https://doi.org/10.32762/eygec.2025.18

USE OF THE DETERMINISTIC AND PROBABILISTIC METHODS IN SLOPE STABILITY CALCULATIONS

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ABSTRACT

The article presents the results of slope stability calculation using deterministic and probabilistic approaches in a 2D setting. The deterministic method is based on the average value of the Coulomb strength parameters and soil specific gravity, and the slope stability analysis is performed using the limit-equilibrium methods: Bishop, Fellenius, Morgenstern-Price, Spencer, Janbu, Shahunyants. The probabilistic approach takes into account spatial variability, which is determined using the Inverse Distance Weighted. The analysis results show the influence of deterministic and probabilistic approach on the safety factor, the probability of failure, and the reliability index of slopes.

Keywords: slope stability, deterministic and probabilistic methods, probability of failure, reliability index.

INTRODUCTION

Slope stability assessment has been actively carried out since the beginning of the 20th century. In Sweden, a method of circular cylindrical sliding surfaces with a slope split into separate slices was proposed, which is still used with various modifications. During the following decades, F. Fellenius (1936) modernized the Swedish calculation method. In the mid-1950s, N. Yanbu (1954) and A. Bishop (1955) continued this work. Later, other calculation methods were proposed: by N. Morgenstern and V. Price (1965), Spencer (1967), and others.

The problem of slope stability is related to risk and reliability. Therefore, one cannot rely on any one stability coefficient when taking measures to prevent the slope from collapsing. Slope reliability analysis includes the calculation of the reliability index or, alternatively, the probability of failure (Huvaj & Oguz, 2018; Lemos et al., 2020; Pereira & Scalioni, 2020). It is also important to take into account the spatial variability of soil properties (Ding et al., 2022), which in most cases are assumed to be constant in slope stability calculations.

From a practical point of view, various methods should be used to get a more reliable result. Therefore, various analysis methods and two approaches were used in this study: deterministic and probabilistic. In both cases, a digital slope model is used, developed on the basis of soil testing data by cone penetration (Robertson & Cabal, 2015).

DIGITAL SLOPE MODEL

The digital slope model was developed using cone penetration test (CPT) data at 9 sites (Fig. 1) in the Geotek Field program (www.geotek-bim.ru).

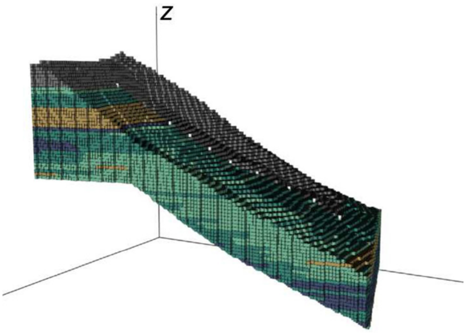

Figure 1 *Three-dimensional digital model*

Using the appropriate correlation equations, the soil parameters necessary for calculating the stability coefficient are determined: the specific gravity of the soil (γ); cohesion (c) and the angle of internal friction (φ) at each of the CPT sites.

The soil parameters in the space between the workings are developed (Fig. 2) by a certain method with inverse distance weighted (Panhalkar & Jarag, 2015).

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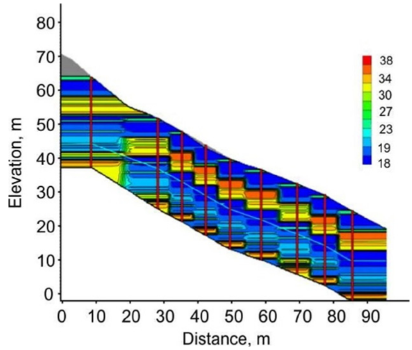

Figure 2 *An example of the distribution of the angle internal friction*

The soil parameters are defined in the nodes of a cubic grid with a default size of 1x1x1 m. The grid size can be changed, but it should be borne in mind that reducing the size leads to a significant increase in time for subsequent calculations of the stability coefficient. In this study, the soil array is discretized into 434506 eight-node elements, measuring 1x1x1 m.

DETERMINISTIC AND PROBABILISTIC APPROACH

In the deterministic approach, the calculated values of the soil parameters are determined at nine sites and taken as the average values in each soil layer.

In the probabilistic approach, the calculated values of soil parameters are determined both at the CPT sites and in the space between them, taking into account spatial variability.

The slope stability calculation (Fig. 1) was performed using the following methods: Shahunyants, Fellenius, Bishop, Morgenstern-Price, Spencer, Yanbu and the method of unbalanced forces using a probabilistic and deterministic approach.

For example, sliding surfaces with different stability coefficients and a sliding surface with a minimum stability coefficient for the Bishop method are shown in Fig. 3.

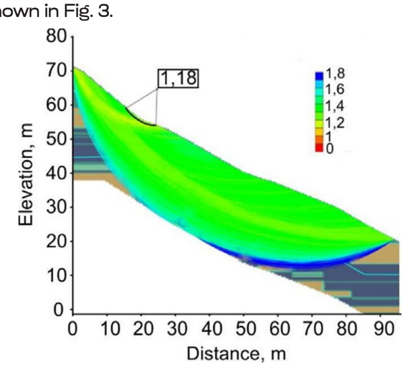

Figure 3 *The results of the calculation of stability coefficients by the Bishop method*

Probabilistic methods are used to assess slope stability more often than to solve any other foundation design problems. The rule of thumb is that the shear strength parameters, mainly the cohesion and the angle of internal friction, should be considered as random variables. In the considered case, the probability of failure (P_f) and the reliability index (β) are calculated by the Monte Carlo method (Ding et al., 2022; Umrao et al., 2024).

To calculate the P_f slopes using a probabilistic analysis based on marginal equilibrium, a critical sliding surface with a minimum stability coefficient is searched for, using each implementation of the soil strength parameters (cohesion and/or angle of internal friction) as their average value. The probability of failure is defined as the ratio of the number of implementations with a stability coefficient of less than one ($k < 1$) to the total number of implementations.

The required minimum number of implementations is determined by the dependence $N > 100/P_f$ to estimate the probability of failure when coefficient of variation k reaches less than 0.1. In some cases, thousands of implementations are required for Monte Carlo simulation. It is believed that in order for the coefficient of variation of the stability coefficient to be less than 30%, it is necessary to perform $10/P_f$ deterministic calculations (Ching et al., 2009).

Monte Carlo simulation offers a practical approach to reliability analysis, since the stochastic nature of the system response (output data) can be probabilistically reproduced. Using this method, it is possible to determine the properties of soils, based on their known (or assumed) probability distribution.

For this purpose, it is necessary to define a probability density function for each of these variables. In this case, these are c, φ and γ. Usually, a normal distribution is assumed for these parameters. Then the corresponding coefficient of stability limit for each set is calculated. These values of the stability margin coefficients are plotted on a probability graph to determine their distribution. The reliability index (β) and the probability of failure (P_f) are then calculated using the probability distribution of the stability coefficient. This approach can be applied to any method that uses limit equilibrium, including calculating slope stability.

Figure 4 shows the critical sliding surfaces and values of stability coefficients by the Bishop method, determined by deterministic and probabilistic approaches. It can be seen that in the limit state, the volume of deformable soil under the deterministic approach is significantly smaller than in the probabilistic approach.

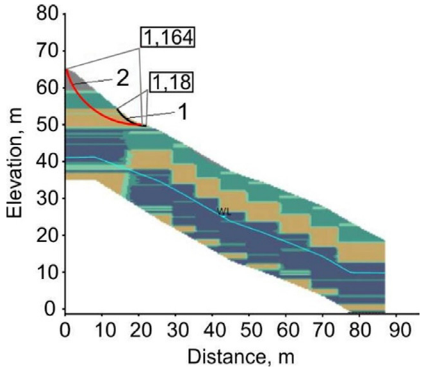

Figure 4 *Sliding limit surfaces from deterministic (1) and probabilistic (2) modeling*

CONCLUSION

Slope stability was calculated using several methods of marginal equilibrium in order to determine the stability coefficient and estimate the probability of slope failure using a deterministic and semi-probabilistic approach. In the deterministic approach, the properties of the soil are determined only on the investigatied sites, and in the probabilistic approach, additionally in the space between the sites. In the latter case, interpolation using the inverse weighted distance method is used.

Comparison of the results of deterministic calculation by various methods of marginal equilibrium showed practically identical critical values of stability coefficients. The average values of the stability coefficients vary in the range from 1,900 to 2,212.

The values of the probability of failure and the reliability index obtained by the Monte Carlo method using a deterministic and probabilistic approach showed that there was no influence of spatial variability on the stability of the slope in the considered case.

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