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Numerical modelling of the pit wall stability while optimizing its boundaries to ensure the ore mining completeness

Olena Sdvyzhkova [1], Serik Moldabayev [2*], Dmytro Babets [1], Atac Bascetin [3], Gulnur Asylkhanova [2], Assel Nurmanova [2], Vira Prykhodko [1]

[1] *Dnipro University of Technology, Dnipro, Ukraine*
[2] *Satbayev University, Almaty, Kazakhstan*
[3] *Istanbul Technical University, Istanbul, Turkey*

**Corresponding author: e-mail s.moldabayev@satbayev.university*

Abstract

Purpose is to assess changes in the stress-strain state of walls along the whole periphery of a super-deep open pit while optimizing its current and final boundaries for the complete ore excavation.

Methods. Finite element 3D analysis of stress-strain state (SSS) of the soil and rock mass relies upon the models varying in their scales. Macrolevel model includes the full pit helping perform initial evaluation of its stability depending upon changes in the general wall slope along the pit periphery. Then, the macromodel is separated into sectoral models with smaller scales oriented radially in such a way to include potentially unstable wall areas. The sectoral models make it possible to show the complex bench line in more detail after the peripheries were optimized in terms of economic factor and simulate layered structure of the rock mass. Elastoplastic model of the medium as well as Mohr-Coulomb strength criterion has been implemented using RS3 (Rocscience) program codes.

Findings. An indicator of wall strength (safety factor) distribution along the pit periphery has been identified; potential sliding surfaces within each of the separated open pit sectors have been localized based upon the shear strength reduction (SSR) procedure. Influence by the general wall slope as well as by the indicator of the ore excavation completeness on the stripping ratio has been demonstrated.

Originality. For the first time, two-level modelling has shown difference in a safety factor depending upon a model scale and a reflection degree of the soil-rock mass structure. In the context of the actual mining and geological conditions of Kacharsky open pit, changes in the safety factor along the pit periphery have been identified depending on the general slope of the wall.

Practical implications. Based upon the pit wall stability along the whole periphery, the possibility has been substantiated to optimize its design boundaries for the excavation of those amenable ore reserves, occurred near them, inclusive of ore, occurring in a bottom, which mining is impossible due to inaccessibility.

Keywords: *ore excavation, deep open pit, numerical modelling, final boundary optimization*

1. Introduction

In the context of valuable mineral exploration, driving the modern world, open pit excavation is rather an important mining technique. Currently, optimization of open pit extraction is playing a key role. All stakeholders of mining industry are working toward a common goal, i.e. minimization of the final production cost of ore [1]-[3].

The problem-solving needs the balanced approach involving decrease in stripping ratio as well as prevention of an open pit wall flattening [4]. In light of natural resource friendliness and minimization of damage to natural landscape, it becomes quite important to perform complete excavation of ore body [5]. The latter means preventing from the fact that some share of the deposit in the neighbourhood of the open pit boundary remains unrecovered.

While talking of the reserve mining completeness, the majority of researchers substantiate expediency of transition to underground ore extraction. For example, authors of paper [6] denote that some of the world largest open pits will consider the possibility to move to underground mining owing to the chance to get access to the increased reserves and extend operation period of an open pit. Papers [7], [8] evaluate transition to underground mining using such indicators as producing rate and operating efficiency, working and capital costs, mineral value and income per ton of ore, and initial rate of return on investment. It should be mentioned that sometimes the certain share of ore body is near the open pit periphery while staying beyond boundaries of its initial design. The problem is to mine the ore body share in such a way to prevent from the open pit wall flattening [9] and ensure work safety where the open pit becomes deeper.

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Schematically, a vertical ore body within an open pit is represented as a quadric cylinder [10] or as a rectangular prism inside the truncated cone (Fig. 1). In the latter case, some share of the deposit is beyond the open pit boundary, and it cannot be extracted for a variety of reasons. Minimization of the deposit share volume (parameter V_0 in Figure 1) becomes the strategic step to reduce the total mining cost.

It is obvious that the general slope of the open pit wall γ plays the key role while achieving balance between the output and operational safety. The larger the slope γ is, the smaller the open pit wall as well as stripping ratio is, and the less prime cost of the ore is. Nevertheless, greater amount of border rock remains unmined. Hence, it results in the loss of profit by the enterprise and irrational use of the subsoil. The most important factor, being the wall stability, depends upon the slope which control means safe operation of both personnel and mechanisms.

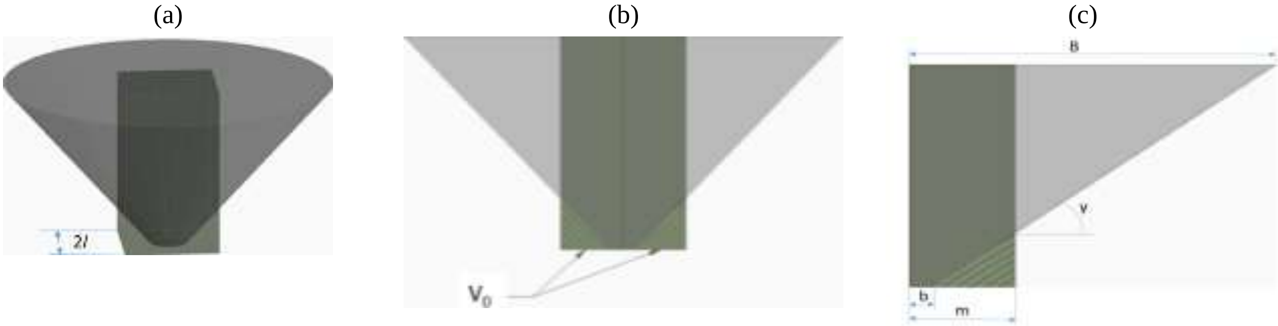


Figure 1. Idealized scheme of the mutual positions of ore body and open pit boundaries: (a) three-dimensional representation of intersection between the open pit bowl and ore body; (b) a plane section of an area including border zone of the ore deposit; (c) analytical model to identify V_0 volume of the border rocks

The balance between geometry of benches and berms, controlling functionality of excavation stability, and decrease in the overburden amount, on the other hand, is the key moment to construct both the current and final open pit boundaries. Various algorithms as well as software, based on them, are applied to define the optimum alternative. Among other things, 3-D Lerchs-Grossman approach is used in a Whittle program [11]. Authors of [12] describe practices to construct digital boundaries of an open pit by means of the Whittle soft combined with SURPAC program. In terms of each variant of an open pit peripheries, detalized with the help of Surpac, economic characteristics are identified which comparison proposes the most reasonable design. The well-known *floating cone* algorithm has been improved in paper [13]. Authors of paper [14] suggest their own methods for the automated construction of an open pit boundaries providing the most profitable economic indicators. Multi-criteria evaluation with the use of PROMETHEE II and AHP programs, implementing multi-criteria decision-making (MCDM) approach has been demonstrated by [15], [16] papers.

However, the majority of the cited papers ignore influence of the key factor, being the basis of optimal design, i.e. a wall slope providing adequate stability. The matter is that together with physic-mechanical characteristics of rocks, being components of an open pit wall, the wall geometry as an aggregate of benches, berms, and ramps, is the fundamental factor making it stable [17]-[19].

Paper [20] concerns stability of an open pit walls during its long-term operations under successive removal of semi-steep layers. Nevertheless, changes in wall stability have been considered only in terms of one section despite the fact that the research subject is a round-shaped open pit and it is of interest to analyze wall stability as a whole throughout the open pit perimeter, especially while reconsidering the object design focused on the complete excavation of the reserves.

Paper [21] emphasizes the importance of simultaneous optimization of design periphery of an open pit as well as evaluation of slope stability. Authors of the paper denote that due to the risks of catastrophic slope failure, the stability slope analysis is an integral component of engineer projects of any open pit. Unfortunately, rather often original design concepts and geotechnical evaluations are considered separately. Authors of papers [22], [23] also focus on wall slope stability under their geometry optimization.

Purpose of the represented paper is to optimize open pit boundary involving in mining the largest amount of periphery reserves with simultaneous modelling of stress-strain state (SSS) of the open pit walls as well as their stability evaluation based upon numerical methods. Among other things, finite element method, being well-developed and applied successfully to evaluate wall stability [24]-[26], is applied to define SSS of open pit walls.

2. Methods and materials

2.1. Evaluation of the influence of an open pit wall slope on the volume of periphery rocks

Relying upon the idealized model, shown in Figure 1, periphery rock volume V_0 is the difference between the prism amount volume (i.e. ore body) and the cone volume share (i.e. open pit) from the bottom up to the prism and cone cross-point. The point ordinate:

$$h_{nep} = \frac{H}{B-b} \cdot (m-b) = \tan\gamma \cdot (m-b), \quad (1)$$

is defined from intersection of the cone generator and a line coinciding with the prism face. The difference between the prism volume with h_{int} height and $4ml$ area ($2l$ is the ore body length), and the truncated cone with analogous h_{int} height, larger radius m, and smaller radius b will be:

$$V_0 = m^3 \cdot \tan\gamma \cdot \left(4\frac{l}{m} - \frac{\pi}{3} \cdot \left(r^2 + r + 1\right)\right). \quad (2)$$

In this context, $r = b / m$ ratio characterizes the ore body share being mined when the open pit bottom is being achieved. It is obvious that open pit wall slope γ and r coefficient, showing the share of peripheral rocks which cannot be mined, are the main parameters identifying difference of the mentioned volumes.

Increase in the ordinate of the wall slope upsizes the ordinate h_{nep} of the prism and cone intersection; hence, increase in the volume of the unmined peripheral rocks takes place. On the other hand, it has been mentioned above that increase in the wall slope will decrease the open pit width 2*B*, and, hence, stripping ratio will decrease as well. Apparently, there is some compromise decision as for selection of economically feasible wall design slope γ. Nevertheless, stable outcrop under the geological conditions should be the key factor in this regard.

2.2. Design of the open pit boundaries

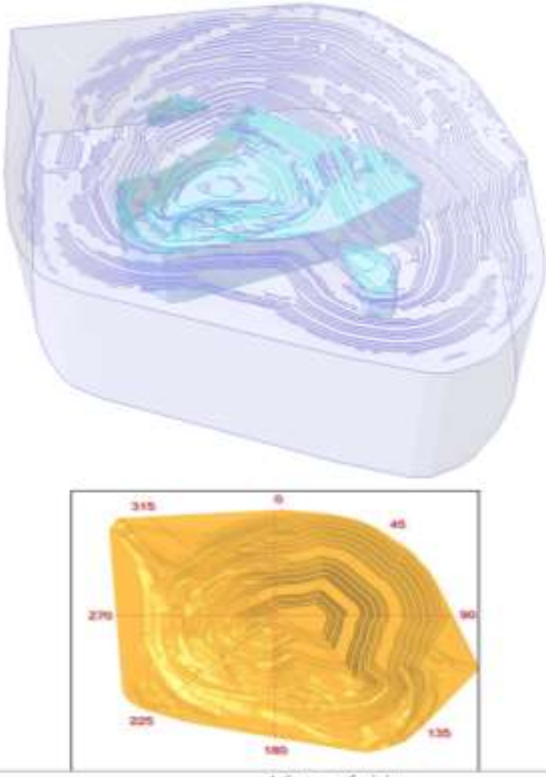
Boundaries are optimized and wall stability of a super-deep open pit is evaluated for Kacharsky deposit of magnetite ore located in the north of Kazakhstan (Kostanay Region). In plan, the open pit shape approaches a circle. By the end of mining operations, dimensions have been the following: 3000-m length over the surface (latitudinally; 2900-m width over the surface (meridionally); 430-m bottom length; 175-m bottom width; 723-m open pit depth; and 530-m elevation of the open pit bottom. The ore body mining takes 25 stages through excavation of 25 inclined layers.

Mining plan correction as for excavation of amendable and almost inaccessible ore generated the necessity to develop alternative digital open pit contours using SURPAC software. Bench line has been corrected in such a way to involve maximally the whole ore body especially in the bottom part of the open pit. Optimal alternative has been selected of 10 designed variants since it provides the best economic indicators. Further, while transforming 3D AutoCAD files, the digital pit boundaries are exported to a program calculating SSS characteristics of the rock-soil mass, and evaluating wall stability. Figure 2 shows the open pit boundaries during stage 4 of mining when the open pit depth is 300 m.

Similar digital models have been developed for each following stage of the ore body mining. The next step is export of the digital model to SSS calculation module to understand whether changes in the open pit boundaries influence wall stability; especially, whether boundary optimization stipulated decrease in the stability margin. For the purpose, digital representation of the open pit boundaries is used to construct a geomechanical model demonstrating actual structure of the rock mass, physic-mechanical characteristics of rocks, and loading and consolidating in terms of boundary problem of mechanics of solids.

2.3. Geomechanical modelling

SSS for peripheral rock mass in a super-deep Kacharsky open pit is calculated using finite element method (FEM). Authors of paper [27] believe that under the conditions of the current progress of computer facilities, preference should be given to 3D numerical models for complete consideration of stress and strain tensors defining wall stability. It is especially important for such circular open pits as Kacharsky pit. Authors of paper [28] have applied algorithm of finite differences, implemented in FLACK 3D software, and also proved advantages of spatial identification of rock mass SSS while evaluating open pit wall stability. Hence, the license RS3 Rocscience software, to which digital 3D boundaries of the open pit have been exported, was used to develop the finite element model.



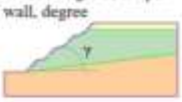
4-th stage of mining								
Cross-section angle, degree	0	45	90	135	180	225	270	315
Overall angle of the pit wall, degree 	20.38	18.6	18.47	14.16	19.85	19.38	18.82	18.71

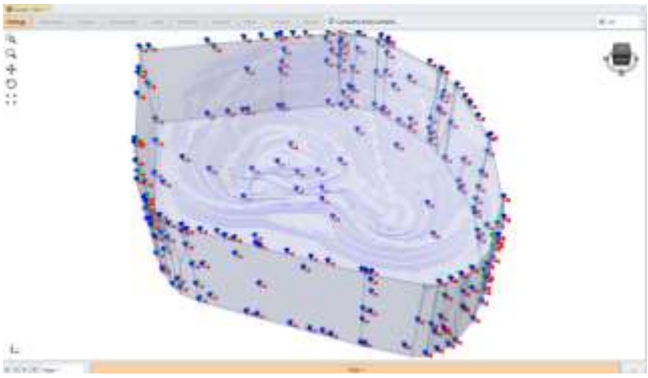
Figure 2. Optimized open pit boundaries involving the whole ore body within bottom of the quarry

The paper proposes a new approach, involving two level of model construction. Algorithm of such a two-level modelling consists of two stages:

Stage 1. Development of the generalized numerical model of the whole pit bowl (macrolevel model) which finite element mesh consists of large tetrahedral elements with 40-50-m linear size (admissible number of finite elements is 1-1.5 mln) making it possible to represent integrally its geometry throughout the perimeter (Fig. 3). Within the stage, homogeneous rock mass is simulated to reduce the number of internal borders. As for calculation period and the occupied computer memory, the model efficiency helps evaluate primarily the pit wall stability throughout its perimeter, and demonstrate hazardous areas stipulated by the overall wall slopes throughout the quarry perimeter.

Stage 2. The open pit bowl sectorizing using the principle of potentially hazardous area coverage. The sectors are separated by means of vertical planes coming fan-shapedly from the pit centre (Fig. 3b). In such a way, smaller models are constructed. Each separated sector should involve completely the potential instability zone. The decreased model scale makes it possible to reduce size of the finite tetrahedral elements down to 10-15 m, and make the mesh denser. At the stage, all available geological information is introduced concerning weak interlayers, faults, and fractures. In addition, physical and mechanical characteristics of ore and overburden are also introduced. Moreover, the stage involves rock mass SSS and safety factor recalculation considering varying layer stiffness.

(a)



(b)

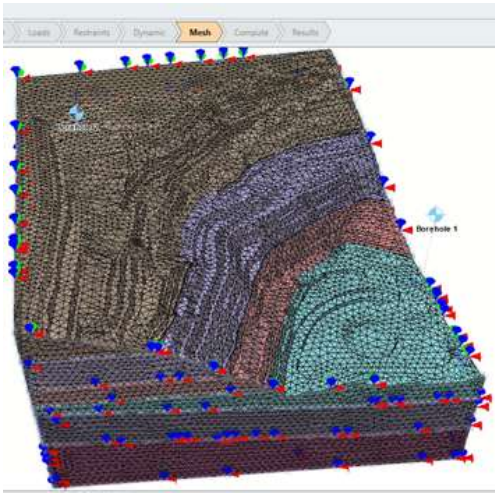


Figure 3. 3D macrolevel model of Kacharsky open pit involving ore bodies: (a) finite element mesh and boundary conditions; (b) separated sector model

Relying upon the sectoral models, deformation processes within the layered rock mass is analyzed in detail. Zones of potential formation of slip planes are localized which could not be identified on the macromodel of the whole pit bowl.

While simulating the three-dimensional rock mass area, boundary conditions are defined through the attachment of the model movements: XY plane (being the model bottom) is attached on X, Y, and Z axes; YZ plane is attached on X and Y axes; and XZ plane is attached on Y axis. Finite element SSS analysis of the rock-soil mass is performed in elasto-plastic formulation based upon Mohr-Coulomb failure criterion [29] widely used in geomechanical problems along with the Hoek-Brown failure criterion [30]-[32]. The open pit wall stability is evaluated through shear strength reduction procedure specified in [28], [33].

The method assumes that after the model has been developed, shear strength of all material components either increases iteratively or decreases by strength reduction factor (SRF) times until the model collapse being a sharp displacement change within the monitored point as well as the iteration process divergence while solving the basic FEM equation system. In such a way, SRF value shows how many times rock-soil strength should be changed to give rise to a slope failure, i.e. it is the analogue of a safety factor (SF). Namely, SRF coefficient will be further analyzed as the key value characterizing the pit wall stability.

In the context of the macromodel, the homogeneous rock mass is characterized by following physic-mechanical properties: cohesion is 475 kPa; friction angle is 36º; and Young's modulus is 4.65 GPa. As for sectoral models, physic-mechanical characteristics of rocks and soil are sized in accordance with Table 1.

Table 1. Physic-mechanical rock characteristics

Rocks	Cohesion, kPa	Friction angle, degrees	Young's modulus, GPa
Magnetites	910	34	7.0
Metasomatites	290	32	9.0
Porphyrites	296	29	7.3
Limestones	475	36	4.65
Crystalline schists	450	31	6.1

The ore zone is of a complex structure; it consists of lens-shaped and thick sheet-like body. The deposit thickness is 200 up to 350 m. Within different areas of the open pit, ore reserves (i.e. magnetites) are localized at 150-570-m depth. For the most part, porphyrites, crystalline schists, and metasomatites, which thickness is 40-100 m, occur over them. Limestones occur at 50-100-m depth. Their thickness is 20-50 m.

3. Results and discussion

3.1. Evaluation of the open pit walls under the optimized current and final boundaries of the pit

The open pit bowl (macrolevel model) was simulated for each mining stage, which means removal of yet another near-vertical layer. RS3 software analyzes stresses and strains within each point of the rock mass using FEM together with Mohr-Coulomb strength criterion and identifies the minimal of SRF throughout the open pit perimeter. The minimum values are associated with zones of the greatest shear strains as well as the largest total displacements (Fig. 4). During mining of the first three inclined layers when loose overburden is excavated, the overall slope wall γ is not more than 17º throughout the open pit perimeter which maintained rather high wall stability. At the first 3 stages, SRF experiences minor changes, i.e. 2.6-2.52. However, distributions of total displacements within each stage, represented in a colour scale, differ. Areas of the largest displacements (red), which may arise potentially if shear strength decrease is 2.6-2.52 times (according to SRF = 2.6-2.52), are localized in the north-eastern and eastern parts of the open pit at stages 1, 2, and 3.

At stage 4, when overall slope angle within the northern and southern parts of the open pit increases up to 19-20º, SRF drops down to 2.23 value (Figs. 4 and 5). The largest displacement zones are almost symmetrical within the northern and southern parts of the open pit.

It should be mentioned that observational benchmark stations, mounted in 2022 within the southern share of the open pit wall (elevation +194 m / +85 m) helped record horizontal 16-mm displacement in the line of a local profile. In this regard, other benchmark stations, arranged throughout the open pit perimeter, recorded neither horizontal nor vertical deformation; hence, the rock mass is completely stable. Consequently, the numerical modelling result is confirmed concerning the fact that potential instability is more probable within the southern share of the open pit.

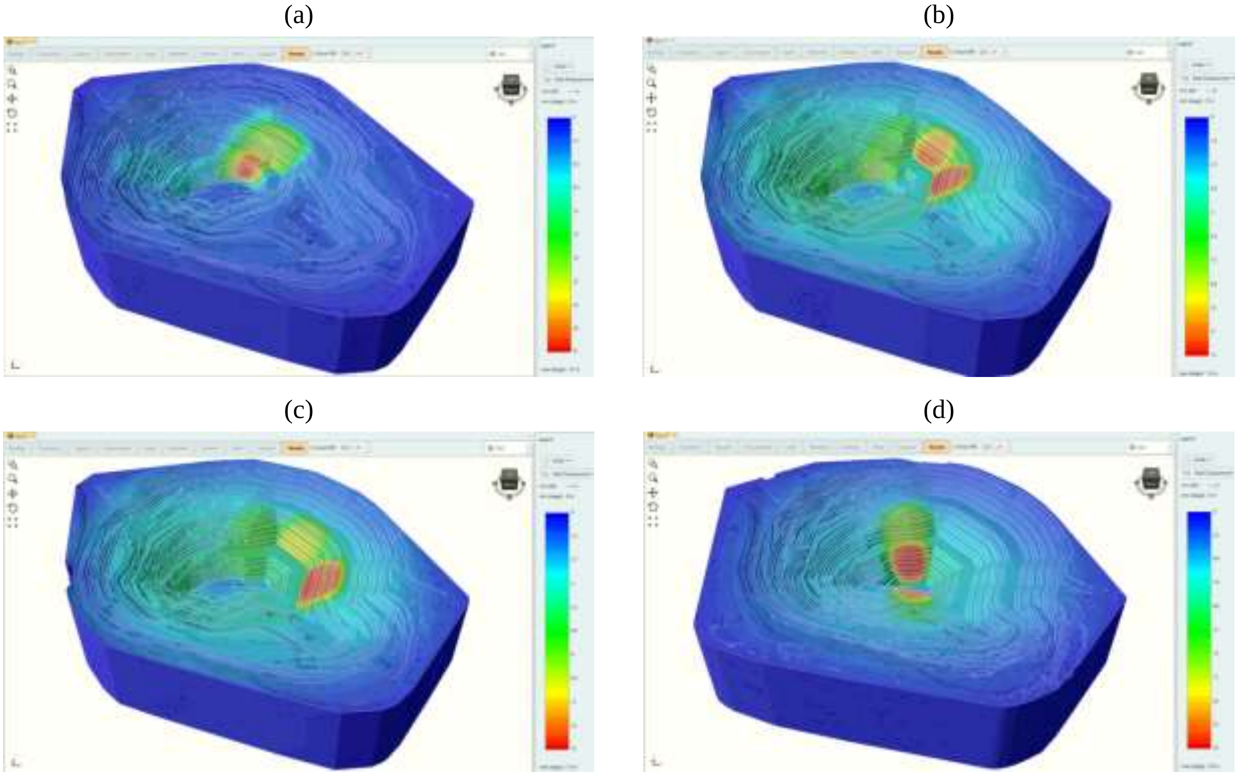


Figure 4. Distribution of displacements within macrolevel model walls: (a) stage 1; (b) stage 2; (c) stage 3; (d) stage 4

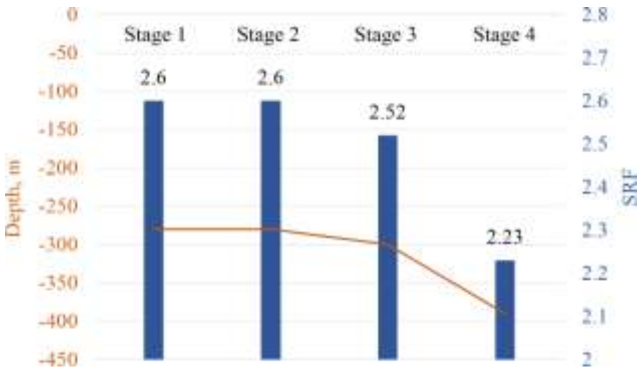


Figure 5. Change in the minimal SRF throughout the open pit perimeter at first 4 stages of inclined layer mining

Relying upon the obtained potential distributions of displacements and the slip plane localization, we have divided the model of mining stage 4 into the eight sectors: northern (N); northwest (NW); western (W); south-western (SW); southern (S); south-eastern (SE); eastern (E); and north-eastern (NE) (Fig. 6). As a result, eight sectoral finite element models have been obtained making it possible to analyze rock SSS in more detail taking into consideration boundaries of layers and assigning various physic-mechanical characteristics.

Analysis of the simulation results, based upon the sectoral models, has shown the following. Expectedly, SRF values vary for different sectors (Fig. 7), i.e. for different parts of the open pit. The abovementioned depends upon differing geometry of bench line as well as upon various layer shapes.

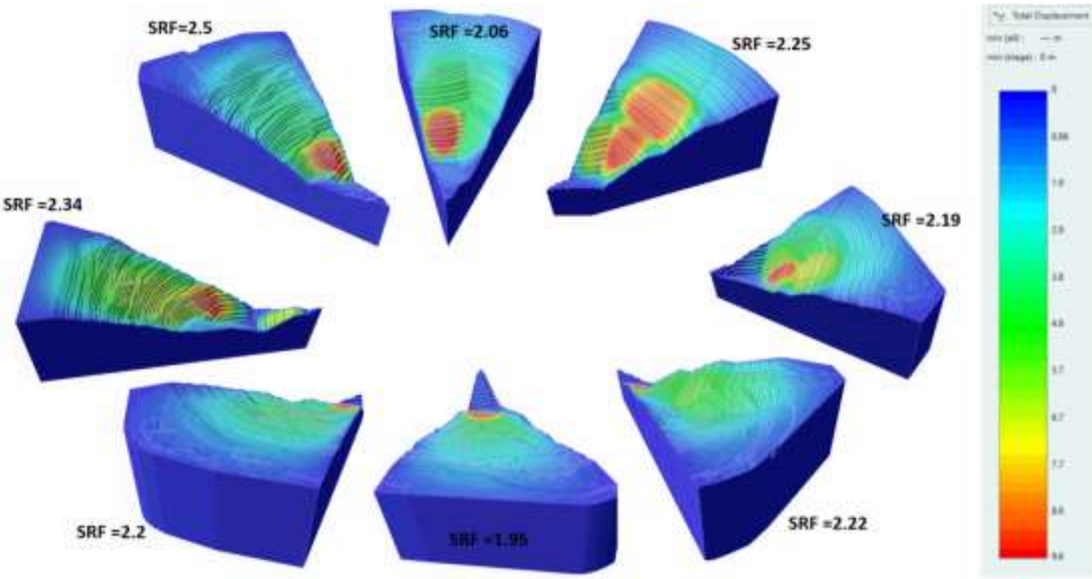


Figure 6. Distribution of displacements, localization of slip planes, and SRF identification for sectoral models of mining stage 4

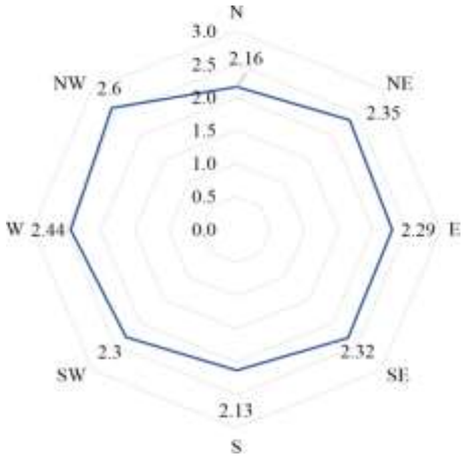


Figure 7. SRF distribution over the sectors for mining stage 4

Potential slip plane, associated with the greatest total displacements, have been located for each sectoral model. The difference between slip planes is that each of them is implemented with a diverse safety factor (SRF). It should be mentioned that even without consideration of a rock mass structure and difference in physic-mechanical characteristics of layers, the SRF in the most "unfavourable" southern part of the open pit is less than that one obtained on the macromodel. It is 2.13 (to compare with 2.23), i.e. deviation is almost 4%. It is obvious that such a difference in the SRF depends upon generation of a smaller finite element mesh. Owing to that, it became possible to represent thoroughly in the model a line of steeply inclined benches and identify more accurately a tensor of normal and tangential stresses within each of the finite elements and, consequently, evaluate the SRF to a greater extent showing how far the model is from collapse.

Following addition of layers with various stiffness to the model decreased minimal SRF with S sector down to 1.96. Hence, representation of actual complex rock mass structure with numerous boundaries has stipulated 12-13% deviation from the minimal SRF value of the homogeneous model. It depends upon the fact that within the southern part, near-wall rock mass consists of less hard sandstone layers which is demonstrated by the detalized sectoral model. Difference in SRF for sector N is only 4% to compare with that one obtained on the macromodel. The matter is that within the area, near-wall mass is represented by rocks which strength is close to the averaged values used for the macromodel analysis.

Design of following excavation stages, i.e. consequent removal of inclined layers, assumes naturally increase in wall slopes throughout the perimeter. As it has been abovementioned, optimization of the current boundary according to the factor of minimal ore losses within the peripheral area means the balance between the interest to limit the open pit perimeter by designing near-vertical bench line, on the one hand. On the other hand, it is required to involve in the mining as much as possible of the peripheral ore. As a result, the numerical model of the final excavation stage, exported from SURPAC software, provides the total 29-30º wall slope throughout the perimeter when the open pit achieves final design depth. FEM-analysis, based upon the macromodel, has shown that the Southern wall S remains potentially hazardous at the final mining stage. In addition, potential slip plane is also formed within the Eastern wall E. Figure 8 shows a pattern of displacement distribution throughout the pit perimeter as well as the slip surface localization.

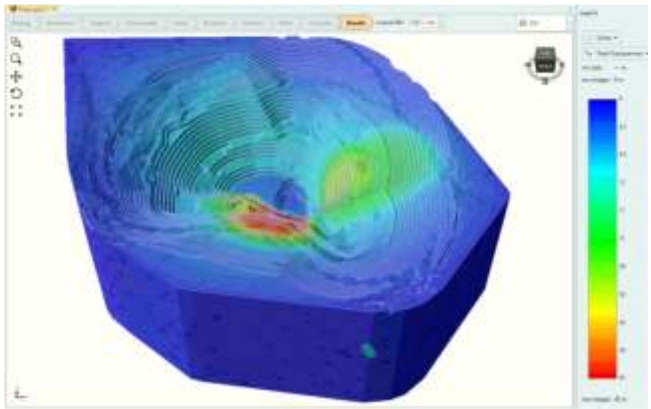


Figure 8. Distribution of displacements and localization of slip planes at the final mining stage

1.53 is the minimum of a safety factor (SRF) throughout the perimeter. It takes place within the Southern share of the open pit (S). In accordance with the design standards [34], safety factor cannot be more than 1.3. Hence, if SRF = 1.53 then in average the wall can be assumed as rather stable throughout the perimeter. Nevertheless, according to the developed methods, more accurate simulation of bench geometry as well as consideration of varying hardness of rock layers involved the model sectorizing, and each sectoral model filling with additional information on boundaries of the layers and their physic-mechanical characteristics. The abovementioned has helped evaluate wall stability for each separated sector (Fig. 9). As in case of the first stages, detalization of boundaries and rock mass structure has stipulated differences in the minimal SRF for the macromodel and SRF for each sectoral model.

In such a way, for S and E sectors, SRF within corresponding models decreased to 1.47 and 1.49 values to compare with 1.53 for homogeneous model of the final mining stage. Namely, SRF decreased by 2.5-3.9% only due to more accurate representation of bench line. Inclusion of layers, differing in their physic-mechanical characteristics, decreased SRF in S sector down to 1.38, i.e. by 9.6%; in E sector the decrease was down to 1.4, i.e. by 8.5%.

The simulation has shown that throughout the perimeter, rock mass is rather stable, and safety factor is not less than 1.3 [33] (being its standard value) even at the final excavation stage within a zone of the pit deepening (Fig. 10).

The obtained results show that the final open pit boundaries pass design standards in terms of geomechanical factor. Slope of walls, providing their stability, is 29-30º.

3.2. Evaluation of ore losses while optimizing the pit boundaries

Relying upon the simplified scheme, shown in Figure 1, dependence (2) helps evaluate losses connected with the fact that the certain share of periphery rocks, occurred within the bottom part of the open pit, cannot be mined due to the complicated access. Graph in Figure 11 explains that ore loss value within the periphery zone V_0 / V_{or} (in percentage of the total ore reserves) increases depending upon the general slope of the pit with the $r = b / m$ ratio reduction characterizing the unmined ore body share. In this context, V_{or} is the whole ore body volume, i.e. $V_{or} = 4Hml$ prism volume.

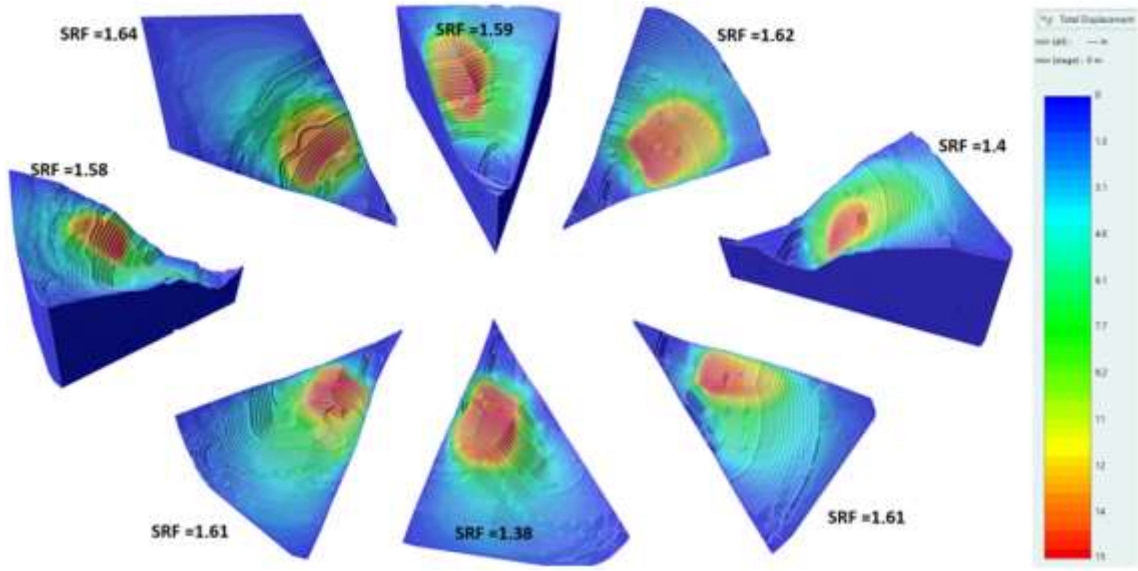


Figure 9. Distribution of displacements, localization of slip planes, and SRF identification for sectoral models of a mining stage 25

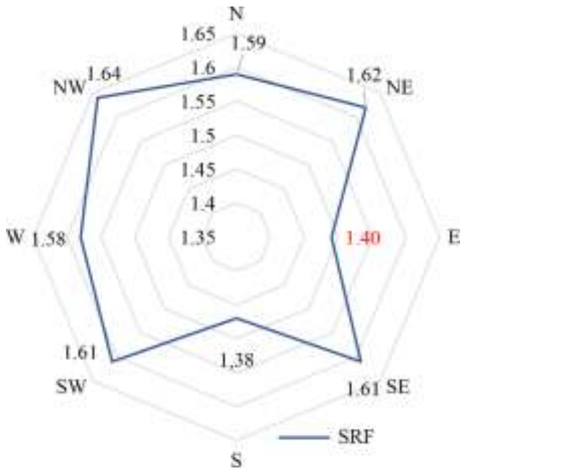


Figure 10. SRF values throughout the perimeter (final excavation stage 25)

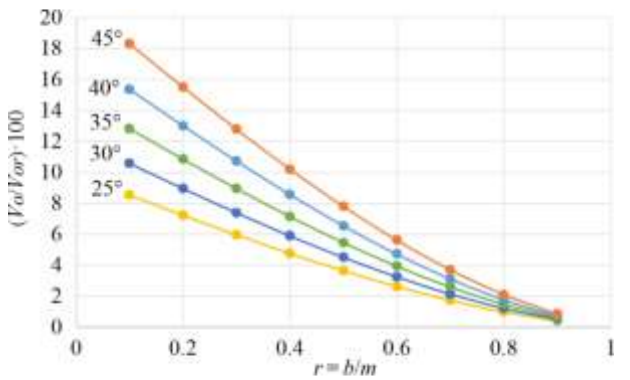


Figure 11. Changes in the periphery rock volume V_0/V_{or} (in percentage of the whole ore amount in a prism with 2m, 2l, and H sizes) depending upon b / m parameter (the graph has been drawn for l = m and H / m = 3.0)

If 50% of the ore body share within the bottom part remain beyond the open pit boundaries ($b/m = 0.5$) then in terms of wall slope losses it will be up to 4% of the total ore amount. Increase in wall slope up to 40º will result in almost 6.8% losses, i.e. 1.8 times with the same $b/m = 0.5$ ratio. If b/m ratio increases then ore losses will be decreased. The most optimistic variant is if across the bottom, the open pit geometry covers completely the ore body periphery ($b/m = 1$). In this case, the losses become zero; however, increase in the open pit width across its bottom in terms of the specified wall slope will increase surface width of the open pit (dimension B in the Figure 1) and, consequently, stripping ratio k_s:

$$k_s = \frac{\Delta V}{V_{or}} = \frac{\pi}{12} \cdot \left(3r^2 + 3rq + q^2 ctg^2 \gamma\right) - 1. \quad (3)$$

In this context, ΔV is overburden amount being equal to difference of the whole rock volume inside a cone with its lower base b, upper base B, height H; and ore volume V_{or} within a rectangular prism ($V_{or} = 4Hml$); and $q = H/m$. Graphs in Figure 12, constructed under $q = 3.0$, show increase in the stripping ratio along with $r = b/m$ ratio increase depending upon a wall slope.

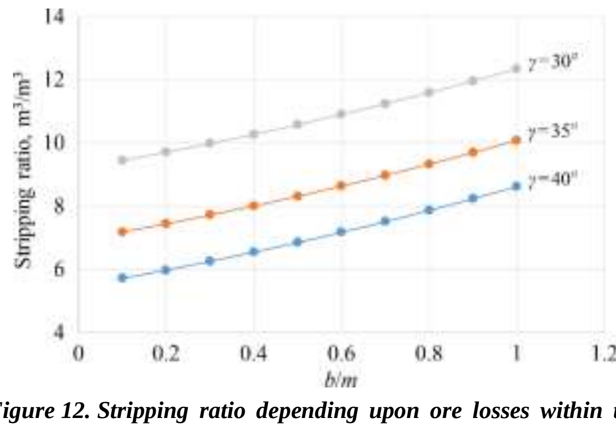


Figure 12. Stripping ratio depending upon ore losses within the bottom portion of the pit

If share of the unmined ore within the pit bottom part decreases (i.e. when b/m ratio increases) then the stripping ratio grows from 10.5 up to 12.3 with 30º wall slope, and b/m € [0.1, 1.0].

Despite the hypothetical increase in overburden operations, a decision has been made to avoid ore losses within the pit bottom. For the pit periphery, constructed using SURPAC software and relying upon such an option to achieve the best economic performance, the total stripping ratio is not more than 10 m^3/m^3. In reality, for the optimized pit boundaries only at the first excavation stages (i.e. when only loose overburden is removed), the stripping ratio values are similar to those ones shown in Figure 12. Stripping ratio decreases along with the mining of each inclined layer (Fig. 13). At the stage 4, the stripping ratio drops down to $k_s = 5.8$ value, achieving $k_s = 1.1$ value at the stage 13. At the stage 25, $k_s = 0.88$ value is achieved to be considered as economically feasible taking into consideration the current world iron ore prices.

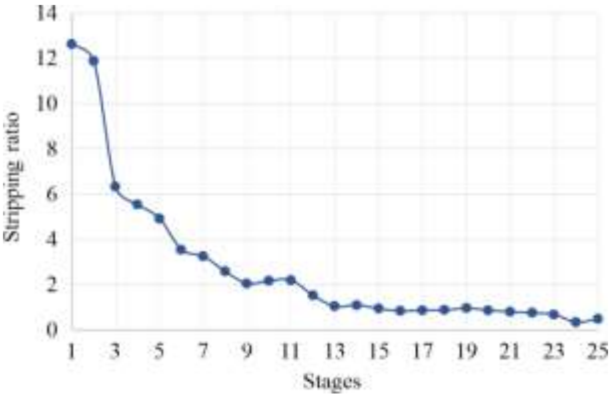


Figure 13. Changes in the stripping ratio at each mining stage in Kacharsky open pit

Consequently, the designed stage-by-stage boundaries of super-deep Kacharsky open pit provide stable decrease in the stripping ratio owing to the development of complex bench line, and coverage of all periphery ore reserves. In this regard, wall stability within the quarry is maintained throughout its perimeter at safety factor level, being nor less than 1.38 due to wall slope not exceeding 29-30º.

Despite the fact that SF = 1.38 is not less than the standard $SF_s = 1.3$, the wall stability within lower levels should be controlled constantly by surveying with the involvement of geophysical techniques. SF = 1.38 was obtained on the basis of a deterministic approach ignoring the variation of physic-mechanical characteristics. Nevertheless, numerous authors focus on probabilistic assessment of slope stability [35], [36] showing that at the expense of stochastic dispersion of the characteristics, the safety factor also varies within a range connected functionally with variation range of rock properties. Consequently, optimization of quarry boundaries does not imply an open pit wall flattening from the viewpoint of safety (loss of stability below standard), economy (stripping ratio restriction), and environment (limitation of mine land allotment).

In such a way, the tendency to minimize ore losses within a peripheral zone of a deep open pit is aimed at maximization of the benefits from ore mining and trading. Moreover, it complies with the current ideas of resource-saving technologies and minimization of damage to the environment. However, the inaccessibility of ore deposit within the pit bottom sharpens contradictions between the desire to perform complete ore extraction and need to ensure the rock mass stability as well as operating safety. Undoubtedly, open pit boundary optimization to mine all standard ore reserves should follow economic factor. Nevertheless, heavy restrictions on the stability factor should be observed. It is the principle the paper adheres to. Skill in geomechanical forecasts should be mentioned [37]. The forecasts rely upon the approved algorithms (FEM is involved particularly) and software. In addition, they should be verified by the complete complex of survey activities including aerial mapping [38]; interpretation of satellite data [39] using artificial intelligence techniques [40]; and seismoacoustic forecast [41]-[43].

4. Conclusions

The idealized geometrical model of the open pit and ore body shows that ore loss values within the peripheral zone V_0 / V_{or} (in percentage of the total ore reserves) increases along with increase in the overall wall slope of the open pit, and decrease in $r = b / m$ ratio characterizing the unmined ore body share. Among other things, if 50% of some portion of the ore within the bottom part remains beyond the pit boundaries ($b / m = 0.5$) then ore losses will be up to 4% of the total reserves in terms of 29-30º wall slopes. Increase in the wall slope up to 40º will result in up to 6.8% losses, i.e. 1.8 times under the same $b / m = 0.5$ ratio.

Under the b / m ratio increase, i.e. in the process of the pit widening across its bottom, surface width of the open pit also increases in terms of the specified wall slope. Consequently, stripping ratio grows. Particularly, if the unmined ore portion within the pit bottom decreases (i.e. when b / m ratio undergoes a rise) then the stripping ratio increases from 10.5 to 12.3 under 30º wall slope, and b / m € [0.1, 1.0].

It follows from the previous two points that the substantiated design of bench line and berms, and, hence, a wall slope, is of the key importance from the viewpoint of loss minimization. In this regard, stability of soil-rock outcrops as well as operational safety is the restricting factor.

Expediency of two-level numerical simulation (particularly, FEM-analysis), has been shown for the conditions of the super-deep Kacharsky open pit being of a round shape. This approach means development of a macromodel of the whole pit bowl and its application to identify such wall sectors where potential formation of a slip plane is the most possible. More accurate evaluation of wall stability throughout the open pit perimeter need the macromodel division into separate sectors with the detailed simulation of the wall line and the layered structure of the rock-soil mass. Downscaling of the sectoral models, i.e. more detailed representation of the wall geometry, has resulted in the decreased indicator of the wall stability within 2.5-3.8% to compare with that minimal SF obtained for the macromodel. Simulation in the sectoral models of the layered rock mass structure stipulated 12-13% SF decrease to compare with the micromodel.

At the final stage of the ore body excavation after the open pit deepening down to 720 m, SF is forecasted as 1.38-1.4 if the overall wall slope through a perimeter is 29-30º.

Despite the fact that SRF = 1.38 is not less than the standard $SF_s = 1.3$, situation with wall stability maintenance at lower levels should be controlled constantly by surveying with the involvement of geophysical techniques.

Optimization of the open pit boundaries, performed to involve in excavation the largest ore amount within the peripheral zone inclusive of simultaneous wall stability maintenance, makes it possible to forecast $k_s = 1.1$ stripping ratio at stage 13. Its decrease is forecasted to be $k_s = 0.88$ at final stage 25, which is economically feasible taking into consideration the current world iron ore prices.

Author contributions

Conceptualization: SM, AB; Data curation: DB; Formal analysis: OS, VP; Funding acquisition: SM; Investigation: DB, AN, VP; Methodology: OS, AB; Project administration: SM; Resources: SM; Software: DB; Supervision: OS, SM; Validation: GA, AN; Visualization: GA; Writing – original draft: DB; Writing – review & editing: OS. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Чисельне моделювання стійкості бортів кар’єру при оптимізації його контурів для забезпечення повноти виймання руди

О. Сдвижкова, С. Молдабаєв, Д. Бабець, А. Баскетін, Г. Асилханова, А. Нурманова, В. Приходько

Мета. Оцінка змін напружено-деформованого стану бортів вздовж усього периметра надглибокого кар’єру при оптимізації його поточних та фінального контурів, що спрямована на повноту виймання рудного покладу.

Методика. Скінчено-елементний 3D аналіз напружено-деформованого стану (НДС) ґрунтово-породного масиву визначається на основі моделей різного масштабу. Модель макрорівня включає повну чашу кар’єру та дозволяє зробити первинну оцінку стійкості, яка обумовлена зміною генерального кута нахилу борту по периметру кар’єру. Потім макромодель розбивається на секторальні моделі меншого масштабу радіально орієнтованими площинами так, щоб охопити потенційно нестійкі області борту. Секторальні моделі дозволяють більш детально відобразити складну лінію уступів після оптимізації контурів за економічним фактором, а також імітувати шарувату структуру масиву. Пружно-пластична модель середовища та критерій міцності Кулона-Мора реалізовані в кодах програми RS3 (Rocscience).

Результати. Встановлено розподіл показника стійкості борту по периметру карєру та локалізовано потенційні поверхні ковзання у кожному із виділених секторів кар’єру на основі процедури “зниження зсувної міцності” (Shear Strength Reduction). Показано вплив генерального кута укосу борту та показника повноти виймання рудного покладу на коефіцієнт розкриву. Встановлено реальну зміну коефіцієнта розкриву на кожному етапі відпрацювання рудного тіла при оптимізації контурів кар’єру з метою забезпечення повноти виймання руди.

Наукова новизна. Вперше на основі дворівневого моделювання показано різницю у визначенні коефіцієнта запасу стійкості залежно від масштабу моделі та ступеня відображення структури ґрунтово-породного масиву. Для реальних гірничо-геологічних умов Качарського кар’єру встановлено зміну показника стійкості вздовж периметра кар’єру залежно від генерального кута укосу борту.

Практична значимість. На основі оцінки стійкості бортів кар’єру по всьому периметру обґрунтовано можливість оптимізації проєктних контурів кар’єру з метою залучення у відпрацювання тих кондиційних запасів руди, що знаходяться поблизу контуру, у тому числі в донній частині, але не виймаються у зв'язку з складнощами щодо доступу до цих запасів.

Ключові слова: *видобування руди, глибокий кар’єр, чисельне моделювання, оптимізація фінального контуру*

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