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The methodology of Hoek-Brown criteria parameters distribution for probability assessment of open pit wall stability in *FLAC*/*FLAC3D*

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1 INTRODUCTION

Providing rational pit angles, which ensures their stability and minimizes the volume of mining costs, requires a detailed study of such factors as lithology, rock mass properties, jointing, tectonics, ground water level etc. The mentioned factors for pit walls vary widely and characterized by a considerable degree of heterogeneity. This circumstance assumes to give preference to probabilistic stability assessment (PSA) of pit walls.

Methodologies of PSA of pit walls being improved and updated with new studies all the time. However, there is no uniform methodology for the implementation and interpretation of the PSA of pit walls results. We carried out studies comparing the results of probabilistic methods for assessing stability. The linearization method, the linearization method with the refinement and the Monte Carlo method were compared. As a result of the study, we came to the conclusion that the most reliable results of PSA are obtained on the basis of the "classical approach" by calculating the factor of safety by modeling (playing) random variables using the Monte Carlo method.

Probability methodologies of pit wall stability assessment, as a rule, based on the assumption that random variables taking part in stability calculations obey the normal distribution law (NDL). Statistical analysis of geological investigation studies and lab test results get on that not always random variables obey NDL. It is often when random variables that do not obey NDL have the most significant influence on the value of factor of safety (FoS), and on the distribution law of factor of safety, which is also a random variable. Thus, the assumption that all random variables obey NDL decreases the accuracy of probability assessment of pit wall stability.

2 DESIGN AND ANALYSIS

Based on the mathematical theory of experiment planning, we performed a general sensitivity analysis of Hoek-Brown criteria parameters, slope angle and groundwater level (hgw) for slope stability in order to understand which of these factors has the greatest impact on the stability of a pit slope. The computational experiment was carried out on a test example of 400 meters height pit wall. The following parameters of Hoek-Brown criteria took part in the sensitivity analysis: σ'_{ci} - compression strength of undisturbed sample; GSI – geological strength index; m_i – parameter determined by the results of triaxial tests.

Parameter D – characterizing the degree of disturbance of the rock mass from the methods of its processing was excluded from sensitivity analysis. This was made due to the parameter D characterizes the degree of disturbance of the layer from the slope face. Because of blasting the near-surface region is formed in which the strength properties of the rock mass are significantly reduced. During stability modeling, the shear surface is formed in this near-surface region and thus makes difficult to assess the overall stability of the pit wall. The remaining parameters of the Hoek-Brown criteria (m_b, s, a) were calculated based on known equations depending on the values of σ'_{ci}, GSI and m_i.

The variation range of the factors of the general pit angle (α) and hgw was chosen based on practical experience. The factors and the variation range are given in Table 1. Forty-four computational experiments were performed. The sensitivity analysis was made based on the Pareto diagram constructed from the results of calculations and their statistical processing. All possible options of pit slopes with the corresponding geometry size and properties of the rock mass were modeled.

Table 1. Factors and range of variation.

Levels of variation	Factors and their sequence number				
	1	2	3	4	5
	σ'_{ci}, MPa	GSI	m_i	α, degree	hgw, m
Maximum	10	10	4	25	50
Minimum	150	90	10	60	350

According to the results of sensitivity analysis, the dominant factor is the GSI – geological strength index, which describes how heavy jointed rock mass is and is determined by the results of the engineering-geological studies. The GSI parameter in its influence on the stability of the pit wall is twice the factor than the compressive strength of the undisturbed sample and three times more important than the general slope angle and groundwater level. Thus, the distribution law of pit wall FoS is primarily affected by the distribution law of GSI parameter, which, by its genesis for each selected pit wall sector is individual and does not always obey the NDL. Because of that, the choice of the average GSI for stability analysis reduces the reliability of the results and may have a conservative or vice versa overestimated value.

The methodology of playing random variables, which do not obey the NDL, based on identifying the empirical distribution function (F_x^*) of the random variables by geological domains of the pit wall. Playing random variables by geological domains in accordance with defined F_x^* was implemented by the Monte-Carlo method thanks to the possibilities of *FLAC*/*FLAC3D* (Itasca 2016, 2017) equipped with the built-in random number generator function.

The playing algorithm is compiled using *FISH* codes so that each zone of the grid assigned the played value of a random number. Formed in this way the numerical model of the pit wall describes the geomechanical model of the jointed rock mass with considering defined F_x^* of random values. The proposed methodology for playing random variables for a probabilistic assessment of the pit walls stability is a distinguishing feature from all previously used approaches of random variables in the pit wall rock mass.

In our practice, we used to make stability assessment of a pit slope consisting of rock mass with significant variation in the GSI parameter. Structural geology specialists could not identify in geological zones patterns of alternating of a disturbed and undisturbed rock mass. The GSI values ranged from 5 to 90. Statistical processing of the drilling results showed that the GSI does not obey the NDL, and therefore, the choice of the average GSI value for stability analysis worsens the reliability of the assessment.

Figure 1 shows the results of playing the GSI over the empirical distribution function F_{GSI}^* over geological domains that form the real pit wall in the calculated area. Same approach in *FLAC3D* is presented in Figure 2.

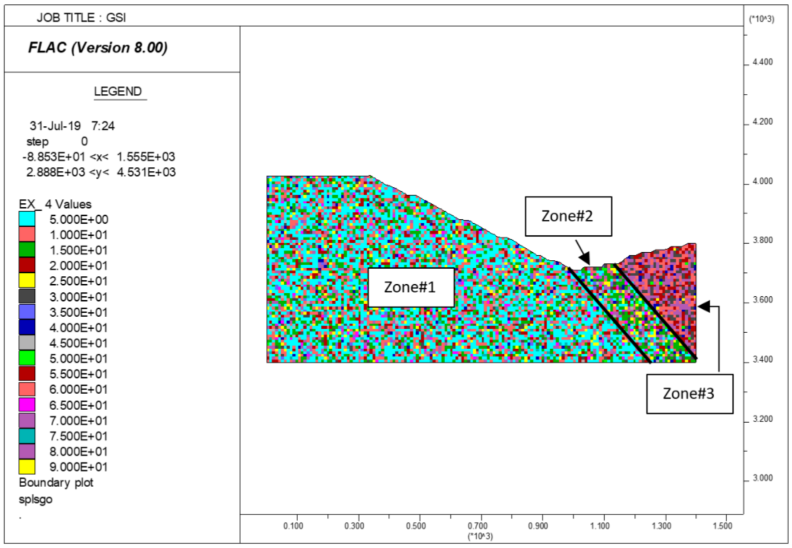

Figure 1. The results of GSI playing on the F_{GSI}^{*} in *FLAC*.

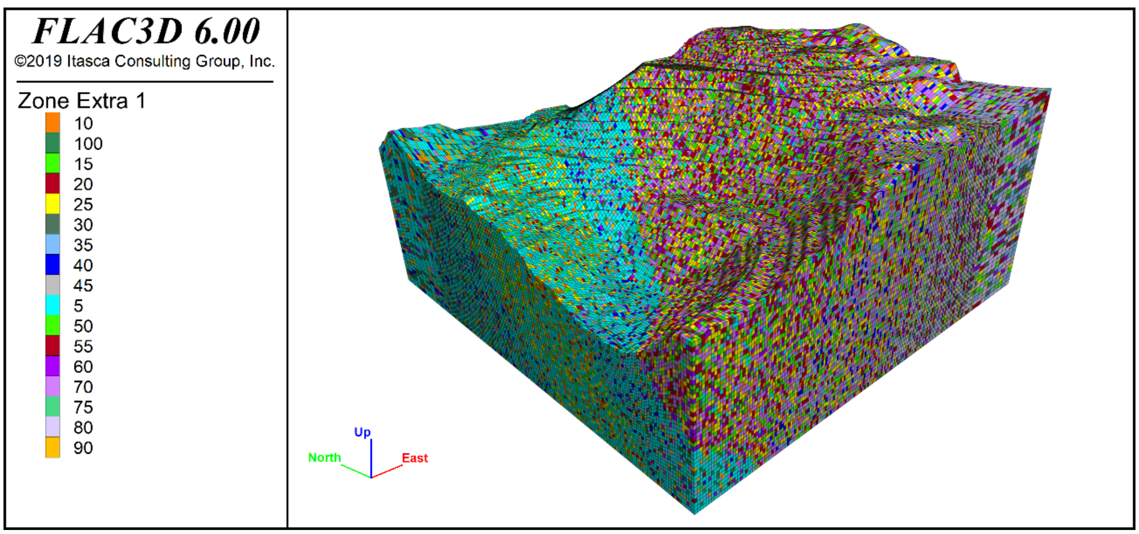

Figure 2. The results of GSI playing on the F_{GSI}^{*} in *FLAC3D*.

3 RESULTS AND DISCUSSION

Based on the proposed methodology for playing random variables, the PSA of one of the sections of the open pit of the Kumtor gold mine was produced. This assessment was made for two variants of the general angle of the slope. In the first variant, the value of the angle was 36 degrees, for the second variant 26 degrees. The first variant consists of 100 computational experiments and the second variant of 55. The minimum and sufficient amount of experiments performed for the implementation of statistical analysis was determined by the known Equation 1:

$$n_{min} = t^2\,\sigma^2/\delta^2 \tag{1}$$

where: n_{min} – the minimum amount of experiments required to provide the desired accuracy of the estimate ($\delta = 0.01$) FoS with reliability $\gamma = 0.99$; t – parameter determined by the Student's distribution for a given volume and a known standard deviation σ.

The laws of the distribution of FoS for each of the variants were determined. For the variant with general pit wall angle 36 degree it does not obey NDL due to the criteria of Kolmogorov-Smirnov p<0.2 and the criteria of Shapiro-Wilk p=0.0016<0.05. It turned out that the distribution of the random variable FoS is closest to the Weibull distribution law with parameters λ = 1.0264 and k = 37.067. The verification of the Weibull distribution hypothesis was carried out according to the criterion of agreement X^2. The observed value of X^2_{obs}= 2.48 turned out to be less than the critical X^2_{crit}= 14.07 at the significance level α = 0.05 with the number of degrees of freedom r = 7. The calculated probability of stability loss in the Weibull distribution was P (FoS <1) = 31.66%. For the variant with general pit wall angle 26 degree, FoS obey the NDL. The criteria of Kolmogorov-Smirnov p>0.2 and the criteria of Shapiro-Wilk p=0.278>0.05. For NDL with the values of mathematical expectation M (FoS) = 1.22 and standard deviation σ = 0.023, the probability of collapse was P (FoS <1) = 0.0%.

The stability calculation was performed for the average values of random variables. In this case, FoS = 1.275, which goes beyond the upper limit (1.26) of the confidence interval.

According to this method, the parameters of the Hoek-Brown criterion for the three-dimensional model of the pit wall in the *FLAC3D* program were played out. As a random variable, on the basis of which it is possible to produce a PSA of the pit, can be the magnitude of the displacements. If the displacements do not stop, it is considered that the pit wall is unstable. Otherwise, pit wall stability is considered to be ensured. In this case, the number of played variants in which the pit wall is unstable (n) referred to the total number of played variants (N) gives a relative collapse frequency (n / N), which can be considered as the probability of collapse.

4 CONCLUSIONS

The Monte Carlo method of playing random variables not obeying the NDL on the basis of the empirical distribution functions of these random variables gives a reliable result of a probabilistic assessment of the stability of the pit walls. The reliability of results is ensured by the capabilities of *FLAC*, which allows to fully automate all stages of probabilistic assessment of sustainability.

The stability of the pit walls is estimated directly by calculating FoS, which is a random variable. For the probability assessment P (FoS <1), it is necessary to know the distribution law of FoS, which is not always obeyed to the NDL. As studies have shown, the GSI parameter dominates the others and makes a decisive contribution to the law of distribution of FoS. This means that the law of distribution of the FoS of the pit depends primarily on the law of distribution of the GSI parameter and for each sector of the pit wall will be individual. Therefore, in order to avoid errors in determining P (FoS <1), it is necessary to reveal the theoretical distribution law for FoS. In those cases when it is not possible to select the theoretical distribution law, it is necessary to plot the distribution function FoS and determine the value of P (FoS <1) from the chart.

The decision on the stability of the pit wall is made on the basis of a comparison of P (FoS <1) with a given critical probability P_{crit} of the pit wall collapse. P_{crit} is set depending on the presence of infrastructure objects on the day surface located within the formed surface of a possible collapse. We believe that the most acceptable values of P_{crit} can be taken from 5% to 0%.

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