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COMPARATIVE STUDY OF SEMI-PROBABILISTIC AND PROBABILISTIC APPROACHES FOR SLOPE STABILITY ASSESSMENT. STUDY CASE

BY

FLORIN BEJAN*

Technical University “Gh. Asachi” of Iasi,
Faculty of Civil Engineering and Building Services

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Abstract. Slope stability analyses are largely carried out by deterministic methods using single conservative values of ground parameters and relatively large safety factors. In Eurocode 7 the safety is placed on material properties (strength) and on action, prescribing the use of partial factors. However, the slope stability analyses yields single valued estimates for the minimum factor of safety which indicates if the slope is stable or unstable. The use of probabilistic methods has the advantage of providing a complete framework for the safety analysis determining the actual probability of failure. For the present study, a hill slope located in Iasi City has been selected for stability analysis using semi-probabilistic and probabilistic approaches. The slope stability was analysed using limit equilibrium method for calculation of factor of safety and probability of failure. The probabilistic analysis was done using Monte Carlo simulation. The analysis was done for both static and seismic conditions. The variability of the water table location was accounted for in the study. From the analysis, it was concluded that the pseudo-static case is critical for this hill slope.

Keywords: limit equilibrium; generalized methods of slices; Monte Carlo simulation; probability of failure.

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*Corresponding author: *e-mail:* florin.bejan@tuiasi.ro

1. Introduction

Landslides, the result of slope failure, represent one of the most frequently experienced natural hazards faced by many countries. Recently, a global dataset of fatal non-seismic landslides, covering the period from January 2004 to December 2016 have shown that in total 55,997 people were killed in 4,862 distinct landslide events (Froude and Petley, 2018). The same study have demonstrated that fatal landslide occurrence triggered by human activity is increasing and may be more detrimental to future landslide incidence than climate change. Settlements are often built on hazardous land around urban centres and on roadsides because of the benefits of service access and employment opportunities. Construction of buildings and development of cities on steep-slope terrain require analyses of slope stability taking into account the geology, surface drainage, groundwater, and the shear strength of soils.

In geotechnical design, the level of safety may be evaluated in several ways, as given in Table 1 (Mustaffa *et al*., 2009).

Table 1
Safety Levels Applied in Geotechnical Design (adopted by Mustaffa et al., 2009)

Safety level	Description
Level 0	▪ Deterministic method ▪ Should not be applied
Level I	▪ Semi-probabilistic approach. Also known as load resistance factored design ▪ Standard design procedures (Eurocode 7) ▪ Utilizes a single partial coefficient (safety factor) to represent an uncertainty variable ▪ Design strength < design load x safety factor
Level II	▪ Approximations of the full probabilistic approach ▪ Each variable (strength and load) is approximated by a standard normal distribution ▪ Probability of failure computation is simplified by idealizing (linearizing) a failure surface
Level III	▪ Full probabilistic approach (more advanced) ▪ Each variable (strength and load) is defined by its own probability density functions ▪ All variables are treated based on the knowledge of distribution ▪ Utilizes the exact failure surface which requires numerical integration of simulation ▪ Information needed for this method is not always available and even if they were, the calculations would be overwhelming

Level I methods are used as the common practice when analysing slope stability. It offers values of partial safety factors for the most common strength and load parameters. A safety factor approach offers a safety measure but does not provide a full picture of reliability level of the slope stability. The question a geotechnical engineer should ask is not if the slope will fail but instead what the probability is that it will fail. This question can only be answered from probabilistic perspective (Level II and III).

This paper presents stability analyses performed for a hill slope composed by two independent layers, which was excavated to make room for a new five-storey building. Slope stability calculations were performed with the SLIDE program considering limit equilibrium method. Seismic action was taken into account using pseudo-static approach. Then, a probabilistic analysis was performed for the slope using Monte Carlo simulation to determine the probability of failure (PF) of the factor of safety (FS). At the same time, the sensitivity of each parameter on the factor of safety was analysed.

The objective of this research is to demonstrate that probabilistic methods are indispensable in slope stability analysis by understanding the concept of reliability analysis and its application in slope stability analysis.

2. Site Description and Geotechnical Characterization

The site selected for the study is located in Iasi City, which is one of the largest urban areas in Romania. The general geological framework is given by Sarmatian alternating sedimentary deposits consisting of clay, marl, sandstone, gravel and sand and surface alluvial, colluvial and delluvial deposits. From seismic point of view, Iasi City is subjected to earthquakes, originating in Vrancea zone. According to P100-1/2013, the design peak ground acceleration specific for Iaşi City, is equal to a_g = 0.25 g, considering a mean period of recurrence of 225 years and 20% probability of overpassing it in 50 years.

The critical cross-section used in the stability analyses of the slope was selected based on the geometrical characteristics of the slope, ground water table location and shear strengths of the soil. The critical cross-section location is showed in Fig. 1. Three boreholes were drilled manually along the slope profile. The boreholes showed that the slope was composed of brown to grey clays with intercalated thin sand and silt lenses. All the boreholes were terminated when the borings reached a hard consolidated clay with calcareous concretions (Fig. 2). Ground water in BH3 and BH3 was observed and measured 24 hours after the boring. Ground water was not present in BH1.

Particle-size distribution analyses on samples obtained from the boreholes indicated that the soils are composed of 54% clay, 33% silt and 13%

sand on average. The soils were found to have natural water content of 18 to 27%; natural unit weight of 19.6 kN/m^3, liquid limit of 58% and plasticity index of 39% on average.

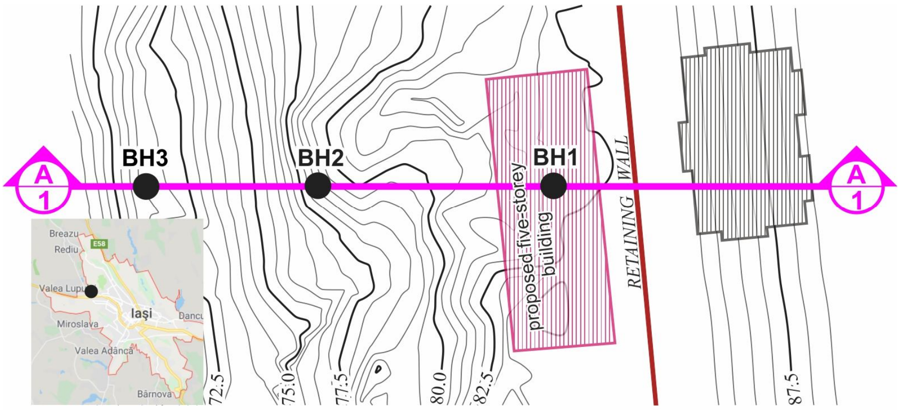

Fig. 1 – Plan view of the slope with boreholes' locations.

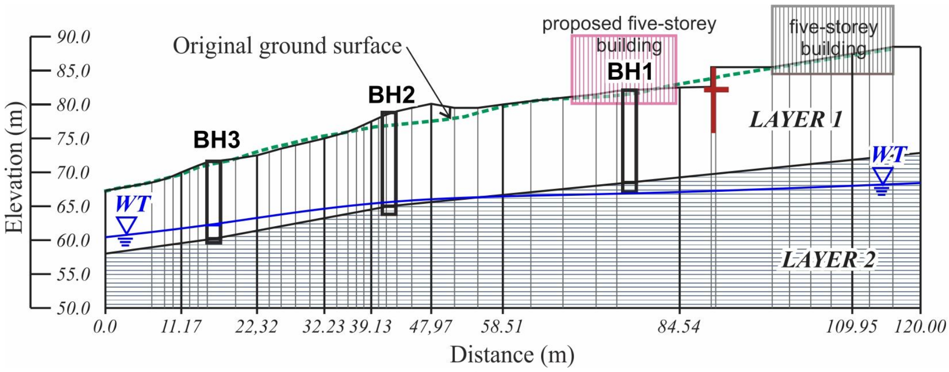

Fig. 2 – Slope profile at Section A-A.

A total of nine direct shear tests (STAS 8942/2-82) were conducted on soil samples and the results are summarized in Table 2.

Table 2
Results of the direct shear tests

Sample no.	1	2	3	4	5	6	7	8	9
Friction angle, φ (°)	4.25	9.15	10.60	3.80	8.20	7.40	15.40	12.20	9.10
Cohesion, c (kPa)	38.05	29.12	35.25	37.80	38.90	24.40	39.12	41.87	47.90

The laboratory test results presented in Table 2 are evaluated by determining the minimum, maximum and average values, as well as the standard deviation (Table 3).

Table 3
Statistical analyses of the geotechnical strength parameters

	Angle of internal friction, φ (°)	Cohesion, c (kPa)
Processing type	Logarithm distribution	Standard distribution
5% average percentile	6.36	33.17
Minimum value	3.80	24.40
Maximum value	15.40	47.80
Mean value	8.17	36.92
Standard Deviation	1.16	2.28
Coefficient of variation	0.22	0.19

As a simplifying assumption, the soil unit weight and shear strength parameter values were assumed constant through the soil profile for both static and seismic conditions.

3. Calculation Methodology

3.1. Semi-Probabilistic Slope Stability Analysis

Slope stability analyses were performed according to Eurocode 7 and Eurocode 8 for static and seismic loading conditions, respectively. Among the biggest changes in the design practice introduced by Eurocodes were the partial factors on soil strength, resistance and loads. Whilst some of the partial factors for actions have been determined based on probabilistic methods the material and resistance factors for geotechnical design has mainly been determined based on calibration to old codes (Lansivaara and Poutanen, 2013).

In EC 7, it is recommended that the calculated probability of the minimum value governing the occurrence of the limit state considered should not be greater than 5 %. Since slope stability problems usually involve a large volume of soil, the 5 % fractile is applied to the mean values of soil strength parameters, this is more realistic, the sliding surface is then seen as an averaging system (Frank et al. 2004) (Larsson, 2018). Using the values from Table 2, a lognormal distribution was assumed for the friction angle with a characteristic value of 6.36°. The characteristic value of cohesion used in the semi-probabilistic analysis is 33.17 kPa.

Most of European countries have chosen either Design Approach (DA) 1 or 3 for slope stability under static conditions. DA1 consists of two combinations of sets of partial factors. For slope stability, DA3 is analogous to DA1.C2 because the loads applied on the surface are treated as geotechnical actions (Bond *et al.*, 2013). Therefore, in this study, the Design Approach 1 (DA1) was adopted for slope stability analyses under static conditions. For drained analyses of slopes, DA1 partial factors are:

- DA1.C1 $\gamma_G = 1.35$ $\gamma_Q = 1.50$ $\gamma_\varphi = \gamma_c = 1.00$
- DA1.C2 $\gamma_G = 1.00$ $\gamma_Q = 1.30$ $\gamma_\varphi = \gamma_c = 1.25$

Design parameters entering the calculations are obtained by dividing the characteristic values by corresponding partial factors γ_φ and γ_c.

According to Eurocode 8, the stability verification under seismic conditions may be carried out by means of simplified pseudo-static methods, in which the design seismic inertia forces F_H and F_V acting on the ground, for the horizontal and vertical directions respectively, shall be taken as:

$$F_H = 0.5 \cdot \alpha \cdot S \cdot W, \quad (1)$$

$$F_V = \pm 0.5 \cdot F_H \ \ (\text{for } \mathrm{a_{vg}/a_g} > 0.6), \quad (2)$$

where: α is the ratio of the design ground acceleration, a_g, to the acceleration of gravity, g; a_{vg} the design ground acceleration in the vertical direction, a_g the design ground acceleration, S – the soil parameter (in the Romanian seismic design code P100-1/2013, $S = 1$); W – the weight of the sliding mass.

In stability analyses under seismic conditions, the characteristic values of soil parameters are used without applying any partial factors on soil properties. The design values of the seismic inertia forces used in slope stability analyses of the critical cross section A-A are: $F_H = 0.125$ and $F_V = 0.062$ W.

For the location of ground water table two situations were considered – (1) current water table observed during the slope investigation and (2) water table located on current slope surface for the case of static loading. Assuming the water table is located on the slope surface represents the worst ground water conditions with respect to stability calculations.

The building load in the slope stability analyses was modelled by applying a distributed load equal to $P = 100$ kN/m^2 for both the case of static and seismic loading.

3.2. Probabilistic Slope Stability Analysis

The probability analysis is one of the techniques which are being employed to overcome the uncertainties in stability assessment of slopes.

Reliability of slope stability is frequently measured by Reliability Index (RI) and probability of failure (PF). PF is defined as the probability that the minimum factor of safety (FS) is less than unity. Various solution methods have been proposed to estimate PF and RI. Among the most widely used methods is the Monte Carlo simulation.

The Monte Carlo method uses random or pseudo-random numbers to sample from probability distributions and, if sufficiently large numbers of samples are generated and used in a calculation such as for a factor of safety, a distribution of values for the end product will be generated (Hoek, 2007).

An iterative process using deterministic methods of slope stability analysis is applied in this technique. The method consists in four steps: (1) choosing a random value for each input variable according to assigned probability density function; (2) calculating factor of safety by using a proper deterministic slope stability analysis method based on selected values in step 1; (3) repeating steps 1 and 2 for many times as necessary; (4) determining distribution function of factors of safety and probability of failure.

The probability density functions of friction angle and cohesive strength adopted in the analysis are shown in Fig. 3. Using the values from Table 2, a lognormal distribution has been assumed for the friction angle with a mean value of 8.17°, a maximum value of 15.40°, a minimum value of 3.83 and a standard deviation of 1.16°. A value of 36.92 kPa has been chosen as the mean cohesion and the standard deviation has been set at 4.17 kPa. The minimum and maximum values of possible cohesion used in the probabilistic analysis are 24.40 and 49.43 kPa respectively. The friction angle and the cohesive strength have been kept independent for this analysis.

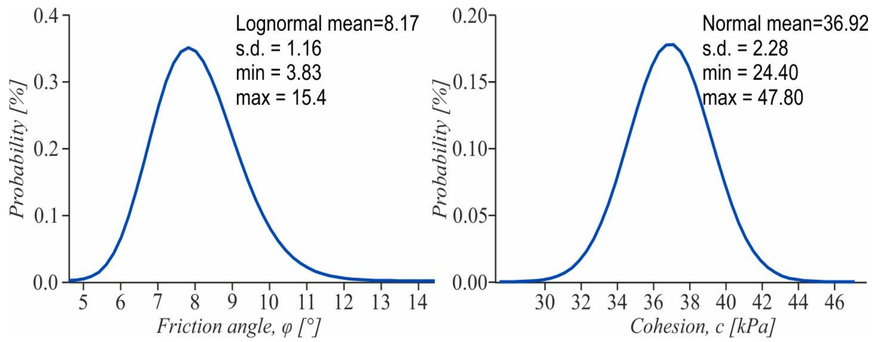

Fig. 3 – Probability density functions for friction angle and cohesion.

An exponential distribution was used for the water table location (Fig. 4). The minimum location of the water table was considered the water table observed during the slope investigation and the maximum location of the water table was considered the slope surface. The normalized mean was set to 0.3.

The distribution of values of α used in these calculations was estimated by means of an exponential distribution with a mean value of α = 0.125, a maximum of 0.25 and a minimum of 0 (Fig. 4). An exponential distribution suggests that large earthquakes are very rare while small ones are very common. Also in the probabilistic analysis was used a correlation coefficient of 0.5 between the horizontal and vertical seismic coefficients.

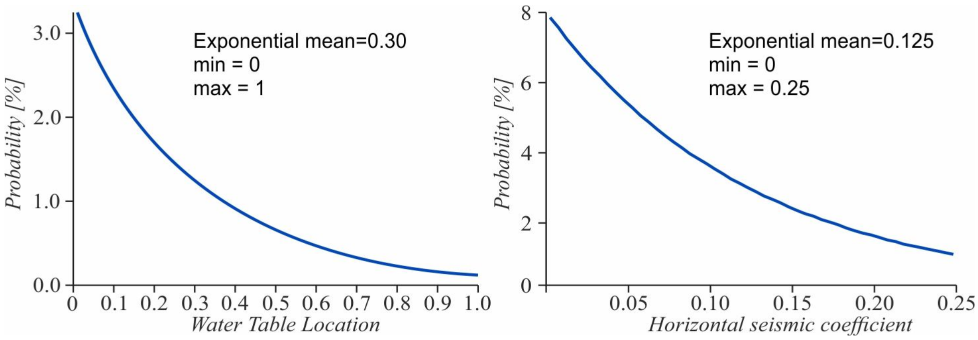

Fig. 4 – Probability density functions for water table location and horizontal seismic coefficient.

4. Results

In this paper, for the deterministic, semi-probabilistic and probabilistic slope stability analyses, Slide software was used. More particularly Spencer's limit equilibrium method was applied by subdividing the potential sliding mass into a number of 50 slices and by assuming circular slip surface (Spencer, 1967). The determination of the critical slip surface, which has the overall minimum factor of safety, was performed using the 'slope search' method. The number of surfaces considered in the analyses was set to a value of 10 000.

4.1. Results of the Semi-Probabilistic Approach

The stability analyses under static condition of the slope were performed with the characteristic values of the shear strength parameters applying partial safety factors from Eurocode 7. The results of the stability analyses are summarized in Table 4.

Figs. 5 and 6 present the results of slope stability analyses under static loading conditions using the limit equilibrium method. When considering current location of the water table the minimum factor of safety was obtained in DA1.C1 with a value of 1,284 which exceeds the generally acceptable value of 1.0, indicating that the slope is stable (Fig. 5).

Table 4
Summary of the Results Obtained by Semi-Probabilistic Approach

Analysis situation	Water table location	Design approach	Factor of safety
Static condition	Current water table	DA1.C1	1.284
		DA1.C2	1.363
	water table on slope surface	DA1.C1	1.095
		DA1.C2	1.146
Seismic condition	current water table	-	1.095

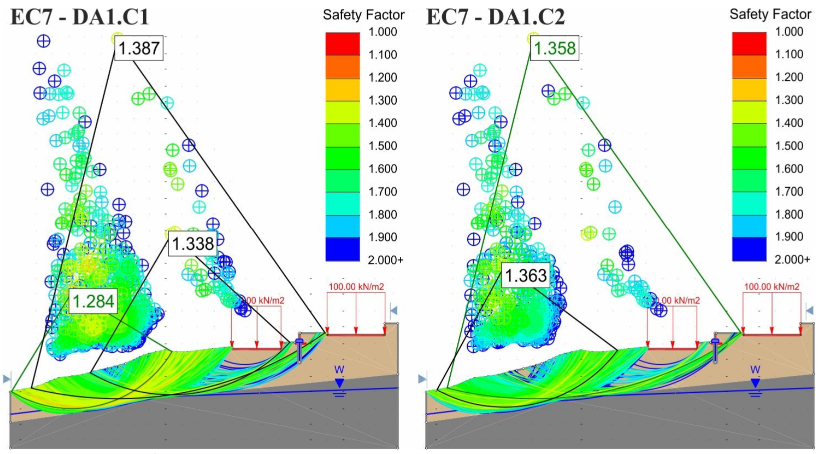

Fig. 5 – Results of semi-probabilistic slope stability analyses under static conditions with current water table.

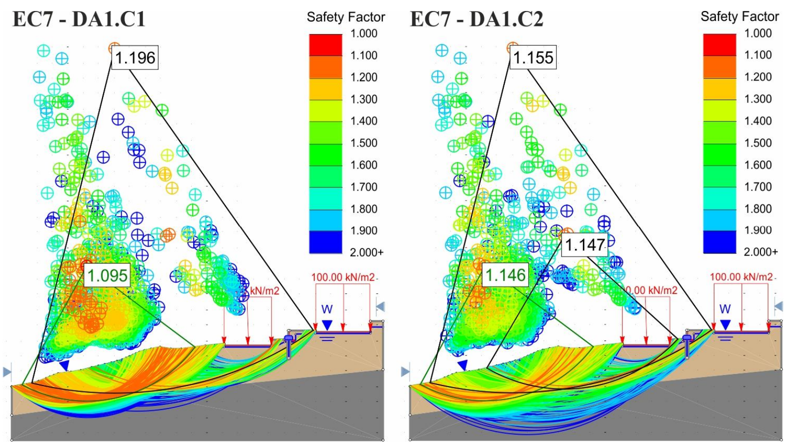

Fig. 6 – Results of semi-probabilistic slope stability analyses under static conditions with water table located on slope surface.

The minimum factor of safety becomes quite critical in the case of water table located on slope surface with a value of 1,095 (Fig. 6).

In Fig. 7 are presented the results of the slope stability analyses under seismic conditions, using a pseudo-static approach.

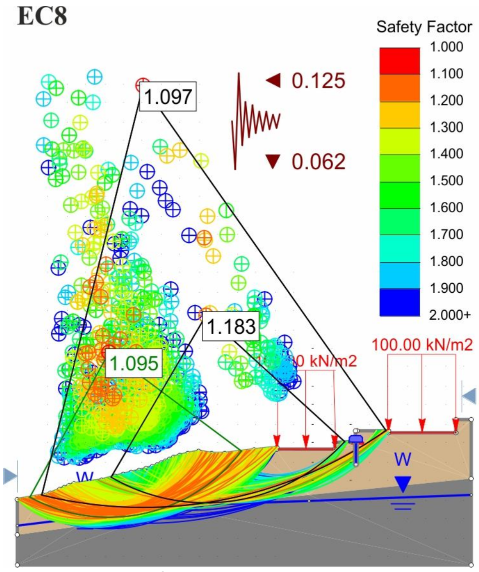

Fig. 7 – Results of semi-probabilistic slope stability analyses under seismic conditions.

The results of semi-probabilistic slope stability analyses with limit equilibrium method indicate acceptable safety factor values for both static and seismic loading conditions. By observing the results of the analyses illustrated in Figs. 5,...,7, it is concluded that the resulting safety factors correspond to slip circles passing through the lower part of the slope.

4.2. Results of the Probabilistic Approach

The Slide program allows probabilistic analyses using Monte Carlo method. The user can choose to use the options 'Global Minimum' or 'Overall Slope'. In this paper, 'Global Minimum' option was adopted, where the probabilistic analysis is performed on the critical slip surface calculated by a deterministic stability analysis. The factor of safety is calculated N times (where N is the number of iterations) for this slip surface, by using a different set of values, generated randomly. Random properties were obtained by statistical evaluation of available geological and geotechnical data from laboratory as well as field. The number of iterations performed to achieve the convergence by the Monte Carlo Method was set to 100 000.

The results of the probabilistic analysis are presented in Fig. 8.

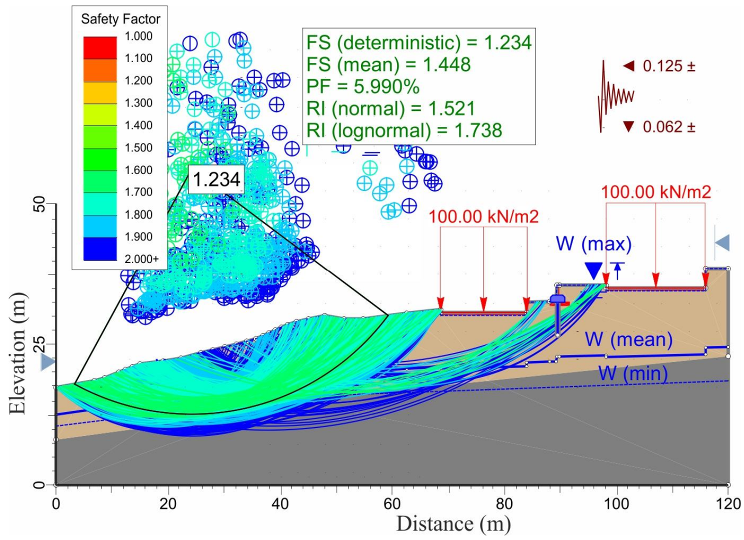

Fig. 8 – Results of probabilistic slope stability analyses.

For this case the distribution of the factor of safety (Fig. 9) indicate a probability of 6% that FS < 1, i.e. there is a substantial probability that a failure could occur. For this reason is recommended to use remediation methods that eliminates this risk.

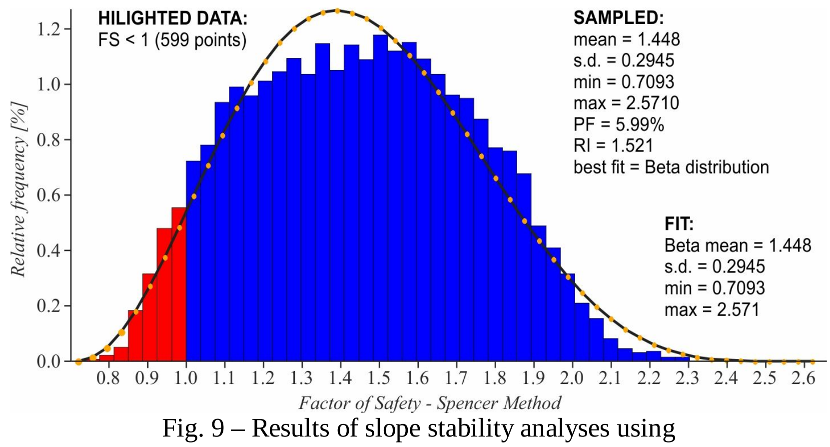

Fig. 9 – Results of slope stability analyses using Eurocode 8 (seismic conditions).

The point where the sensitivity curves cross is the factor of safety at the mid-point of the ranges for each of the variables considered (Fig. 10). For this example, seismic loading has big influence on stability decreasing the factor of safety from 1.92 to 1.24.

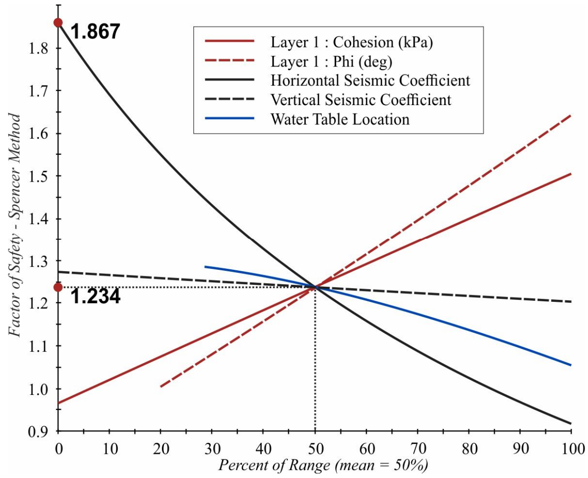

Fig. 10 – Sensitivity plot of considered variables

5. Conclusions

In this paper the local stability of a hill slope, located in Ia□i City, was analysed using limit equilibrium method for calculation of factor of safety and probability of failure. At the same time the sensitivity of each parameter on the factor of safety was analysed. The probability analysis was performed using Monte Carlo simulation using randomly selected discrete values of each variable from their probability distribution.

In the semi-probabilistic approach, the minimum factors of safety are larger than 1.0 indicating that the slope is stable. Instead, the probability of failure with a value of 5,99%, indicates a substantial probability that a failure could occur. Therefore, remediation methods to reduce the risk of failure are recommended. Based on the results of this study we conclude that the application of partial factors of safety as described in Eurocode 7 (EN 1997-1) for slope stability do not provide a reliable tool for judging the safety of slopes.

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STUDIU COMPARATIV AL ABORDĂRILOR SEMI-PROBABILISTICE ŞI PROBABILISTICE PENTRU EVALUAREA STABILITĂȚII PANTELOR. STUDIU DE CAZ

(Rezumat)

Analizele pentru evaluarea stabilității pantelor sunt realizate în cea mai mare parte cu metode deterministe folosind valori conservatoare unice pentru parametrii pământului şi valori relativ mari ale factorilor de siguranță. În Eurocod 7, siguranța este aplicată proprietăților materialelor (rezistențe) şi asupra acțiunilor, recomandând utilizarea factorilor parțiali de siguranță. Totuşi, analizele de stabilitate a pantelor dau

valori unice pentru factorul de siguranță minim ce indică dacă versantul este stabil sau instabil. Utilizarea metodelor probabilistice are avantajul de a furniza un cadru complet pentru analiza stabilității determinând probabilitatea de cedare. În acest studiu, pentru analiza stabilității folosind abordările semi-probabilistice şi probabilistice, a fost selectat un versant din oraşul Iaşi. Stabilitatea versantului a fost evaluată folosind metoda echilibrului limită calculând factorul de siguranță şi probabilitatea de cedare. Analiza probabilității a fost realizată folosind simularea Monte Carlo atât pentru condiții de încărcare statice cât şi seismice. Variabilitatea nivelului apei subterane a fost considerată în acest studiu. În urma realizării analizelor, a rezultat că acțiunea seismică este critică pentru acest versant.