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Probabilistic assessment of slope stability at ore mining with steep layers in deep open pits

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Abstract

Purpose. A methodology development for predicting the geomechanical situation when mining an ore deposit with steep-dipping layers, taking into account the uncertainty in determining the rock properties, which is a consequence of the rock mass heterogeneity.

Methods. The assessment of the open-pit wall stability is based on a combination of numerical simulation of the rock stress-strain state (SSS) and probabilistic analysis. The finite element method is used to determine the changes in the SSS that occur at various stages of mining operations due to design changes in the overall open-pit slope angle. The elastic-plastic model of the medium and the Mohr-Coulomb failure criterion are implemented in the codes of the 3D finite element analysis program RS3 (Rocscience). Stochastic simulation is used to assess random risks associated with natural object state variations.

Findings. The distribution of maximum shear strains, which localizes the real or potential sliding surfaces in the open-pit wall at various stages of ore mining, has been identified. Based on the Shear Strength Reduction procedure, the open-pit wall Strength Reduction Factor (SRF) has been determined. The probabilities of open-pit wall stability loss, as well as the decrease in the strength reduction factor below the standard level at all stages of the ore body mining, have been revealed.

Originality. For the first time, for real mining-geological conditions of a deep ore open pit, the dependence of the strength reduction factor on the overall wall slope angle, which changes during mining of each steep layer, has been determined. For each stage of mining operations, for the first time, the probability of a decrease in the open-pit wall stability below the standard level has been determined based on stochastic simulation.

Practical implications. The ratio between the open-pit contour characteristic (overall slope angle) and the probabilistic safety factor is the basis for practical solutions to ensure the efficiency and safety of mining at various stages of friable and hard overburden excavation, ore extraction, as well as for the subsequent optimization of the open-pit design contours.

Keywords: *surface ore mining, slope stability, numerical simulation, probability, stochastic simulation*

1. Introduction

1.1. Problem formulation

The use of classical schemes for mining the steep ore bodies at depths of more than 400 m causes significant difficulties in maintaining the production capacity of open-pits [1]. Conducting mining operations along the entire perimeter of the open pit with longitudinal panels complicates the organization of their implementation [2]. The mining efficiency can be increased by concentrating mining operations on a relatively small area by forming a working zone with minimum sufficient dimensions [3]. In this way, the intensity of ore mining increases with the minimum current volumes of stripping operations [4]. Reducing the volume of stripping operations, as well as transferring them to later periods of production, is most often achieved by conservation of certain working wall zones with subsequent reactivation [5]. Practice shows that such a method of conducting mining operations is expedient with a relatively small production capacity of minerals [6].

In large open pits, the suspension of stripping operations in certain working wall zones, especially in round-shaped open-pit fields, leads to an annual increase in stripping backlog and a decrease in production capacity [7]. In the most unfavorable cases, a reduction in production capacity with a significant backlog of stripping operations can negate the benefits of surface mining method. The push back of permanent and temporary walls of deep open pits during the period of reconstruction and reactivation of mining causes significant technological difficulties. This is caused by the violation of transport links between the lower horizons and the upper ones, an increase in the transportation distance, as well as

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deterioration in safety conditions on the lower benches [8]. The study [9] indicates the need to form optimal profiles of temporarily non-working walls and to optimize the open-pit space. The management of the working zone during the period of conservation and formation of temporarily non-working walls, as well as during the reactivation of the walls, requires the creation of new methods and techniques for conducting mining operations in cramped conditions.

For such conditions, a mining method with steep-dipping layers is substantiated [1]. Changing the height of a temporarily inactive wall makes it possible to stabilize the volume of stripping operations and ensure the current stripping ratio, which is close to average. However, the concept of staged mining of deep open pits has been developed only for steep elongated deposits, while for round-shaped deposits it requires additional substantiation. Currently, the above method of mining ore with steep-dipping layers is tested in Kazakhstan under the conditions of the Kacharsky iron ore deposit. Unlike elongated open-pit fields, mining operations in a round-shaped open pit are conducted along the entire perimeter of an open pit in all its walls. In the study [7], the expediency of mining the benches with transverse panels along hard overburden rocks and ore is substantiated for these conditions. The implementation of mining with transverse panels is the most rational option for the operation of powerful excavator-automobile complexes, since the high-performance use of these complexes is achieved precisely on wide sites, where it is possible to switch from a dead-end turn of dump trucks to a loop for loading rock mass. Wide sites also make it possible to implement multi-row short-delayed blasting with the breaking front directed to the rock mass rear. Due to this, the number of collisions of rock pieces during blasting increases and their spread towards the mined-out space decreases.

Mining of benches with transverse panels makes it possible to increase the working zone slope angle, that is, to conduct mining with steep-dipping layers. In this case, the push back of the open-pit walls is significantly reduced and, accordingly, the current volumes of stripping operations are significantly reduced. However, increasing the slope angle in the working zone will increase the risk of the rock mass unstable state [10]. The risks of reducing the stability of the walls are relevant both in ore and coal open pits, as evidenced by kinematic analysis results given in the study [11]. Therefore, the introduction of new technical solutions that affect the issues of the limiting state of rock outcrops requires constant geomechanical support, both on the basis of instrumental control [12] and by mathematical modeling of the rock mass SSS at each stage of mining operations.

1.2. Review of research on assessing the stability of slopes in open pits

In design practice, methods based on the theory of limit equilibrium (Bishop, Yanbu, Morgenstern-Price, Maslov – Berer) [13]-[15] and the theory of limit analysis are still used to assess the stability of slopes [16], [17]. The authors in the work [18] describe a methodology that combines geophysical methods and modeling using the SLIDE program, which implements limit equilibrium analysis. Using the Flashres64 multichannel ultra-high-density electrometer, a weak layer of weathered rocks and a karst cavity have been revealed within the open-pit boundaries in southern China. However, direct modeling of the complex rock structure is impossible within the framework of the selected method. Therefore, the presence of a weak layer is taken into account indirectly, by reducing the strength rock mass properties based on the Hoek-Brown failure criterion, which is used further in the Slide calculation module.

In the work [19], it is also noted that engineering calculations when designing of surface mining in Australia are often based on limit analysis methods. However, the authors indicate that real cases of slope failure in open pits are associated with the structural peculiarities of the rock masses. In such cases, the numerical methods of solid mechanics (finite element method, finite difference method, discrete element method) are more efficient, since the rock heterogeneity can be taken into account in numerical algorithms directly, without using special techniques [20]. In the work [21], the soil displacement mechanism is studied both by limit equilibrium methods and by numerical simulation. Numerous examples of numerical simulation of the pit wall stability are given in the work [22]. The authors in the work [23] show the efficiency of the discrete element method in the analysis of the influence of geological disturbances on the stability of slopes in surface mining. Numerical analysis makes it possible to reveal the influence of each structural layer on the stability of rock outcrops.

In the work [24], it is noted that slope stability is a serious problem in surface and combined mining of copper ore. Therefore, empirical analysis and numerical modeling by the finite difference method using the FLAC 3D (Itasca) program are used in an integrated manner to predict slope stability. A methodology that combines numerical analysis and satellite radar interferometry is given in the work [25]. Here, the finite element method is used in 2D setting, implemented in the RS2 code (Rocscience). The possibilities of detecting unstable slopes and describing the mechanism of their destruction based on the FEM analysis are demonstrated at the site of a former mining enterprise in southern Spain. Finite element analysis in the implementation of the same software (an earlier version – PHASE 2) is successfully applied to analyze the stability of slopes in the South Brazil gold mine [26]. Similar approaches, but using 3D FEM analysis, are demonstrated in the work [27]. The authors show the advantages of 3D numerical modeling compared to 2D models.

1.3. Unsolved problem identification

The above review shows that the effective implementation of new technological schemes aimed at intensifying mining should be substantiated from the point of view of a safe stable state of rock outcrops, especially in terms of mining steep ore deposits. In this case, a rational cost balance can be achieved by mining the ore body with steep-dipping layers, that is, by forming outcrops, the stress-strain state of which is close to the limiting state. The operations organized in the conditions of the limiting state of the open-pit walls require not only constant physical monitoring of outcrops, but also a pre-calculation of stability at each stage of mining, that is, during mining of each subsequent steep layer. In other words, ensuring the safety of operations requires a current geomechanical prediction that is able to respond both to the planned changes in the bench angles, when deepening the open-pit bowl and to local challenges associated with unpredictable changes in the structure and properties of rocks, the complication of the hydro-geological situation, etc.

Modern numerical methods for assessing the rock SSS are a fairly proven tool for assessing the slope stability. The finite element method is the most used numerical method, which makes it possible not only to determine the rock SSS, but also to assess the effectiveness of geotechnical measures to strengthen rocks and soils [28], [29]. At the same time, most researchers note that despite the mathematical accuracy of the FEM and a wide class of problems to be solved, the reliability of numerical simulation and predicting on this basis the stability of outcrops is largely determined by the reliability of determining the rock properties [30], [31]. The well-known uncertainty in obtaining the mechanical characteristics of soils and rocks has been a subject of discussion in the field of geomechanics for many decades [32]-[34]. Researchers associate the variability of mechanical properties to the disturbance of the rock structure, in particular, to fracturing [35], as well as to the rock mass water-cut [36].

It follows from the above that the current prediction of changes in the state of rock outcrops under the influence of various mining-technical and mining-geological factors requires the use of effective 3D models for predicting stability, as well as risk assessment, which is impossible within the framework of deterministic models [37], [38]. The methodology for predicting the state of the open-pit walls at the stages of mining, where the ultimate limiting stress state of outcrops is reached, must necessarily be based on a stochastic model [39]. This research is aimed at developing such a methodology.

The research purpose is to develop a methodology for the current prediction of the geomechanical situation when mining an ore deposit with steep-dipping layers. The methodology is based on a combination of numerical (finite element) analysis of changes in the rock SSS caused by design changes in the overall open-pit slope angle, as well as stochastic simulation [40]-[42], which makes it possible to assess random risks associated with natural variations in the object state [43].

2. Materials and methods

2.1. Study area

Engineering-geological conditions of mining the Kacharsky deposit of magnetite ores are characterized by a thick stratum of friable deposits, the presence of weakening surfaces in the hard rocks, as well as systems of multidirectional fractures. The open-pit wall stability when mining with transverse panels in steep layers is assessed as a section close to profile #19 (Fig. 1). The design depth (horizon -570 m) is achieved by the organization of 25 stages.

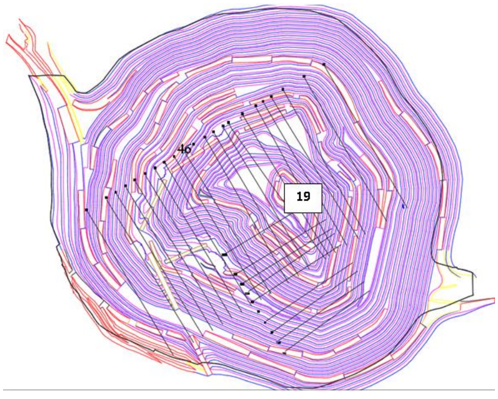

Figure 1. Plan of mining the Kacharsky open pit with the plotted section line #19

At each stage, the open-pit wall contour and the overall slope angle change, leading to a change in the rock mass stress-strain state, and, consequently, the degree of pit wall stability. The research objective is to assess these changes at each of the 25 stages of mining the ore body.

2.2. Numerical simulation of open-pit wall stability

Initially, a digital 3D representation of the ore body at each stage of mining was performed using the SURPAC software (Fig. 1), the files of which were then imported into the software for geomechanical 3D modeling RS3 (Rockscience), designed to calculate the stress-strain state (SSS) of rocks and assess the open-pit wall stability. The section at the 1st stage of mining is presented in Figure 2.

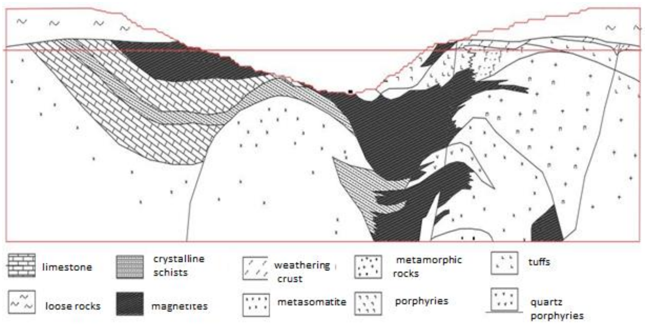

Figure 2. The Kacharsky open-pit section over the 19th profile at the 1st stage of mining

For the Kacharsky open-pit profile #19, at stages from 0 to 9, mining operations are performed until the transition of the limiting surface contour. The limiting surface contour is achieved at the 10th stage. To determine the mass SSS, the well-tested finite element method (FEM) mentioned above is used, implemented in the licensed code RS3 (Rocscience). The calculation scheme (Fig. 3a) includes the wall part, composed of overburden rocks and hard rocks. These rock layers are modeled based on the data on their thickness, occurrence parameters, as well as physical-mechanical rock properties.

(a)

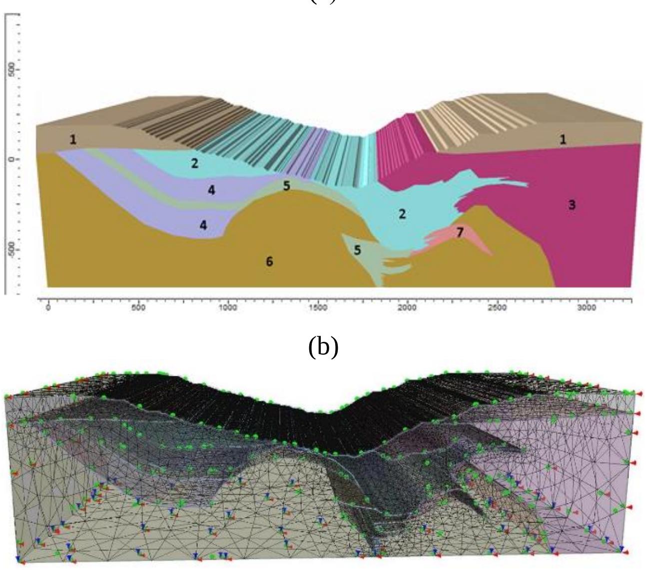

Figure 3. Geometrical pattern of the area (corresponds to the 1st stage of mining the ore body in the studied area of the deposit over the #19 profile): (a) the model of layers; (b) finite element model; 1 – friable rocks; 2 – magnetites; 3 – metamorphic rocks; 4 – limestone; 5 – crystalline schists; 6 – metasomatites; 7 – quartz porphyries

The calculation scheme changes at each subsequent stage, that is, during mining of each subsequent layer, caused by a change in the wall contour. Thus, the methodology of the current prediction provides for the creation of 25 finite element models, the difference of which is the wall geometry, as well as the ore layer configuration, which also changes as it is mined.

From the point of view of mathematical implementation, at each stage, the external contour of the model, free from fixing, changes. Other boundary conditions remain unchanged: the XY plane (model bottom) is fixed on the X, Y and Z axes; the YZ plane is fixed on the X and Y axes; the XZ plane is fixed on the Y axis. The finite element mesh of the model (Fig. 3b) is obtained by uniformly partitioning the area into 10-node tetrahedra. The number of elements for the above model is 267595. The coordinates of the model points, as well as the physical-mechanical properties of rocks and ore are the input modeling data (Table 1).

Table 1. Physical-mechanical properties of rocks and ore

Name of the rock	Cohesion, KPa	Specific weight, kN/m^3	Internal friction angle, degree
Limestones	475	27	36
Crystalline schists	450	26	31
Magnetites	910	38.7	34
Metasomatites	290	27.8	32
Porphyries	296	26.5	29
Friable rocks	40	18	28
Metamorphic rocks	450	28.3	31

The finite element analysis of the SSS is performed in an elastic-plastic formulation and the slope stability is assessed based on the Mohr-Coulomb yield criterion:

$$\tau = c + \sigma_n tg\varphi \,. \qquad (1)$$

where:

τ – tangential stress (shear stress);

σ_n – normal stress;

φ – internal friction angle;

c – cohesion.

The safety factor is determined by organizing the "Strength reduction" procedure, described in detail in [44], [45], according to which the FEM analysis is performed during n iterations. At each i-th iteration ($i = 1, n$), the initial strength parameters φ and c decrease by F_i times ($F_i = F_{i\text{-}1} + \Delta F$), where ΔF is the iteration increment, the value of which depends on the initial stability assessment in accordance with (1). If at the values of the strength characteristics φ / F_i and c / F_i, there is a loss of slope stability, the value of F_i is called the critical strength reduction factor, which is associated with the safety factor. In the FEM algorithm, the term "stability loss" means the geomechanical model collapse in the form of large irreversible deformations. In this case, from a mathematical point of view, there is a divergence in the solution of the system of "force-displacements" linear equations.

The calculation results at each iteration are the following rock stress-strain state components: normal and tangential stresses, longitudinal and shear strains, as well as the displacements of the study area points associated with them. Of greatest interest are the maximum shear strains, the localization of which is interpreted as a sliding surface.

2.3. Consideration of the variability of the rock properties. Analysis of random risks

As noted above, variability is an inherent property of natural materials, and rocks are no exception to this rule. It occurs as a result of various processes of formation and transformation of rocks, including diagenesis, fractional crystallization, change through fluid circulation, and metamorphism. All this has a local effect on the mechanical parameters of rocks, as a result of which there is an uncertainty in the physical-mechanical properties of the rock required for geomechanical analysis. Uncertainties also arise from the difficulty of measuring key geomechanical properties, such as the internal friction angle or cohesion. Any of these measurements has some error due to the sampling and preparation process, sensitivity and calibration of the measuring devices.

The direct result of the variable rock properties within the studied area is the variability of the strength reduction factor of the open-pit benches and the wall as a whole. To assess this variability, in this paper, a parametric study of the finite element model is performed, that is, a computational experiment is carried out in the selected range of input data (parameters). Simulation modeling of the open-pit wall stability is performed using the module of the RS2 licensed program, which allows organizing a simulation procedure for assessing the SSS within the determined range of the initial data variation, namely, the indicators of the strength and deformation properties of rocks. A two-point assessment method is used for the first and second statistical moments of uncorrelated variables. The points for assessing the random variables in this method are located at the level of ± standard deviation with respect to the mean value. The method requires 2k solution estimates, where k is the number of random variables.

At each stage of numerical modeling, the probability of a stable slope state is determined by assuming a normal distribution for all input and output random variables [46], [47]. The probabilities are calculated that the critical SRF will be less than1: $p\,(\text{SRF} < 1)$, as well as that the SRF will be below the standard level, that is, below than 1.3: $p\,(\text{SRF} < 1.3)$. Here $p(A)$ is probability of the event A.

3. Results and discussion

3.1. Numerical modeling of the rock mass SSS and assessment of the stability of the open-pit walls

Of practical interest is the assessment of the stability of the open-pit walls after reaching the open-pit limiting surface contour and the beginning of its deepening. Thus, at stage No.9, the potential sliding surface is displaced from the area of friable overburden rocks to the area of hard rocks (Fig. 4). With the resulting slope angle equal to 20º on the left wall of the model and 17° on the right wall, the minimum strength reduction factor (SRF) is 1.71. That is, it does not drop below the maximum acceptable level according to the design standards (SF = 1.3).

The next series of calculations is devoted to assessing the open-pit wall stability after the transition of the limiting surface contour by mining operations at stages No. 10-25. While, from the 10th to the 19th stages, the resulting open-pit wall angles increase insignificantly (from 20 to 25º), respectively, and the SRF decreases slowly, to a level of 1.65 at the 19th stage. Significant changes occur at the 20th stage of mining. SRF at this stage decreases sharply, immediately to a value of 1.59.

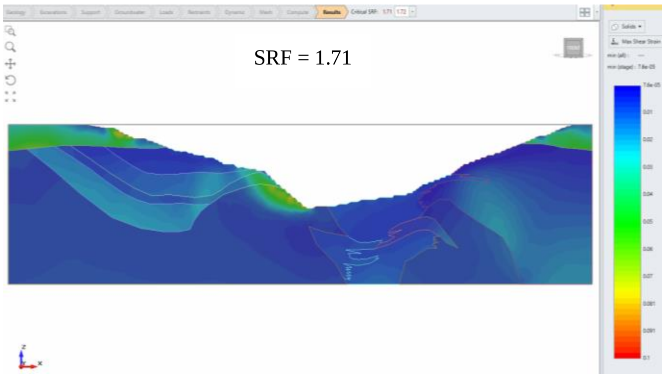

Figure 4. Distribution of maximum shear strains (potential sliding surface – green color) at the 9th stage of mining

The potential for the sliding surface development not only remains in the left wall (in the area of the steep ore layer), but also appears in the right wall of the model (Fig. 5). This is conditioned by the suspension of mining operations in the open-pit area corresponding to the left wall of the model, and the development of mining operations in the right wall.

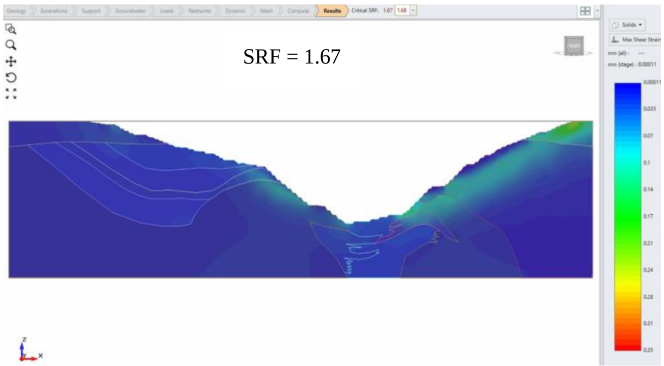

Figure 5. Distribution of maximum shear strains (potential sliding surface – green color) at the 19th stage of mining

At the subsequent stages No. 21-25, the mining space continues to deepen, the overall slope angle increases, and, accordingly, an intensive decrease in SRF occurs, the value of which at the final stage is 1.42. At these stages, the distribution pattern of displacements and shear deformations, associated with the ore layer mining in the right wall, changes. Now it is here that the potential sliding surface is localized (Fig. 6).

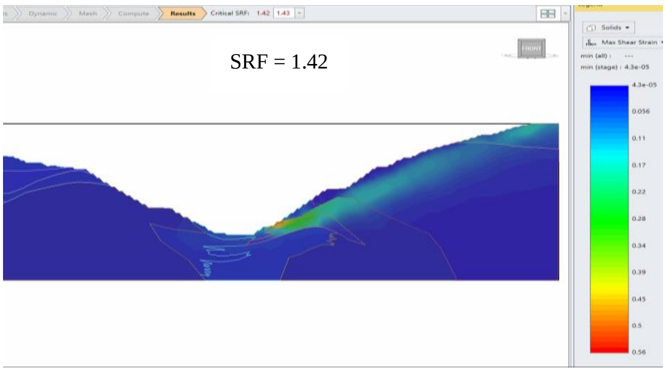

Figure 6. Distribution of maximum shear strains (potential sliding surface – green and yellow colors) at the 25th (final) stage of mining

The graph of the change in the strength reduction factor (Fig. 7) shows that when the overall slope angle increases from 17^0 at the 1st stage of mining to 30° at the 25th stage, the SRF decreases from 1.89 to 1.42.

It is important that at the final stage of mining the ore layer, the SRF of the open-pit wall does not drop below the maximum standard value of 1.3.

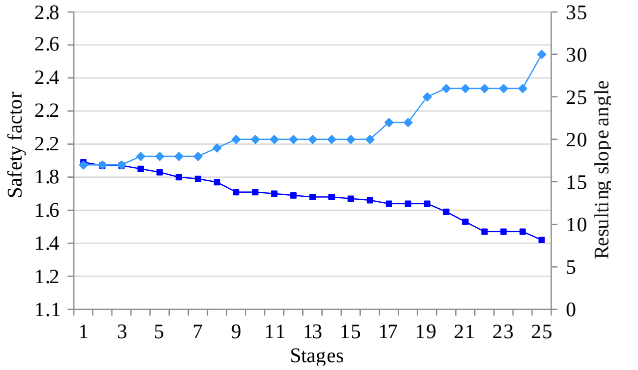

Figure 7. Changes in the resulting slope angle and the corresponding strength reduction factor (SRF) values at all stages of mining operations

It should be noted that this result has been obtained for the calculation scheme that includes rock layers with specified mechanical properties, that is, within the framework of a deterministic model of the environment without taking into account the possible initial data variation. A well-known fact is the stochastic variation in the rock properties, due to their heterogeneity, and observed as a result of testing rock samples in the form of a variation of physical-mechanical characteristics even within the same lithological variety. Since the assessment of outcrop stability is directly related to what rock properties are entered into this assessment procedure, the strength reduction factor should also be considered as a stochastic value, for which an appropriate range of variability should be indicated, depending on the variability of the rock properties.

3.2. Stochastic simulation of rock properties variability. Probabilistic assessment of the strength reduction factor

It is noted above that a multivariate simulation algorithm can only be implemented in a 2D setting, since it requires a large amounts of RAM and computational time. It should also be emphasized that within the framework of the plane deformation hypothesis (2D model), the strength reduction factor is lower than in the 3D model. In the work [44], a correction factor has been obtained for recalculating the results obtained for different calculation schemes:

$$k_{3D} = \frac{SF_{3D}}{SF_{2D}} = 1.08\,, \qquad (2)$$

where:

SF_{3D} – strength reduction factor (SRF), obtained as a result of 3D modeling;

SF_{2D} – strength reduction factor, obtained as a result of 2D modeling of the same open-pit profile. Taking into account this coefficient, all the simulation analysis results have been corrected.

Probabilistic assessments have been performed for all mining stages along profile #19, that is, for each mined steep layer. The initial data variation (the internal friction angle and the cohesion) is set within 20%.

Of greatest practical interest is the assessment of the risks of stability loss at the final 25th stage of mining (level – 570 m). When the maximum mining depth is reached, the mean (first order moment) for SRF is m_{SRF} = 1.21; the mean square deviation is 0.063.

The probability of realization of sliding on the surface presented in Figure 8 is 12.55%. The probability that the SRF will be lower than the design one, that is, below 1.3, is: $p(\text{SRF} < 1.3) = 95\%$.

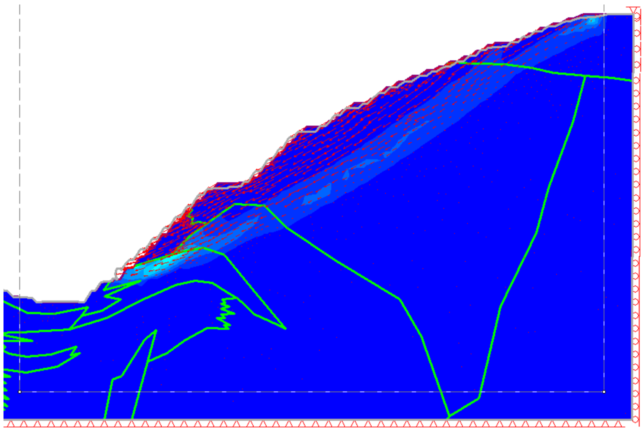

Figure 8. Displacement vectors and sliding surface at SRF equal to the mean (m_{SRF} = 1.21)

The probability of a decrease in SRF below the design level varies at each stage of mining (Fig. 9), which is conditioned by a change in the geometry of the benches and the overall slope angle of the walls.

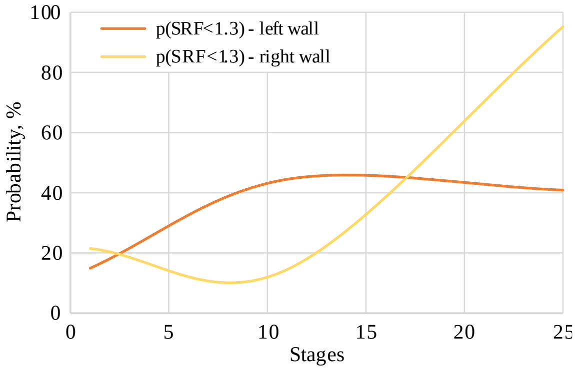

Figure 9. Probability of a decrease in SRF below the design level at various stages of mining operations

The probability of a decrease in the open-pit western wall stability (right wall of the model) below the design level increases intensively after the 10th stage, that is, with the beginning of the open pit deepening into the hard rocks. This fact should be taken into account when designing the staged open-pit contours. If the deterministic calculation shows that at the final 25th stage of mining, the wall is sufficiently stable (with a safety factor of 1.42), then, taking into account the possible variation in the rock strength properties, there is a high (at the level of 95%) probability of a decrease in stability below an acceptable level. The risk of stability loss can be mitigated by changing the order of mining soft and hard overburden so that after the 20th stage, changes in the overall slope angle of the wall do not lead to a decrease in SRF. Another solution to the issue can be measures to strengthen fractured rocks in areas where the SRF is less than the standard value. In particular, technologies for injection of polymer resins and rock bolting can be used [48]. In any case, the determined dependences of the change in the safety factor for each mined layer of rocks and ore is the basis for subsequent open-pit contour optimization [49].

Thus, the development of new technological schemes in mining ore bodies requires the geomechanical situation assessment with each change in the staged open-pit contours. In addition, to eliminate geomechanical risks at the final stages of mining, a probabilistic slope stability analysis is required. The performed computational experiment makes it possible to simulate a stochastic combination of unfavorable factors that influence on the strength properties of rocks: presence of fracture systems, water cut, proximity of large geological faults [50], and propagation of natural fractures under the influence of operating mechanisms [51]. These risks should be taken into account when designing mining operations. Stochastic simulation offers additional opportunities in the field of design along with field observations and laboratory research [52].

4. Conclusions

The assessment of the open-pit wall stability is an integral part of designing the open pit. The development of modern digital technologies makes it possible to recreate in geomechanical models all the details of the open-pit contours, the rock mass geological structure, as well as the stages of mining developing. This paper shows an effective combination of digital representation of the staged open-pit contours in the SURPAC program and numerical simulation of the stress-strain state of rocks using the finite element method in the RS2 and RS3 software codes from Rocscience Company.

Modeling of 25 stages of mining a steep ore body is an imitation of a quasi-static change in the open-pit wall stability as it deepens. Staged modeling makes it possible to quickly assess the geomechanical situation depending on changes in the open-pit contour as mining operations develop. In particular, it is shown that when changing the overall slope angle of the wall from 17° at the 1st stage of mining to 30° at the 25th stage, the strength reduction factor decreases from 1.89 to 1.42. An important result is that at the final stage of mining the ore layer, safety factor does not drop below the maximum standard value of 1.3.

Despite the optimistic result described above, the risks associated with the uncertainty in determining the strength properties of rocks, in particular, cohesion and the internal friction angle, should take into account. The variability of these values is caused by the rock mass heterogeneity and manifests itself when testing rock samples in the form of a stochastic variation of values relative to the average. In this research, stochastic simulation has been performed, the basis of which is the variation of the initial data within 20%. For the 25th stage of mining, the average value for SRF is $m_{SRF} = 1.21$, the mean square deviation is 0.063. The probability of slope stability loss is 12.55%. The probability that the SRF at this stage will be below the standard one (1.3) is 95%.

The assessed risks should be taken into account when designing mining operations. In particular, for the simulated profile #19, the risk of stability reduction can be mitigated by changing the order of mining soft and hard overburden after the 20th stage of mining in order to reduce the wall overall slope angle.

The modeling results can be used to develop measures to strengthen fractured rocks in areas where the SRF is less than the standard value. The determined dependences of the change in the safety factor for each mined layer of rocks and ore is also the basis for the subsequent optimization of the staged open-pit contours.

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Ймовірна оцінка стійкості укосів при видобутку руди крутопохилими шарами в глибоких кар’єрах

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Мета. Розробка методики прогнозу геомеханічної ситуації при відпрацюванні рудного покладу крутими шарами з урахуванням невизначеності у знаходженні властивостей гірських порід, що є наслідком неоднорідності породного масиву.

Методика. Оцінка стійкості борту кар’єру заснована на комбінації чисельного моделювання напружено-деформованого стану (НДС) масиву та ймовірнісного аналізу. Методом скінчених елементів визначено зміни НДС, які мають місце на різних стадіях видобувних робіт внаслідок проектних змін генерального кута укосу кар’єру. Пружно-пластична модель середовища та критерій міцності Кулона-Мора реалізовані в кодах програми скінчено-елементного 3D аналізу RS3 (RocScience). Стохастичне моделювання застосовано з метою оцінки випадкових ризиків, що пов’язані з природними варіаціями стану об’єкта.

Результати. Встановлено розподіл максимальних зсувних деформацій, що локалізує реальну чи потенційну поверхні ковзання в борті кар’єру на різних стадіях відпрацювання руди. На основі процедури зниження зсувної міцності (Shear Strength Reduction) встановлені показники запасу стійкості борту кар’єру (SRF – Strength Reduction Factor). Визначено ймовірність втрати стійкості борту карєру, а також зниження показника стійкості нижче нормативного рівня на всіх етапах відпрацювання рудного тіла.

Наукова новизна. Вперше для реальних гірничо-геологічних умов глибокого рудного кар’єру встановлена залежність показника запасу стійкості від генерального кута укосу борту, що змінюється при відпрацюванні кожного круто нахильного слою. Для кожного такого етапу гірничих робіт вперше визначено можливість зниження стійкості борту кар’єру нижче нормативного рівня на основі стохастичного моделювання.

Практична значимість. Співвідношення між характеристикою контуру кар’єру (генеральний кут укосу) та імовірнісним показником стійкості є основою для практичних рішень щодо забезпечення ефективності та безпеки відкритих гірничих робіт на різних етапах відпрацювання рихлого та скального покриття, видобування руди, а також для подальшої оптимізації проектних контурів кар’єру.

Ключові слова: *видобуток руди, стійкість укосу, чисельне моделювання, ймовірність, стохастичне моделювання*