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TECHNOLOGY OF AN OPEN PIT REFINEMENT UNDER LIMIT STABILITY OF SIDES

Purpose. To establish the feasibility of refining deep open-pit mines below the boundary of the use of combined motor-conveyor transport with an increased slope angles of the pit walls using the developed transport unit for reloading rocks to overlying horizons during the reactivation of pillars under transport berms.

Methodology. Preparation of a digital block model of the deposit, the elaboration of 3D geomechanical models for the dynamics of mining, 2D and 3D numerical simulation of the rock stress-strain state of the outcrops of opencast workings, mathematical modeling of stepwise ore reserves and mining schedule, patent research and feasibility study.

Findings. It is advisable to carry out mining in terms of the marginal rock state with an increase in the slope of the pit sides below the limit of application of the cyclic and continuous method in ultra-deep open pits. Such design of pit sides is achieved when benches are mined from top to bottom within the boundaries of steeply inclined layers with the use of inter-bench loaders of the developed designed in the completion zone. Provisions for the selection and feasibility of using the loader in the deep zone are formulated based on demarcation of application zones of cyclic (road transport) and cyclic-flow (combined road-conveyor transport) technologies.

Originality. Schematization of the mining operation was performed based on the calculated values of safety factor of sides, which allows increasing the slope angles of the pit walls of even ultra-deep open pits in the completion zone. It was found that with deepening of mining, the zones of potential sliding move away from the loose overburden to lower ore benches closer to the final depth of the Kacharsky open pit (760 m), but the safety factor corresponds to the required value according to the design standards.

Practical value. An increase in the slope of the pit walls in the completion zone can be achieved using the developed loading installation, the main difference of which is that it can be moved without dismantling under conditions of reactivation of transport pillars (with an increase in lifting height by 1.5–4.5 times compared to the known equipment).

Keywords: *ore quarry, deep zone, steeply inclined layer, slope stability, transport pillar, loading device, skip*

Introduction. Ensuring effective and safe mining of steeply dipping deposits through deep and ultra-deep (more than 600 m) open pits, especially circular open pits, remains a pressing problem in mining science and practice. Studies by leading scientific centers demonstrate the cost-effectiveness of switching to the progressive cyclic and continuous method (CCM) for mining. However, the optimal depth of emplacement of CCM complexes on rounded open pit fields is limited to a depth of 330–350 m even when steep conveyors are used [1, 2]. Reducing the flattening of open pit sides while finding technological solutions to decrease transportation costs should be comprehensively solved and connected with the development of the whole mining transportation system in the final part of deep and ultra-deep open pits [3, 4].

Therefore, the development of technological solutions for the effective implementation of mining operations below the limit of reasonable use of the cyclic and continuous method on round-shaped open pit remains an urgent scientific and technical problem for the safe extraction of ore reserves with the lowest possible side flattening.

Literature review. Modeling of geomechanical processes is a necessary element in planning mining operations in modern conditions. Any technological solution to improve the efficiency of mineral extraction should be optimal from the point of view of the safety of mining, which is primarily related to the stability of rock openings. Ensuring the stability of the open pit walls remains the most topical problem for mining companies, as it is associated with a large number of influencing factors, whose variability results in changes in the stress-strain state (SSS) of the rock mass [5, 6].

In the paper [7], it was shown that due to physical weathering, unpredictable rock displacements often occur, leading to the reduction in rock strength and failure of slopes in open pits. The deformations of the pit walls are analyzed based on 3D numerical simulations. As a result, the potential mode of destruction for the described type of slopes is predicted and the role of crack development along the weak layer is found.

The authors of the article [8] point out that in the last decade many cases of catastrophic destruction of the open pit walls have been recorded worldwide. The importance of detailed modeling of the geomechanical processes is underlined.

The adequacy of slope stability modeling is ensured only if the initial data are reliable, especially with respect to the mechanical properties of the lithological differences. The authors of paper [9] state that the evaluation of shear strength is crucial for stability analysis, but that few data are available to estimate the actual properties of soils. The authors of paper [10] emphasize that backward analysis combined with monitoring of soil displacements can fill the gap in determining the mechanical properties of soils. They use the FLAC3D software for numerical simulation with the finite difference method.

The mechanism of destruction of the weak layer was determined, and the angle of internal friction of developing weak layers was determined, which compensated for the lack of laboratory tests and allowed the transition from qualitative to quantitative analysis. This can provide a reliable basis for the safe operation of open-pit mines, which was clearly demonstrated in the paper [11].

The modeling of critical conditions of the pit walls is similar in many respects to the analysis of landslide processes. The authors of the paper [12] point out the problem of modeling a landslide in weak soils. A decrease in the strength of the clay layer during plastic deformation leads to irreversible strains, so that soil displacements on a small slope can lead to a series of regressive failures and thus to an unexpected catastrophic landslide. It is noted that successful landslide prediction requires reliable numerical modeling capable of reproducing extreme soil deformations. The positive experience with finite element modeling using the RS3 code is presented.

Thus, when it comes to justifying the stability of open pit walls in mining ore deposits with a thick layer of overlying sand-clay deposits and the presence of areas with a gradient of lithological differences toward the mining area, there is no alternative to 3D numerical simulation of rock stress-strain state.

Ensuring the stability of open pit walls before and after the transition of the surface contour bounding the quarry is an important technological task in the mining of steeply inclined ore deposits. The deformation processes affect a significant part of the mined massif and are caused by the influence of a number of factors, among which the rock physical and mechanical properties dominate, taking into account watering, loading by mining equipment and seismic effects. The authors of [13] point out the need to analyze in detail the stability of the pit walls and individual benches in connection with technological operations in order to substantiate the technology of high-rhythm ore mining. Based on the study on the geological structure and physical-mechanical properties of different lithological varieties, the parameters of the slopes and pit walls in clay rock of the overburden are concretized.

The upper slopes are often at risk of collapse under the influence of natural and man-made factors, which affects the intensity of mining, especially during the rainy season [14]. In this context, the application of laboratory tests and numerical simulations is appropriate for studying the influence of rock watering on the stability of slopes and pit walls. In the article [15], the results of studies on the stability of slopes in Fushun open pit mine (China) subjected to extreme precipitation over a long period of time are presented. Earthquakes are a triggering factor for the stability of slopes, which requires their technical protection. Digital photogrammetry, depth telemetry and infrared scanning technologies are used to evaluate the behavior of overburden [16]. They are effectively used to predict geomechanical deformations of slopes in open pit mines under difficult geological conditions.

The effectiveness of mathematical modeling of rock and soil state depends on the correct choice of failure criteria. Nonlinear plasticity behavior and fracture mechanisms can be considered using the Hoek-Brown criterion and developing stability diagrams that take into account loading conditions and rock mass quality [17].

Estimating the stability of fractured rock slopes is a complex problem of nonlinear and uncertain systems. In the article [18], an interactive method for analyzing the dynamic stability of steep rock slopes with internal cracks is proposed. The application of special interface elements in FEM-analyzes allows one to determine the state of jointed rock mass and, accordingly, the opening stability.

Probabilistic approaches to geotechnical calculations have advantages over traditional deterministic methods because they account for various degrees of variability and uncertainty that are common in rock properties. In the article [19], an evaluation of slope stability using the probabilistic approach in combination with a kinematic analysis based on stereographic projection methods is presented. It is followed by a kinetic analysis using the limit equilibrium method.

The above analysis of methodological approaches to evaluating the stability of mine walls demonstrates that the use of multifactorial geomechanical analyzes in the development of mine plans is feasible.

Unsolved aspects of the problem. There is still no single approach to the safe reactivation of the pillars under the transport berms and increasing the inclination angles of the sides of deep and ultra-deep open pits in completion zone. Such tasks require 3D numerical modeling of the mined rock mass when mining the benches with transverse panels in steeply inclined layers from top to bottom. This implies the problem of expediency of pit walls flattening at the open pit depths of more than 600 m. Existing inter-bench loaders have a limited scope of application due to the need for their dismantling, transfer and installation at a new location. At the same time, the height of loading the rock mass on the overlying horizons does not exceed 30 m.

The purpose of research is to establish the expediency of cleaning-up below the boundary of the use of combined motor-conveyor transport in the lower zone of deep open pits with minimal pit side flattening and increase in their inclination angle. The goal is achieved due to the developed device for transporting rocks to the overlying horizons during the reactivation of the pillars under the transport berms.

Results. A general pattern has emerged whereby the stability of the rock mass decreases as overburden and ore bodies are mined with steeply inclined layers. The schematization of the mining model within the boundaries of the steeply inclined layers was performed based on the calculated values of the resultant slope angle and safety factor (SF) (Fig. 1). Stages Nos. 17, 19, 21 and 25 of the ore body mining on the *19th* profile were selected for modeling. According to the regulations, SF should not exceed 1.3 to provide the safe panel mining. This should be taken into account when mining deepening and reaching the maximum depth of the open pit. To not exceed the limit value of SF, the overlying overburden should be mined simultaneously with the ore body using the transverse panels.

It was found that SF drops from 1.63 to 1.38 in the completion zone of the Kacharsky open pit mine (Fig. 2). FEM-analysis with PHASE2 Rocscience software shows that the layers of the loose overburden are subject to the most intense deformations. However, as the ore deposit is mined and mining operations become lower, the potential sliding zones shift to the lower ore benches of the open pit side.

The 3D numerical simulation was carried out using RS3 code (Rocksciense). The entire perimeter of open pit was modelled. A comparative analysis of the possible rock displacements in the *21st* (Fig. 3) and *22nd* (Fig. 4) stages of mining was done and the most dangerous sectors of the Kacharsky open pit were identified from the ensuring stability point of view. The calculations showed that during the transition of mining operations to the *22nd* stage, the most dangerous sliding area moves from the southern pit side to the eastern side. The potential rock displacements increase by 31 % (from 35 up to 46 m).

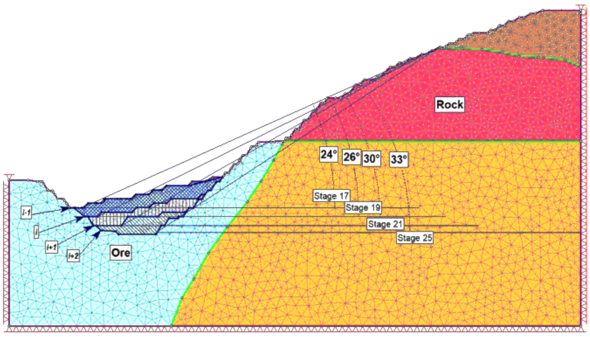


Fig. 1. Schematization of the model of mining overburden and ore body by steeply inclined layers on a profile No. 19 of the Kacharsky open pit mine

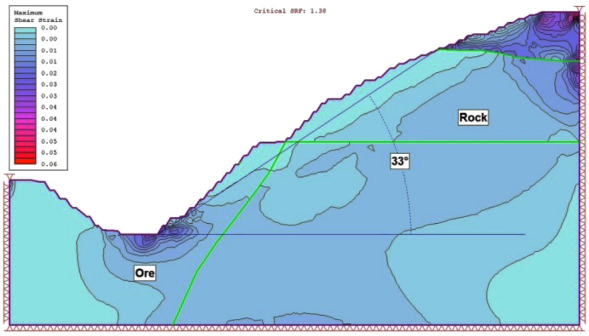


Fig. 2. The results of the SF calculation at the last stage of mining the Kacharsky open pit mine (PHASE2)

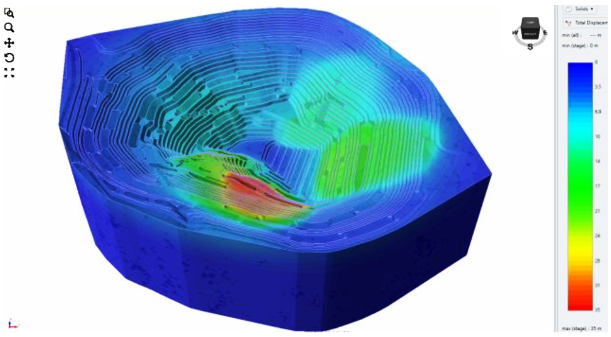


Fig. 3. 3D finite element model of the 21st stage of mining

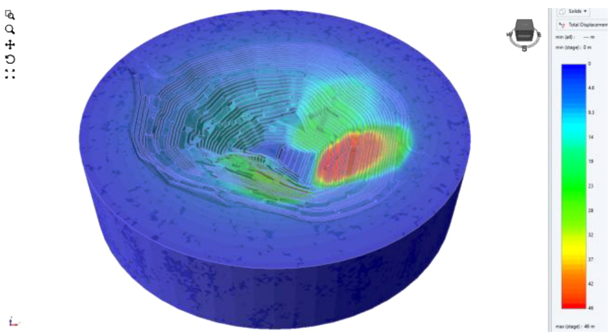


Fig. 4. 3D finite element model of the 22nd stage of mining

The authors of the paper [2] point that an "intermediate" zone should be allocated in addition to the "deep" zone in deep and ultra-deep open pit mines. Mining of this "intermediate" zone is expedient using the cyclical and continuous method with combined motor-conveyor transport.

It has been proven in [2] that the use of steeply inclined conveyors is effective while mining the inclined ore body. At the same time, it was found that, under conditions of the Kacharsky ultra-deep open pit, the economically justified maximum depth of the horizon serving for rock mass reloading from motor transport to the conveyor is 344 m [2]. If the final depth is 760 m, the rock mass should be transported to this horizon by road to a height of about 416 m. Therefore, several problems will have to be solved at once: ensuring the completeness of the deep reserve with minimal flattening of the pit walls and mining the deep reserves at minimal cost.

Studying the maximum strains and displacements in the rock massif nearby the pit contour showed that the decrease in the SF when using the technology of mining with transverse panels in steeply inclined layers occurs due to the complicated deformation processes. That is why the crucial task is the calculation of SF, at which the maximum shear strains in rock mass near the pit wall contour can lead to large-scale sliding.

It has already been mentioned that, according to the design standards, the safety factor should not be less than 1.3 if the slope of the lithological differences in the mined space is smaller than the average angle of the rock internal friction. The 3D numerical simulation with RS3 showed that the critical SF at the final stage of mining is not less then 1.38. At the same time, the inclination angles of the pit sides are the largest in the completion zone, which indicates the possibility of mining with a minimum number of narrow transport berms. This can be achieved with the use of loading devices in the completion zone.

The stability analysis was carried out taking into account a possible deterioration of the rock quality, especially considering the occurrence of regular joint systems. The 2D numerical simulation was performed to consider the rock mass fracturing with use of PHASE2 special options. In this case a greater decrease in the factor of safety and an increase in rock displacements have been obtained as a function of the depth of mining. For the profile No. 19 (Fig. 5), it was found that the maximum displacements increase from 1.4 to 8.5 m when the depth of the open pit is increased from 385 to 760 m, which corresponds to a decrease in SF from 1.72 to 1.1. Such an increase in maximum displacements implies the risk of a sliding surface formation (Fig. 6) in the study area.

A feature of mining operations within the boundaries of steeply inclined layers is that benches are mined with transverse panels from top to bottom. Therefore, the extraction of ore in the mined steeply inclined layer can be started only after the end of the excavation of overburden. Consequently, the time of mining the overburden of the next steeply inclined layer should not exceed the duration of ore extraction in the previous layer. Therefore, the width of the steeply inclined layer should be minimally sufficient to ensure a safe loop turn of the dump trucks. It is important to start mining the rock overburden in a timely manner. This provision allows justifying the depth of the open pit, from which it is possible to proceed to mining the rocks with steeply inclined layers and to ensure a reduction in peak calendar volumes of overburden

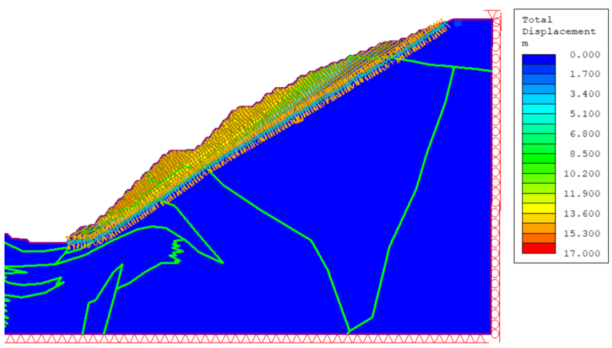


Fig. 5. Maximum displacements in the rock mass at stage 25 (eastern side of the Kacharsky open pit mine)

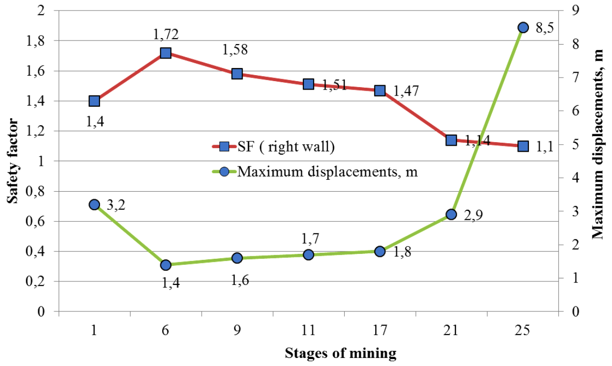


Fig. 6. Safety factor and maximum displacements at various stages of mining with considering rock fracturing

excavation, especially when mining operations approach the limit surface contour of the open pit.

Fig. 7 shows a diagram of the mining schedule using the example of the Kacharsky ultra-deep open pit mine since the volumes of mining operations in the completion zone are of great interest.

We analyzed the period of 10 years before the end of open pit operation, corresponding to the beginning of the decline in ore production relative to the design production capacity. This gives us the following picture. Ore production volumes will decrease from 23 to 1 million tons, and stripping operations will decrease from 15.6 to 0.4 million tons. On average, over the past 10 years, annual ore production will amount to 10.7 million tons, and the excavation of the remaining volumes of rock overburden will be 6.9 million tons.

Rock overburden volumes will decrease by an average of 9 times compared with the beginning of mining the rock overburden with transverse panels in steeply inclined layers. Therefore, it is impractical to flatten the pit sides at great depths of mining. Under such conditions, a more effective solution is the elimination of transport berms with an increase in the resulting slope of the pit side in the completion zone and the use of inter-bench loaders as well as cyclical and continuous method for transporting rock masses.

Existing inter-bench loaders, as a rule, are equipped with steeply inclined belt conveyors, such as, the SIC-30 or MPU-5000K loaders manufactured by the Ukrainian company PJSC Azovmash. A device is also known which consists of sequentially arranged elevators in a tracked base, placed on adjacent benches to load the rock mass from the excavator face to the surface or into a vehicle on a higher-level elevator through a system of lifts.

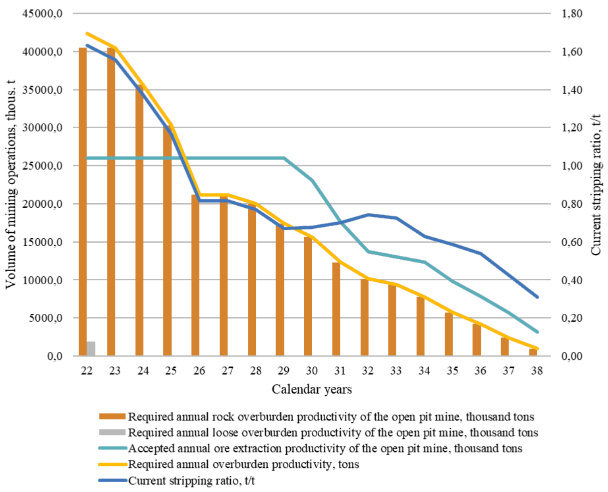


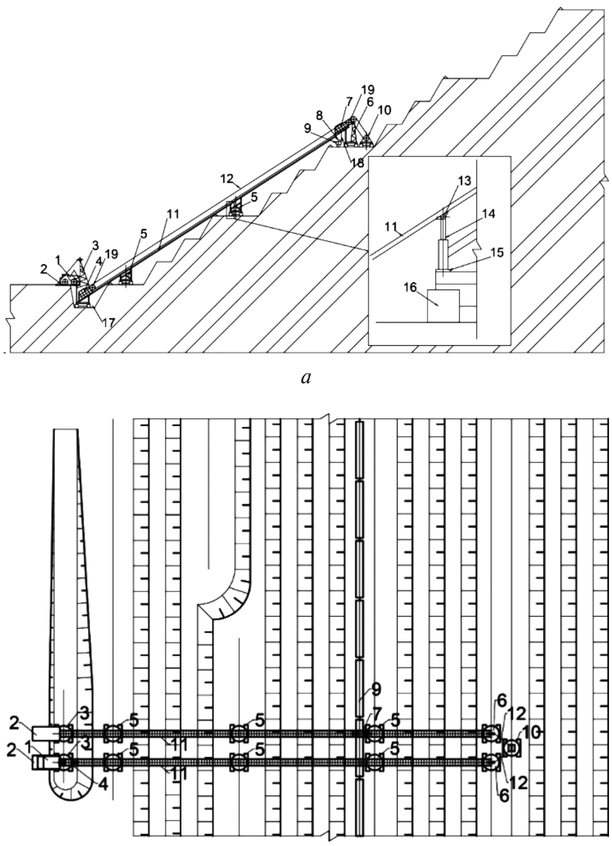
Fig. 7. Calendar schedule of mining operations during completion of the Kacharsky ultra-deep open pit

Such transport system includes plate loaders, as well as several boom lifts on a tracked base, equipped with buckets connected by endless bushing-roller chains. The lifts are located on the platforms of the upper benches one after the other, forming a transport system for inter-bench loading of the rock masses, and the last lift carries out direct loading to another transport vehicle. The system of boom lifts on a tracked base moves following the face advance. The installation is intended for the reactivation of non-working sides of the open pit mine.

The disadvantage of this system is high metal capacity, as well as the need to keep a constant height of the benches and the width of the platforms on which the switch lifts are installed. This is difficult to implement under conditions of open pit ore mining. The refinement of the end caps under the transport pillars for opening the deep horizons of the deposit without additional flattening of the pit sides provides for an increase in the slope angle of the pit side due to the elimination of transport berms, which leads to a decrease in the width of platforms.

The introduction of new elements made it possible to develop a transport installation for shipment of rocks to the overlying horizons together with JSC SSGPO (KZ 34721) [20]. Its main purpose is to depreserve transport pillars and increase the inclination angle of the pit sides in the completion zone. The supports of the transport installation are connected to the transport gallery by hydraulic legs with a hinged or bearing joint at the end of the hydraulic cylinder, while the hydraulic leg is attached by a hinge to the skip rails, and the hydraulic leg foundation is rigidly fixed to the crawler support.

Fig. 8 shows a transport installation for loading of end-to-end stocks under the pillars of transport berms, respectively, in the cross-section and plan, on which *1* is a dump truck; *2* is a lifting bridge; *3* is a crawler reloading device; *4* is a skip under loading; *5* is a crawler support; *6* is an impact machine on a track; *7* is skip under unloading; *8* is unloading guides; *9* is a



a

b

Fig. 8. Transport installation for cleaning-up contour reserves under the pillars of transport berms in the cross-section (a) and plan (b)

vehicle body; *10* is a drive station; *11* is a skip rails; *12* is a skip cable; *13* is articulated (bearing) joint; *14* is a hydraulic leg; *15* is a rigid connection; *16* is a crawler; *17* is a well for the reloading device; *18* is a skip cover; *19* is a skip block.

It may also be recommended to load the rock mass through the feeder hopper directly into the power plant, without the involving the dump trucks. The support on the transport horizon can be equipped with a hopper loader and overload the rock masses into the vehicle body through a plate feeder. There is no need to construct the well under the loader if the loader is installed on the lower horizon of the zone being cleaned-up and equipped with a self-propelled plate feeder. The rock mass is stacked and loaded onto the plate feeder by a wheel loader or excavator. A belt conveyor can be used in the transport gallery instead of a skip lift.

The reduction of the pit side flattening is achieved by using dump trucks with a lifting capacity of 90 tons in the deep zone. At the same time, a reduction in the number of transport berms can be obtained using loading devices, described above. In this regard, the main provisions on the selection and justification of the feasibility of using the reloading device for operation in the deep zone were formulated:

1. The total costs of transporting rock mass under the new scheme of combined in-pit transport with the use of the loading device for operating in the deep zone should be less than the costs of transportation under existing (traditional) schemes.

2. The amount of capital costs for the construction of loading devices, which constitute a new scheme of combined in-pit transport, should not exceed the difference in the cost between the existing and new schemes of combined in-pit transport.

3. The volume of mining and capital works when changing the scheme of combined in-pit transport and structures of the reloading device while deepening of mining should be minimal.

4. The new scheme of combined in-pit transport should make the most effective use of existing transport communications. The construction of new loading devices for operation in the deep zone is permissible only if the total costs of mining are reduced.

5. The introduction of a new scheme of combined in-pit transport using a reloading device for working in the deep zone should not lead to an increase in mineral losses.

6. A smaller number of pillars should be left in order to increase the completeness of the ore body extraction under the transport berms with the use of the loading device for operation in the deep zone.

7. The total distance of rock mass transportation according to the new scheme of combined in-pit transport with the use of developed loading device should not exceed the distance of transportation according to the existing scheme.

8. The cost of mining counted the extraction of overburden when introducing a new scheme of combined in-pit transport with the use of the loading device should not be more than the cost of using the existing scheme and not more than the economically feasible cost.

9. The life of the loading device for operation in the deep zone should be such as to amortize the investment cost of its construction.

10. The downtime of the pit transport during the construction of the loading device for operation in the deep zone should be minimal.

The economic effect of using the transport system to transfer rock masses to horizons above when finishing pillars under transport berms is calculated according to the formula, mln

$$E = \frac{QH}{100}\left(\frac{C_1}{i_1} - \frac{C_2}{i_2}\right) = \frac{23 \cdot 90}{100}\left(\frac{27.28}{80} - \frac{131.6}{1000}\right) = \$4.33.$$

Here Q is the annual productivity of the transport chain, mln tons; H is the height of the rock mass lifting, m; C_1, C_2 are costs of lifting with the use of vehicles and the proposed transport unit, respectively, \$/t·km; i_1, i_2 are the slopes of the motor transport route and the skip hoist, respectively, ‰.

The use of the transport installation for reloading the rock mass to the overlying horizons during the cleaning-up of the pillars under the transport berms allows for the reactivation of the non-working pit side below the zone of application of the CCM complex under conditions of an increase in the resulting slope angle of the pit side. Due to hydraulic legs that regulate the height of the supports *5*, it is possible to move the complex within the zone of completion of the pillars.

Conclusions.

1. The possibility of increasing the slope angle of the pit walls in completion zone up to the limit value when reaching the final depth of 760 m is proved even for ultra-deep ore pits, using the example of the Kacharsky iron ore deposit with a thick layer of loose overburden (on average 160 m). A general pattern of decreasing the pit wall stability was revealed as a function of the slope angle. Numerical simulation showed that with the resultant slope angle of the working pit side of 22–30°, the slope angles in lower part in the completion zone can be increased from 36–38° degrees up to 42–47°. There is a real opportunity to refine ultra-deep open pits without significant flattening of their sides with the use of high-performance technology of mining the pit benches with transverse panels in steeply inclined layers until the completion of mining operations.

2. An increase in the slope of the lower part of the pit sides in the completion zone below the boundary of the application of cyclical and continuous method is provided by the elimination of part of the pillars under the transport berms using the developed design of the transport device for overloading the rock mass to the above horizons. It is advisable to use skips as a load-bearing body of the inter-bench loader. The design of the loader supports allows it to be built with a lifting height of more than 30 m with the possibility of moving along the pit side with variable berm elevations.

The construction of the bridge provides for unloading the trucks directly into the skip on the lower support, and the conveyor belt eliminates the need to use the drive station on a separate support (it reduces the width of the transport horizon up to 18–24 m). The presence or absence of a hopper loader on the transport horizon also affects its width, and, as a consequence, the inclination angle of the transport gallery. The location of the well on the lower horizon affects the mobility of the installation and the angle of its inclination.

3. It was found that at the wall inclination angle of 22–30°, the safety factor (1.38) exceeds the limit value (1.3) by 6.1 %. At the same time, the inclination angles of the pit sides are the largest in the completion zone, which indicates the possibility of mining with a minimum number of narrow transport berms. This can be achieved with the use of loading devices in the completion zone. Thus, it becomes possible to increase the inclination angles of the pit sides in the completion zone of the ultra deep iron ore open pit mine from 36–38 to 42–47° in the direction of the main development of mining operations.

The reduction of lateral flattening in the completion zone of the ultra-deep open pit below the zone of application of the cyclic and continuous method, as well as the annual transportation costs up to 4.33 million USD is achieved by the use of skip transportation with an increase in the transport gallery slope on deep horizons.

4. The increase in the height of rock loading by mobile inter-bench loaders of new design up to 90 m, as well as low annual mining volumes (an average of 17.6 million tons for 10 years before the end of operation of the Kacharsky open pit) and annual savings of up to \$4 million allow recommending the mentioned technology as one of the acceptable solutions to the problem of effective completion of deep and ultra-deep open pit mines.

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References.

1. Anisimov, O., Symonenko, V., Cherniaiev, O., & Shustov, O. (2018). Formation of safety conditions for development of deposits by open mining. *E3S Web of Conferences*, *60*. https://doi.org/10.1051/e3sconf/20186000016.

2. Kuzmenko, S., Kaluzhnyi, Y., Moldabayev, S., Shustov, O., Adamchuk, A., & Toktarov, A. (2019). Optimization of position of the cyclical-and-continuous method complexes when cleaning-up the deep iron ore quarries. *Mining of Mineral Deposits*, *13*(3), 104-112. https://doi.org/10.33271/mining13.03.104.

3. Moldabayev, S., Adamchuk, A., Sarybayev, N., & Shustov, A. (2019). Improvement of open cleaning-up schemes of border Mineral reserves. *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM*, *19*(1.3), 331-338. https://doi.org/10.5593/sgem2019/1.3/S03.042.

4. Moldabayev, S., Sultanbekova, Z., Adamchuk, A., & Sarybayev, N. (2019). Method of optimizing cyclic and continuous technology complexes location during finalization of mining deep ore open pit mines. *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM*, *19*(1.3), 407-414. https://doi.org/10.5593/sgem2019/1.3/S03.052.

5. Bazaluk, O., Ashcheulova, O., Mamaikin, O., Khorolskyi, A., Lozynskyi, V., & Saik, P. (2022). Innovative Activities in the Sphere of Mining Process Management. *Frontiers in Environmental Science*, *10*. https://doi.org/10.3389/fenvs.2022.878977.

6. Shustov, O., Pavlychenko, A., Bondarenko, A., Bielov, O., Borysovska, O., & Abdiev, A. (2021). Substantiation into Parameters of Carbon Fuel Production Technology from Brown Coal. *Materials Science Forum*, *1045*, 90-101. https://doi.org/10.4028/www.scientific.net/MSF.1045.90.

7. Zhao, H., Tian, Y., Guo, Q., Li, M., & Wu, J. (2020). The slope creep law for a soft rock in an open-pit mine in the Gobi region of Xinjiang, China. *International Journal of Coal Science & Technology*, *7*(2), 371-379. https://doi.org/10.1007/s40789-020-00305-4.

8. Zevgolis, I. E., Deliveris, A. V., & Koukouzas, N. C. (2019). Slope failure incidents and other stability concerns in surface lignite mines in Greece. *Journal of Sustainable Mining*, *18*(4), 182-197. https://doi.org/10.1016/j.jsm.2019.07.001.

9. Roháč, J., Scaringi, G., Boháč, J., Kycl, P., & Najser, J. (2020). Revisiting strength concepts and correlations with soil index properties: insights from the Dobkovičky landslide in Czech Republic. *Landslides*, *17*(3), 597-614. https://doi.org/10.1007/s10346-019-01306-4.

10. Hongze, Z., Dongyu, W., Ming, M., & Kaihui, Z. (2020). Parameter inversion and location determination of evolutionary weak layer for open-pit mine slope. *International Journal of Coal Science & Technology*, *7*(4), 714-724. https://doi.org/10.1007/s40789-020-00337-w.

11. Sedina, S. A., Abdikarimova, G. B., Altayeva, A. A., & Rakhimov, N. D. (2021). Application of kinematic stability analysis in determining rational design parameters of career steps. *Series of Geology and Technical Sciences*, *445*(1), 135-143. https://doi.org/10.32014/2021.2518-170X.19.

12. Zhang, X., Wang, L., Krabbenhoft, K., & Tinti, S. (2020). A case study and implication: particle finite element modelling of the 2010 Saint-Jude sensitive clay landslide. *Landslides*, *17*(5), 1117-1127. https://doi.org/10.1007/s10346-019-01330-4.

13. Nizametdinov, N. F., Nizametdinova, R. F., Nagibin, A. A., & Estaeva, A. R. (2020). Slope Stability in Open Pit Mines in Clayey Rock Mass. *Journal of Mining Science*, *56*(2), 196-202. https://doi.org/10.1134/S1062739120026649.

14. Doumbouya, L., Guan, C. S., & Bowa, V. M. (2020). Influence of Rainfall Patterns on the Slope Stability of the Lumwana (the Malundwe) Open Pit. *Geotechnical and Geological Engineering*, *38*(2), 1337-1346. https://doi.org/10.1007/s10706-019-01094-7.

15. Xiangfeng L., Ziyu G., Laigui W., & Han, G. (2021). Analysis on the slope stability of Fushun West Open-pit Mine under superimposed action of rainfall, mine and earthquake. *The Chinese Journal of Geological Hazard and Control*, *32*(4). https://doi.org/10.16031/j.cnki.issn.1003-8035.2021.04-06.

16. Zhang, F., Yang, T., Li, L., Bu, J., Wang, T., & Xiao, P. (2021). Assessment of the rock slope stability of Fushun West Open-pit Mine. *Arabian Journal of Geosciences*, *14*(15), 1459. https://doi.org/10.1007/s12517-021-07815-8.

17. Karrech, A., Dong, X., Elchalakani, M., Basarir, H., Shahin, M. A., & Regenauer-Lieb, K. (2022). Limit analysis for the seismic stability of three-dimensional rock slopes using the generalized Hoek-Brown criterion. *International Journal of Mining Science and Technology*, *32*(2), 237-245. https://doi.org/10.1016/j.ijmst.2021.10.005.

18. Gao, L., Li, T., Liu, X., Qi, H., Fan, S., Lin, C., & Zhou, M. (2021). A novel dynamic stability analysis method for jointed rock slopes based on block-interface interaction. *Computers and Geotechnics*, *134*, 104113. https://doi.org/10.1016/j.compgeo.2021.104113.

19. Obregon, C., & Mitri, H. (2019). Probabilistic approach for open pit bench slope stability analysis – A mine case study. *International Journal of Mining Science and Technology*, *29*(4), 629-640. https://doi.org/10.1016/j.ijmst.2019.06.017.

20. Moldabayev, S. K., Kuzmenko, S. V., Kalyuzhnyi, Y. S., Adamchuk, A. A., & Shustov, A. A. (2020). *Transport installation for the completion of contour reserves under the pillars of railway tracks* (Patent No. 34721).

Технологія доробки глибоких кар’єрів в умовах граничної стійкості бортів

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Мета. Встановити доцільність доробки глибоких кар’єрів нижче межі застосування комбінованого автомобільно-конвеєрного транспорту зі збільшенням кута нахилу їх бортів з використанням розробленої транспортної установки для перевантаження гірських порід на верхні горизонти, при розконсервації цiликів під транспортними бермами.

Методика. Включає побудову блочно-цифрової моделі родовища, підготовку на її основі об’ємних геомеханічних моделей у динаміці розвитку гірничих робіт, 2D і 3D чисельне моделювання напружено-деформованого стану оголень відкритих гірничих виробок, математичне моделювання поетапних запасів руди та графіка гірничих робіт, патентний пошук і техніко-економічне обґрунтування.

Результати. Нижче межі ефективного застосування циклічно-потокової технології в зоні доробки глибоких і надглибоких кар’єрів до кінцевої глибини гірничі роботи доцільно вести в умовах граничного стану масиву зі збільшенням кутів нахилу бортів кар’єру. Досягається така конструкція бортів кар›єру при відпрацюванні уступів зверху вниз у межах круто похилих шарів із застосуванням у зоні доопрацювання міжуступних перевантажувачів розробленої конструкції. На підставі розмежування зон застосування циклічної (автомобільний транспорт) та циклічно-потокової (комбінований автомобільно-конвеєрний транспорт) технологій сформульовані основні положення щодо вибору та обґрунтування доцільності застосування перевантажувального пристрою для роботи у глибинній зоні.

Наукова новизна. На підставі розрахованих значень запасу стійкості бортів виконана схематизація ведення гірничих робіт у межах крутопохилих шарів, що дозволяє збільшити кути нахилу бортів навіть надглибоких кар’єрів у зоні їх доробки. Установлено, що в міру відпрацювання рудного покладу та зниження гірничих робіт, зони деформацій зміщуються з товщі пухких порід розкриву й розвиваються на нижніх рудних уступах ближче до кінцевої глибини Качарського кар’єру (760 м), але коефіцієнт запасу стійкості відповідає необхідному значенню за нормами.

Практична значимість. Збільшення кута нахилу бортів глибоких кар›єрів у зоні їх доробки можливо досягти із застосуванням розробленої перевантажувальної установки, основна відмінність якої від відомих полягає в забезпеченні можливості її переміщення без необхідності демонтажу в умовах розконсервації транспортних цiликів (зі збільшенням висоти підйому в 1,5–4,5 рази порівняно з відомими).

Ключові слова: *рудний кар’єр, глибинна зона, круто похилий шар, стійкість укосів, транспортний цілик, перевантажувальний пристрій, скіп*

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