Probabilistic Analysis of Slope Stability and Landslide Risk Assessment

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Abstract

Provision of social and economic safety is one of the main concerns during territory development with high risks of landslides activities. This issue requires geological risks assessments. Probability evaluation of landslides activity is one of the main parameters in the quantitative evaluation of geological risk.

An application of probability analysis for quantitative evaluation of slopes stability is proposed for risk assessment. It allows characterizing threats by the means of quantitative evaluation. The substantial idea of probability analysis is probability function determination of the factor of safety (FOS) that depends on the input distribution of the physical and mechanical soil parameters of the analyzed slope, as well as other slope activity factors.

This article shows the results of slope stability probabilistic analysis and of the quantitative risk assessment of landslide activity at the studied construction site. For the implemented risk analysis an assumption was made that economic losses depend primarily on the deformation level of the structure foundations.

Keywords: slope stability, probabilistic analysis, landslide risk assessment

Introduction

Currently, considering increasing economic development of territories affected by dangerous geological processes, including landslides, special attention during site investigations is paid to the safety of the structure that is planned to be constructed. The modern concept of complex systems operating assumes a transition from the ideology of "absolute security" to the concept of "acceptable risk." This requires risk

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analysis and development of the risk management system, which means reduce risks to an acceptable level. Thus, the geological risks assessment is currently one of the most important areas of work to ensure the safety of territories, constructed and designed buildings and people living in them. It should be noted that the probability of landslide activity is currently considered as one of the key characteristics in the geological risk quantitative assessment (Bell and Glade, 2004; Crozier and Glade, 2004; Dai et al., 2002; Fell et al., 2007; Glade and Crozier, 2004; Kappesetal., 2012; Pendin and Fomenko, 2015; van Westen et al., 2006; Zerkal, 2009; Zerkal et al., 2014; Fomenko et al., 2018).

Probabilistic analysis in calculating the slope stability is becoming relevant in the world practice and is often used due to increasing understanding of the random variability of the characteristics of the physical and mechanical soils obtained during engineering survey. Considering the wide range of soil properties fluctuations, the probabilistic approach associated, besides all, with their variability assessment, caused, in particular, by climate change, allows us to look at the analysis of landslide hazard more universally from a new perspective.

It should be noted that the conservative deterministic methods of the slope stability calculation widely used at present take into account the variability of landslide formation factors indirectly: their statistically determined design values are used in the numerical models. Safety factors obtained on the basis of such calculations do not really determine the actual level of harm, since it is impossible to establish a relationship between them and the probability of slope failure.

Existing Restrictions of The Use of Slope Stability Quantitative Estimates in Risk Analysis and How to Overcome Them

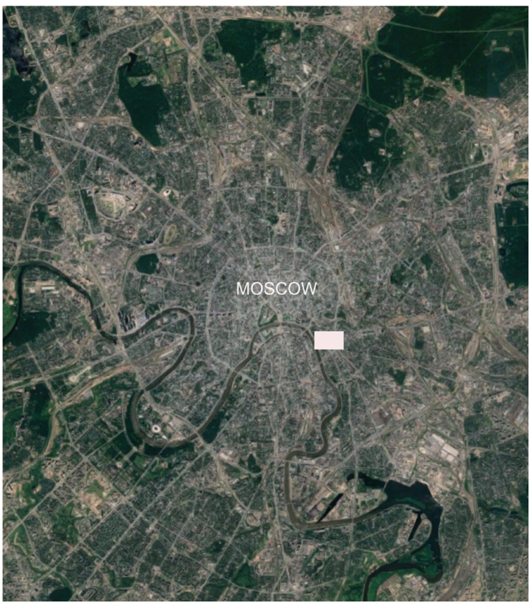
Currently, it is generally accepted to provide a factor of safety (FS) as the resultant value of the quantitative assessment of slope stability. FS is considered as an indicator of the possibility of slope deformations associated with a landslide (Bishop, 1960; Fomenko and Zerkal, 2017; Fomenko et al., 2016; Janbu, 1954; Kang et al., 2019; Krahn, 2004; Morgenstern and Price, 1965; Zerkal and Fomenko, 2013). At the same time, the obtained FSvalue used within the frames of the conventional approaches characterizes the state of the slope instantaneously (Fomenko and Zerkal, 2017; Fomenko et.al., 2016; Kang et al., 2019; Zerkal and Fomenko, 2013). In other words, the calculated value of factor of safety characterizes the state of the slope exclusively at the time when the slope parameters used for calculations were obtained (as a rule, these are mean values of the physical and mechanical properties, averaged statistically). At the same time both in natural and technologically altered conditions the state of soils (as well as their characteristics) in the slope massif are significantly variable under the influence of different factors. However, the traditional "generally accepted" approaches to the slope stability quantitative assessment are based on the idea of "static", time-invariant properties of soils composing the slope massif. Undoubtedly, this is a significant limiting factor in predicting (in time) the possible development of landslide processes, not allowing us to assess the probability of a negative scenario implementation (or hazard) for changing the engineering and geological conditions when the slope becomes unstable.

One of the ways to overcome the existing limitations of quantitative slope stability assessment methods when performing risk analysis is to use probabilistic analysis, which allows characterizing the landslide activation hazard (in terms of probability). The essence of probabilistic analysis in the slope stability quantitative assessment is to obtain the probability distribution function of the safety factor depending on the probability distribution functions of the physical and mechanical characteristics of the soils composing the slope, as well as other factors affecting the development of landslide processes.

Probabilistic Analysis of Slope Stability

The probabilistic analysis in the slope stability quantitative assessment was performed at a10-12 m high right-bank slope of the Yauza River valley in the central part of Moscow (Fig. 1). In close proximity to the slope, the construction of a high rise building is planned.

Fig. 1: The site location in Moscow, Russia



The upper part of the geological section within the studying area is composed (from top to bottom) by man-made soils (units 1.2, 1.3), Quaternary moraine loams of various consistencies (units 5 and 6), Quaternary fluvio-glacial, glacial-lake and lake sands (units 7, 7a, 8, 8b, 9 and 10), which are underlain by upper and Middle Jurassic clays and loams (unit 11), and the Upper Carbonic limestones. In the channel part of the river valley alluvial formations (items 2, 2a, 3 and 4) are developed. The geomechanical design scheme of the slope is shown in Fig. 2. The cohesion and internal friction angle were considered as independent values.

Fig. 2: Geomechanical design scheme of the right-side slope of the Yauza River (Moscow, Russia)

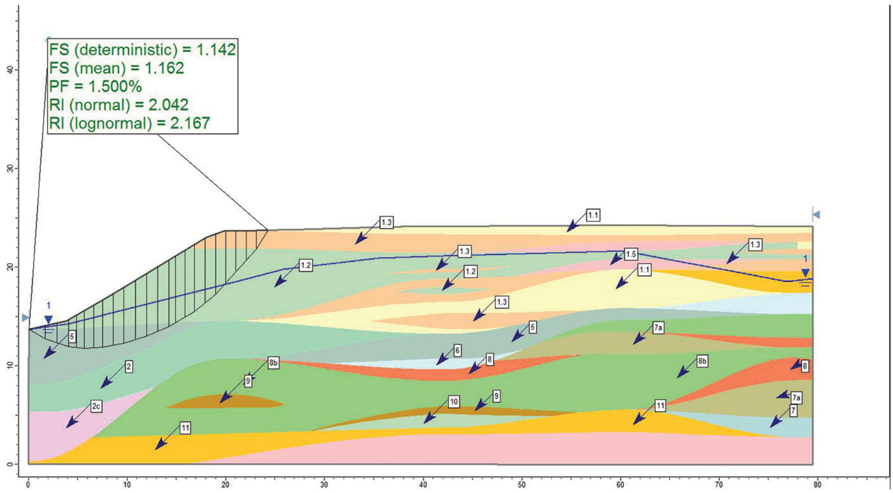


Table 1: Soil properties values and their statistic processing results used for factor of safety calculations

Soil unit	Properties	Average value	Standard deviation	Deviation to minimum	Deviation to maximum
1.2	Cohesion	14	4	4	4
1.2	Internal friction angle	17	5	5	5
1.3	Cohesion	20	5.6	9	8
1.3	Internal friction angle	31	4	5	4
2	Cohesion	2	0.5	2	1
2	Internal friction angle	34	2	4	6
5	Cohesion	12	4	5	6
5	Internal friction angle	19	1.5	1	3

Slope stability was assessed using three calculation methods: Janbu (Janbu, 1954), Bishop (Bishop, 1960), and Morgenstern-Price (Morgenstern and Price, 1965), of which the Morgenstern-Price method is the most rigorous. All of these methods in traditional applications are deterministic since it is assumed that the soils strength characteristics are known and can be set in the form of averaged values used for calculations. However, as noted above, obtaining "accurate", "complete" data that would characterize the slope massif entirely is practically impossible.

A peculiarity of the performed slope stability quantitative assessment is to use for calculations not the averaged values of soil properties, but the entire data set of the soils strength parameters. It should include the properties distribution function, minimum and maximum values, as well as the standard deviation. This approach to taking into account the characteristics of soils provides more complete use of information about their variability obtained during field and laboratory studies. It allows assessing their influence on the slope massif stability. As a result of using the proposed approach a probabilistic quantitative estimate of the slope stability was obtained, which additionally, in contrast to deterministic estimates, characterizes the minimum, average, and maximum values of the slope stability, and the standard deviation in the factor of safety distribution in the test series used for calculations. A description of the methodology for performing a probabilistic quantitative assessment of slope stability can be found in (Zerkal and Fomenko, 2016). The proposed approach to taking into account the characteristics of soils, on the one hand, provided a more complete use of information about the variability of the properties of the physical and mechanical soils, and, on the other hand, made it possible to perform a probabilistic quantitative assessment of the slope stability.

A quantitative stability assessment of the considered right side slope of the Yauza River showed that for the given indicators of soil properties variability, the slope is stable (average FS = 1.03 ÷ 1.162, depending on the calculation method). At the same time from Figure 3 which shows the integral probability curves for the slope stability values variability, the slope failure probability for the given soil properties variability is from 1.5 per cent (Morgenstern-Price method) to 33.3 per cent (Janbu method). For further analysis, it is advisable to accept the results obtained by the most rigorous Morgenstern-Price method.

The summary results of slope stability probabilistic quantitative assessment are given in Table 2, the cumulative distribution of the safety factor obtained by various methods is shown in Fig. 3.

Fig. 3: Integral probability curves for the stability of the right-bank slope of the Yauza River (Moscow, Russia) at the study site

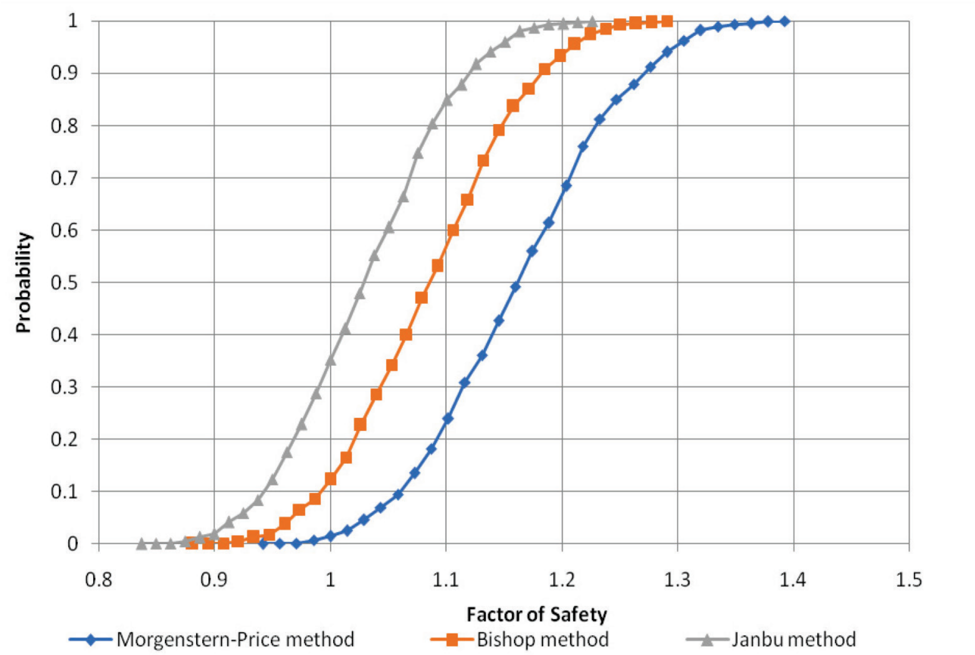


Table 2: Probabilistic quantitative slope stability assessment obtained by different methods (without taking into account the quality of initial engineering geological information)

Factor of safety	Morgenstern-Price method	Bishop method	Janbu method
Average value (deterministic approach)	1,16	1,09	1,03
Standard deviation	0,08	0,07	0,07
Minimum	0,95	0,89	0,85
Maximum	1,38	1,29	1,22
Probability of landslide process development (Safety factor <1)	1,5%	12,3%	33,3%

As can be seen from Table 2, a quantitative assessment of the slope stability performed by various methods resulted in close average values of the factor of safety, which differ depending on the used calculation method. Following the traditional approach to the slope stability analysis, they obtained FS values would become the basis for the conclusions that the slope is generally stable but is close to the limiting equilibrium state. It would be impossible to draw any additional conclusions base on the obtained FS values without additional calculations.

At the same time, the analysis of the slope deformations probability obtained by the selected calculation methods allows us to evaluate the influence of the calculation method on the resulting estimates of the landslide activation possibility (Table 2). The probability of landslide development in the considered area obtained by various methods differs more than 20 times. The highest probability (33.3 per cent with the minimal average FS value) was obtained by use of the Janbu method. The lowest values were obtained by use of the Morgenstern-Price method (1.5 per cent with the maximal FS average value).

Geological Risk Assessment

The performed slope stability probabilistic analysis at the study site made it possible to obtain a probability index of the slope destabilisation. Taking in mind that close to this site the tall building is designed, it allows performing a quantitative assessment of the economic risk from the possible landslide formation. Use of this methodology is considered by Moscow regulatory documents (Guidelines, 2002).

The differentiated economic risk of landslide losses was estimated as the full and specific (reduced to the unit area) values of this risk according to the following formulas:

$$R_e(H) = P(H)*P_s(H)*V_e(H)*D_e,$$

$$R_{se}(H) = R_e(H) \ / \ S_o$$

where $R_e(H)$ and $R_{se}(H)$ – are correspondingly full (per cent of the building cost/year) and specific (per cent of building cost/m^2 year) damage risk from the landslide hazard H; P(H) – landslide hazard (H) realization within the certain area, numerically equal evaluated slope stability loss probability; $P_s(H)$ – geometric probability of object exposure by the landslide hazard H in the area; S_o – object area (m^2); $V_e(H)$ – economic vulnerability of evaluated object to the landslide hazard H; De – the object cost before the landslide hazard (accepted as 100 per cent).

The vulnerability values defined for surface deformations at the base of the building foundation adopted in (Guidelines, 2002) were taken as indicators of the designed building economic vulnerability. Obviously, the development of such deformations is possible due to the landslide displacements. The results of a quantitative assessment of the differentiated economic risk from the landslide processes development with the probability of slope stability values obtained using the Morgenstern-Price method variability are shown in Table 3.

Table 3: The differentiated economic risk assessment from the landslide processes development (according to (Guidelines, 2002))

The lifetime of building, years		50	
Footingarea, m^2		7736,8	
Designed values of deformation zone		area, m^2	1235
		probability	0,015*)
Affected area to the full footing area ratio		0,168	
Economic vulnerability of the building		average	0,01
		average max	0,04
Economic risk	average	full, %/year	$2{,}52 \cdot 10^{-3}$
		specific, %/m^2·year	$3{,}43 \cdot 10^{-7}$
	maximum	full, %/year	$1{,}01 \cdot 10^{-2}$
		specific, %/m^2·year	$1{,}37 \cdot 10^{-6}$
Expected full economic damage for 50 years, % of full cost	average	0,126	
	maximum	0,504	

Note: * The probability of slope stability loss, calculated with Morgenstern-Price method

The performed landslide risk calculation for the building designed near the studied slope showed that over 50 years of operation of the building, the average economic damage from landslide activity can count 0.126 per cent of the designed building cost, with maximum values reaching 0.5 per cent of the cost. The obtained landslide risk values for the evaluated building are not significant and apparently, the slope will not require additional strengthening measures.

Conclusion

Assessment of the hazardous geological processes' probability (including landslides) is one of the key characteristics in the quantitative assessment of the geological risk. Utilisation of the probabilistic slope stability analysis based on the elaboration of the probability distribution functions of the factor of safety depending on the probability distribution functions of the various soil characteristics provides data requires for risk analysis. The standard (deterministic) slope stability assessment does not allow obtaining the probability of landslide occurrence.

The results of the landslide risk assessment using the proposed approach can become the basis of the geological risk management both at the construction sites and for the regional landslide risk assessments.

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