this relation shows that with an increase in the correlation distance and therefore with a decrease in heterogeneity in the soils of the dam body, the reliability of the dam also increases.

Conclusion

Stochastic modeling of geotechnical systems is gaining increasing relevance in world practice, with the growing understanding of the discreteness (essentially randomness) of the soil properties values series. Conservative deterministic methods for calculating the stability of slopes consider the soil properties variability only indirectly, using their designed (in statistical terms) values in mathematical models. The safety factor values obtained on the basis of such calculations do not determine the actual hazard level, since it is impossible to establish the relationship between them, their probability and accordingly the probability of the landslide process development. The stochastic approach allows performing a complete landslide hazard analysis and use its results to solve a variety of practical problems. The essence of such analysis is to determine the probabilistic distribution function of the safety factor depending on the probabilistic distribution fields of the physical and mechanical characteristics of the soils composing the dam body.

The performed research allows us to draw the following conclusions:

• in conditions of the geotechnical system uncertainty the safety factor (Fs) cannot be considered a reliable parameter characterizing the dam slopes stability. With an increase in the heterogeneity of the soils composing the dam body, Fs does not change, however, the reliability of the geotechnical system decreases.

• when assessing the dam slopes stability considering the uncertainty factor, it is recommended to use the reliability index (β).

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