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Research into stress-strain state of the mass under open pit with a change in the open-pit bottom width

Askar Imashev[1], Aigerim Suimbayeva[1*], Gaukhar Zhunusbekova[1], Sholpan Zeitinova[1], Aidar Kuttybayev[2], Aibek Mussin[1]

[1] *NJSC "Abylkas Saginov Karaganda Technical University", Karaganda, Kazakhstan*
[2] *Satbayev University, Almaty, Kazakhstan*
**Corresponding author: e-mail suimbayeva.aigerim@mail.ru*

Abstract

Purpose. Studying the stress-strain state of the rock mass under the open pit, taking into account the change in the open-pit bottom width in order to reveal the geomechanical state and determine the safe parameters of the rock bridge.

Methods. The peculiarities of the stress-strain state formation in the transition zone have been studied according to the methodology using numerical research methods and taking into account the geological strength index (GSI). Using this index, it is possible to take into account rock fracturing, water cut, lithology and other strength indicators, due to which there is a correct transition from the rock sample strength to the mass strength.

Findings. Based on the numerical modeling results, it has been determined that an increase in the open-pit bottom width leads to a decrease in the zone of tensile stresses concentration in the arch pillar of the stope block. This, in turn, has a positive effect on the rock bridge stability, that is, the probability of the rock bridge collapse does not increase with an increase in the width of the open-pit bottom.

Originality. For the first time, the dependence has been obtained of the horizontal stresses σ_3 distribution at the stages of the open-pit bottom expansion at the Akzhal Zinc-Lead Mine. This makes it possible to realistically predict changes in the geomechanical state of the rock bridge depending on the width of the open-pit bottom.

Practical implications. When predicting the change in the stress-strain state in the transition zone and determining the rock bridge safe parameters, it is possible to reduce the probability of their destruction and make timely management decisions on safe conditions for mining the reserves.

Keywords: *stress-strain state, protecting pillar, geological strength index, numerical analysis*

1. Introduction

In modern conditions, when a large number of deposits mined by the surface method are switching over the underground mining with caving systems of the reserves under the open pit, a number of very complex geomechanical problems arise, especially in the zone of direct contact between underground mining operations and quarrying operations. The geomechanical processes occurring in this case are determined by a combination of natural conditions and technological factors. The choice of an effective and safe technology for underground mining of reserves located under an open pit should be based on an assessment of the rock mass geomechanical state and its predicted changes in the process of mining operations [1], [2].

One of the most difficult tasks in mining the ore reserves in the zone under the open-pit is the substantiation of the parameters of the protecting pillar (rock bridge), separating surface and underground mining operations, which depends on the stress-strain state (SSS) of the rock mass surrounding the open pit. It is necessary to form a protecting pillar in the context of sequential surface, underground and joint mining of ore deposits in order to prevent the negative seismic impact of blasting operations conducted in an open pit on the SSS of the rock mass surrounding underground mine workings.

At the Akzhal Zinc-Lead Mine, during the transition from surface to underground mining operations, in order to maintain the annual productivity of the mine, quarrying operations and underground mining of reserves are combined in time. In difficult mining-geological and mining-technical conditions of the deposit, protection of underground mine workings from the seismic impact of blasting operations in an open pit is performed by leaving a protecting pillar under the open pit. At the same time, significant ore reserves are left in the open pit walls, mining of which is limited by the need to maintain a protecting pillar in a stable state.

To ensure the safety of mining operations in an underground mine, mandatory control (monitoring) of its geomechanical state is necessary. Therefore, the tasks associated with the assessment of the protecting pillar stress-strain state, when mining the reserves under the open pit and adjacent to the open-pit wall, are of great scientific and practical interest. In this regard, there is a need for geotechnical research to study the geomechanical state of the rock bridge.

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The following scientists V.F. Abramov, V.R. Imenitov, E.V. Kuzmin, V.V. Kulikov, G.M. Malakhov, V.V. Popov and others devoted their work to research into the field of combined technologies with the caving of ores and host rocks, as well as the protecting pillar formation. Among foreign scientists such scientists as T. Carter, D. Whittle, E. Bakhtavar, H. Kumar, D. Deb, D. Chakravarty, K. Kalenchuk, V. Falmagne, A. Gelover, I. Montiel, J. Luzania and others were engaged in studying the peculiarities of the stress-strain state formation of the rock mass under the open pit (transition zone).

An analysis of the world experience in technological solutions for the protecting pillar formation in underground and combined mining practice shows that three methods can be used to determine the pillar stability: empirical methods, numerical modeling and the limit equilibrium method [3]-[5].

There are several empirical methods used to determine the protecting pillar thickness, the most common of which is the Scaled Span Method. The Scaled Span Method concept has been developed on the basis of case studies and provides an opportunity for empirical determination of the protecting pillar parameters [6]. To determine the protecting pillar scalable span, the following Equation is used:

$$C_S = \left(\frac{\gamma}{T(1+S/L)(1-0.4\cos\theta)} \right)^{1/2}, \tag{1}$$

where:

C_s – the protecting pillar scalable span;

S – the open-pit bottom area;

T – the protecting pillar thickness;

L – the open-pit bottom width;

θ – dip angle of the stratified zone/ore;

γ – specific weight of rock or ore in the protecting pillar.

The value of the protecting pillar scalable span can be used in conjunction with the RMR classification to determine whether the protecting pillar is stable or not.

In the work of E. Bakhtavar and K. Oraee [7], in order to determine the optimal thickness of the protecting pillar in mining system with caving, a dimensional analysis approach is used, which is determined by the following empirical Equation:

$$T = \frac{13.22C^{0.03} \cdot S^{0.41} \cdot h^{0.56}}{\gamma^{0.03} \cdot RMR^{0.66}}, \tag{2}$$

where:

C – the adhesion of rocks;

S – the face area of the stope block;

h – the height of the stope block face;

γ – specific weight of rocks.

This formula is based on experimental studies and pilot tests, where it is used to determine the protecting pillar thickness in case of block caving of the rock mass under the open pit. In the world practice of geomechanics, numerical modeling is currently one of the main methods for studying the geomechanical state of the rock mass under the open pit. In addition, it is used to analyze the stability and predict stress changes in the protecting pillar during the development of mining operations [5], [8]-[14].

The limit equilibrium method uses analytical limit equilibrium equations, each of which is developed for a particular failure mechanism [15]. These failure mechanisms are determined by the ratio of the resistance force to the forces that cause movement, and are used to determine the type of the protecting pillar failure.

In the work of K. Pravin [16], a method has been developed for calculating the protecting pillar thickness, taking into account the natural stress field, the parameters of an open pit, the equipment used in an open pit, and the loading by overburden rocks. In addition, analytical dependences have been obtained of the protecting pillar thickness on the SSS of the rock mass located under the bottom of the open pit, the additional load of the rocks adjacent to the open-pit walls, and the inclination angles of the open-pit walls. According to K. Pravin, the protecting pillar thickness functionally varies depending on these factors and the side thrust coefficient according to the law of ½ degree.

N.N. Nasibullin in his work [17] assumes that in the conditions of mining the reserves under the open pit by underground method with caving systems, the protecting cushion parameters should be substantiated on the basis of the dynamic impact of rock pieces collapsing on it from the open-pit walls. The thickness of the protecting cushion, which ensures the efficient and safe underground mining, is determined on the basis of a multifactorial dependence, taking into account the parameters of the movement of pieces, the properties of collapsing rocks and rocks bearing the load, as well as the properties of the mass in which underground mine workings are located. The author determines the minimum width of the near-wall zone (in most cases it does not exceed 50 m) of the protecting cushion, which directly takes up and compensates for the dynamic impact of the falling mass on the ore mass, which takes into account the size of the pieces formed as a result of the open-pit wall caving, the distance of the distribution of these pieces from the wall. Also in his work N.N. Nasibullin has revealed the main factors influencing the protecting cushion thickness and developed a methodology for determining the parameters of the protecting cushion near-wall zone, which takes into account the sizes of the pieces formed as a result of the open-pit wall caving and the distance of their distribution over the open-pit bottom.

Much attention is paid to the study of the geomechanical state of the rock mass under the open pit and the prediction of stress changes in the protecting pillar during the development of mining operations [18]-[22]. It follows from the above that, as a rule, the main place in research is occupied by the analysis of technological processes, the determination of the protecting pillar optimal thickness and the stability of the wall slopes. At the same time, the study of the open-pit bottom width influence on the geomechanical situation in the rock bridge is given a secondary role. Thus, in the works [21], [23], [24], the issues of assessing the rock bridge geomechanical state are studied, taking into account the influence of elevation marks of the open-pit walls. Also, in the work [25] and other works, it is indicated that when studying the stress-strain state of a rock bridge, such conditions as the safety of mining ore reserves, preservation of the open-pit walls in a stable state, and the minimum indicators of losses and ore dilution should be taken into account.

The research purpose is to study the stress-strain state of the rock mass under the open pit, taking into account the change in the open-pit bottom width when mining the reserves under the open pit of the Akzhal Zinc-Lead Mine with the sublevel caving system and to determine the protecting pillar safe parameters with the maximum complete extraction of ore in the walls adjacent to the open-pit bottom.

2. Research methods

The protecting pillar (rock bridge) thickness is determined by the zone of mutual influence of the open pit and underground mine workings. This zone sizes depend on many factors: physical-mechanical properties of the ore and rocks, the mass fracturing, the ore extraction technology, the impact of mass explosions in the open pit and underground mine, the degree of filling the open pit with water and waste rocks, etc. The stress-strain state of the rock mass under the open pit has been studied, taking into account the change in the open-pit bottom width, by performing a complex of geotechnological research, including laboratory testing of rock samples for uniaxial compression, determining the rock quality – Rock Quality Designation (RQD) [26], surveying of rock fracturing, consideration of lithology and water-cut of rocks, as well as determining the Geological Strength Index (GSI) of the rocks [27].

For a predictive assessment of the possible influence of the open-pit bottom width on the rock bridge geomechanical state, numerical modeling of the stress-strain state of the rock mass under the open-pit has been performed with the actual width (20 m) and with an increase in the open-pit bottom space. The peculiarities of the stress state formation in the transition zone have been studied according to a methodology, which uses numerical research methods with account of the geological strength index (GSI) and makes it possible to determine the patterns of SSS variability. The Hoek-Brown criterion has been chosen as an empirical failure criterion for assessing the stability of mine workings [28]. To determine the possible rock destruction zones (zones of inelastic deformations) in the mass under the open pit, numerical modeling has been performed by the finite element method using the "Phase 2" program.

The modeling result reliability often depends on the accuracy of the initial data entered. The initial data for numerical analysis are prepared using the RocData program, which makes it possible to determine the rock mass strength parameters based on the Hoek-Brown and Mohr-Coulomb failure criteria.

The initial data important components are the uniaxial compressive strength of rocks (σ_{compr}) and the Geological Strength Index (GSI). To clarify the mass strength parameters, detailed information is required on the strength properties of rocks, which have been determined by laboratory testing of rock samples from the Akzhal Mine [29], [30]. The average value of the ultimate compressive strength is 76.24 MPa.

The GSI parameter is the result of research by E. Hoek and E.T. Brown on the structural peculiarities and properties of rocks. Classification is constantly being improved depending on the requests arising from design practice. In one of the latest studies by Hoek and Brown [27], it is proposed to determine the GSI index as follows:

$$GSI = 1.5 \cdot JCond_{89} + \frac{RQD}{2}, \quad (3)$$

where:

$JCond_{89}$ – parameter of the rating rock joint classification in accordance with the methodology of the International Society for Rock Mechanics (ISRM) [31];

RQD – rock quality index.

$$JCond_{89} = J_{A4} = J_{A41} + J_{A42} + J_{A43} + J_{A44} + J_{A45}, \quad (4)$$

where:

J_{A4} – an index that takes into account the quality of contact over the joints:

J_{A41} – joint roughness coefficient;

J_{A42} – joint length rating;

J_{A43} – joint emptiness index;

J_{A44} – joint filling index;

J_{A45} – index that takes into account the joint wall weathering.

As a result of mine research (fracturing survey) at the Akzhal Mine, rating indexes have been determined that are $JCond_{89}$ (JA_4) according to the methodology of the International Society for Rock Mechanics (ISRM) [31]. The indexes in points are given in Table 1.

Table 1. Determining the rating assessment of the geological characteristics of fracturing JA_4

Parameter	Ranges of values				
A4. Joint characteristic (JCond 89)					
*A*4.1. Joint roughness	Very rough	Rough	Slightly rough	Smooth surfaces	Signs of slipping
Rating J_{A41}	6	5	3	1	0
*A*4.2. Joint length	< 1 m	1-3 m	3-10 m	10-20 m	> 20 m
Rating J_{A42}	6	4	2	1	0
A.4.3. Joint emptiness	Not found	< 0.1 mm	0.1-1.0 mm	1-5 mm	> 5 mm
Rating J_{A43}	6	5	4	1	0
*A*4.4. Joint filler	Not found	Solid filler < 5 mm	Solid filler > 5 mm	Soft filler < 5 mm	Soft filler > 5 mm
Rating J_{A44}	6	4	2	2	0
*A*4.5. Weathering of joint walls	Not found	Slightly weathered	Moderately weathered	Strongly weathered	Fragmented
Rating J_{A45}	6	5	3	1	0
$JCond_{89} = J_{A4} = J_{A41} + J_{A42} + J_{A43} + J_{A44} + J_{A45}$ = 3 + 2 + 4 +2 +5 = 16					

The RQD index is determined as the ratio of the total length of the obtained core pieces with a length of more than 100 mm to its total length [26]. That is, the RQD index has a directly proportional dependence on the number of joints in the rock mass, however, its value can vary significantly depending on the direction of drilling.

Therefore, to equalize this anisotropy, joints in the rock mass volume are also counted. The RQD parameter value for the Akzhal Mine conditions is determined according to the methodology in [31]. The procedure for determining the RQD value is conducted according to the scheme shown in Figure 1. The results of the RQD index determined at the Akzhal underground mine are presented in Table 2.

Thus, as a result of mine research in mine workings located in the mass under the open pit of the Akzhal Mine, the GSI value has been determined by the Formula 1 and is equal to 64.

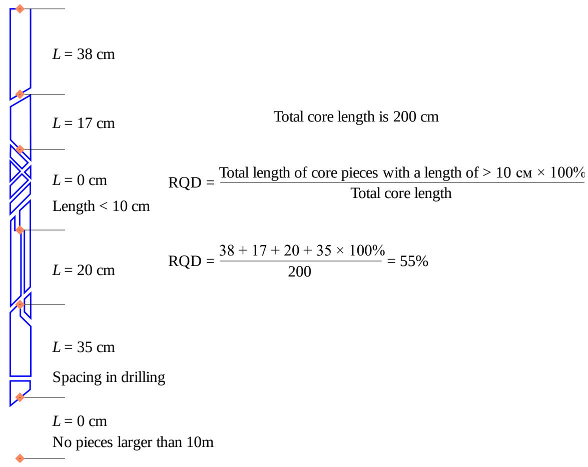

Figure 1. Procedure of measuring and example of calculating the RQD index

Table 2. Results of determining the RQD index

Well intervals, m	RQD values	Rock quality
30.8-38.3	92.6	Very hard
20.3-30.8	84.4	Hard
9.7-20.3	80	Hard
6.7-9.7	61	Medium hard
Average value	80.7	Hard

Then, to prepare the initial data for numerical modeling, the following data are entered into the RocData program:

– uniaxial compression strength of undisturbed rock (sig_{ci}) – 76.24 MPa;

– geological strength index (GSI) – 64;

– undisturbed rock parameter (m_i) – 10 (for limestone);

– mass disturbance by blasting operations (D) – 0 (characterizes the good quality of blasting operations);

– undisturbed rock deformation modulus (Ei) – 21000 MPa (for limestone);

– unit specific gravity of rocks (γ) – 2.7 t/m^3 or 0.027 MN/t^3.

Previously conducted studies for determining the physical-mechanical properties of rocks at the Akzhal Mine [32] and an additional complex of geotechnological research performed as part of this work make it possible to prepare the initial data (strength indexes according to the Hoek-Brown criterion) for numerical analysis of the stress-strain state of the rock mass under the open pit:

– rock type – massive limestones;

– ultimate strength in the mass sig_{cm} – 18.32 MPa;

– the Hoek-Brown criterion: $m_b = 2.64$; $s = 0.018$; $a = 0.502$;

– Poisson's ratio – 0.25.

For numerical analysis of the geomechanical situation in the rock bridge and assessment of the influence of the open-pit bottom width on the stress-strain state of the mass under the open pit, three models have been implemented, taking into account the change in the open-pit bottom space depending on the actual width from 20 to 60 m. The location of mine workings and the stope block, as well as their corresponding connection to the horizons of mining operations, is shown in Figure 2. The horizons for mining operations are chosen in accordance with the actual distance to the open-pit bottom. The stress-strain state of the mass is calculated for the real geometry of the open-pit walls. The asymmetric nature of the stress distribution in the mass under the open pit is a consequence of the difference in the elevation marks of the open-pit walls.

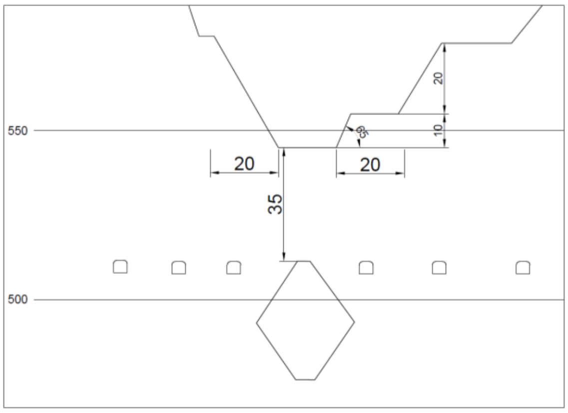

Figure 2. Layout of mine workings and stope block

The transition zone stress-strain state is characterized by changes in the principal stresses, the rock bridge behavior is determined, to the greatest extent, by the presence and value of horizontal stresses [33]. Therefore, they are decisive in assessing the rock bridge stable state.

3. Results and discussion

An analysis of the horizontal stresses distribution for a variant with a design open-pit bottom width of 20 m (Fig. 3) has revealed that an unloading zone is formed in the upper part of the rock bridge (directly in the zone adjacent to the open-pit bottom). With an increase in depth, a stress zone is formed in the middle of the rock bridge, while the most difficult situation occurs in the area in the five-meter zone from the stope block roof, where the stress values reach 2.61 MPa. Above the technogenic outcrop roof, horizontal stresses decrease to a value of 0.93 MPa.

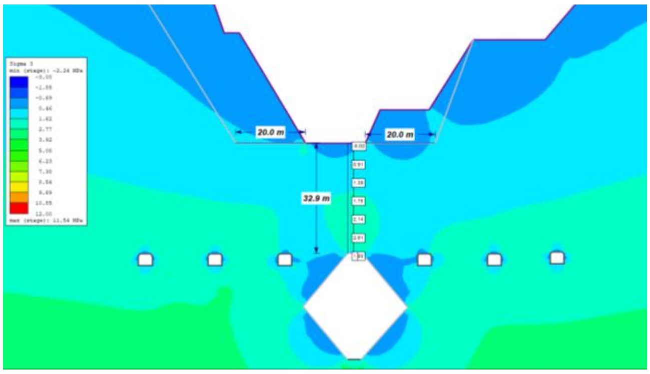

Figure 3. Isolines of horizontal stresses σ_3 for a variant with a design open -pit bottom width of 20 m

As the walls are sequentially mined, with the open-pit bottom expanding 20 m to the right (Fig. 4), in the central part of the rock bridge, the stresses are 1.89 MPa (compared to the initial variant, they decrease by 0.72 MPa). At the junction of the rock bridge lower part with the stope block roof, the value of σ_3 changes insignificantly (0.96 MPa).

The subsequent mining of the walls and the open-pit bottom expansion by another 20 m to the left (Fig. 5) is characterized by an increase in the unloading zone under the open-pit bottom to a depth of 10 m and a further increase in stresses in the rock bridge mass. In the area above the mined-out space, the values of horizontal stresses decrease compared to the previous variants of modeling. It should be noted that the principal stresses arising in the rock bridge with an increase in the open-pit bottom sizes do not exceed the level at which the mass continuity is disturbed.

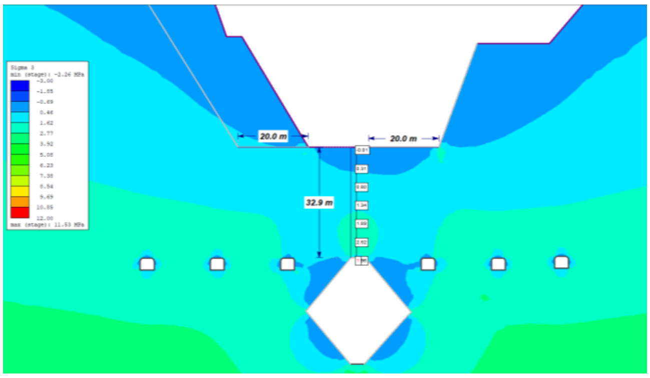

Figure 4. Isolines of horizontal stresses σ_3 for a variant with the open-pit bottom expansion by 20 m to the right

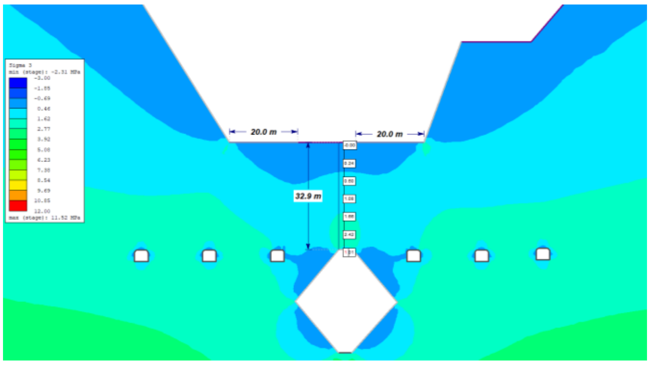

Figure 5. Isolines of horizontal stresses σ_3 for a variant with the open-pit bottom expansion by 20 m to the right and 20 m to the left

The SSS numerical modeling of the mass under the open pit has revealed that with sequential mining of the walls with the expansion of the open-pit bottom up to 60 m, an increase in the unloading zone is observed in the rock bridge upper area. With an increase in depth, a stress zone is formed in the middle of the rock bridge, while the most difficult situation occurs in the area in the five-meter zone from the stope block roof. With an increase in the open-pit bottom sizes, the values of horizontal stresses in this zone decrease from 2.61 MPa (with a bottom width of 20 m) to 1.87 MPa (with a bottom width of 60 m), and in the border mass of the block roof, there is an insignificant increase in stresses (from 0.81 MPa with a width of 20 m, up to 1.32 MPa with a width of 60 m). Figure 6 presents the dependences of the change in the values of horizontal stresses σ_3 at the stages of the open-pit bottom expansion.

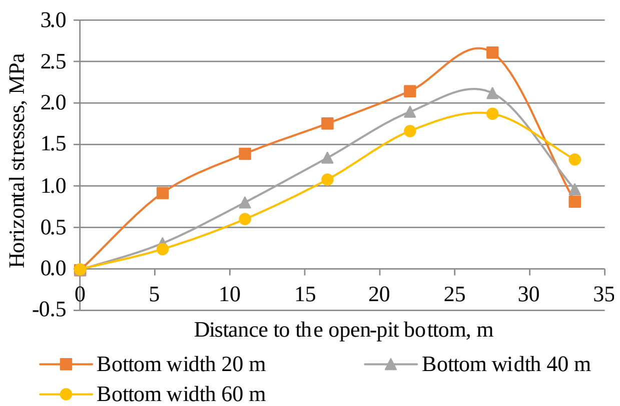

Figure 6. Dependences of the horizontal stresses σ_3 distribution at the stages of the open-pit bottom expansion

The research results show that the influence of the stope block parameters and the open-pit bottom width lead to a slight change in the stress-strain state of the rock mass between the open pit and the underground mine. A significant part of the rock bridge is in a stable state and ensures the safety of mining operations. It should be noted that during the numerical analysis, the seismic effect of the blast force on the rock bridge when mining the ore bodies with the sublevel caving system was not taken into account in detail.

However, when conducting a numerical analysis, the index of rock disturbance by blasting operations was used, the value of which corresponded to the good quality of blasting operations. In further research, it is planned to conduct a study to determine the patterns of change in the index of mass disturbance by blasting operations, depending on the category of rock stability. This will make it possible to correct the geomechanical model during numerical analysis and more correctly assess the rock bridge geomechanical state.

4. Conclusions

To study the stress-strain state of the mass under the open pit, taking into account the change in the open-pit bottom width, a complex of geotechnological research has been conducted in the mining-geological and mining-technical conditions of the Akzhal Mine development. This research complex includes laboratory testing of rock samples, mine research and the stress-strain state numerical modeling of the mass under the open pit.

The information obtained from the results of a geotechnological research complex makes it possible to predict the rock bridge state depending on the open-pit bottom size (width). Based on the numerical modeling results, it can be assumed that an increase in the open-pit bottom width leads to a decrease in the zone of tensile stress concentration in the arch pillar of the stope block, which in turn has a positive effect on the transition zone stability. Thus, the probability of the rock bridge collapse does not increase with an increase in the width of the open-pit bottom. The border area of the rock mass, adjacent to the block 30 m high and mined by the sublevel caving system, is in a stable state. Expansion of the open-pit bottom will not lead to rock bridge mass discontinuity. The general state of the walls is characterized as extremely stable.

The computational model adapted to the real conditions at the Akzhal Mine is a reliable tool for predicting the geomechanical situation in the mass under the open pit for taking timely measures to ensure the safety of mining operations.

Thus, the ability of predicting the change in the stress-strain state in the transition zone and determining the rock bridge safe parameters can reduce the probability of their destruction and make timely management decisions on safe conditions for mining the reserves.

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Дослідження напружено-деформованого стану підкар'єрного масиву з урахуванням зміни ширини дна кар'єру

А. Імашев, А. Суімбаєва, Г. Жунусбекова, Ш. Зейтінова, А. Куттибаєв, А. Муссін

Мета. Дослідження напружено-деформованого стану підкар'єрного масиву з урахуванням зміни ширини дна кар'єру для вивчення геомеханічного стану та визначення безпечних параметрів породного моста.

Методика. Вивчення особливостей формування напружено-деформованого стану перехідної зони проводилося за методикою, заснованою на використанні чисельних методів досліджень з урахуванням геологічного індексу міцності (GSI), який дозволяє врахувати тріщинуватість гірських порід, обводненість, літологію та інші показники міцності, за рахунок чого відбувається коректний перехід від міцності зразка гірських порід до міцності масиву.

Результати. На основі результатів чисельного моделювання встановлено, що збільшення ширини дна кар'єру призводить до зменшення зони концентрації розтягуючих напружень у стелині очисного блоку, що в свою чергу чинить позитивний вплив на стійкість породного моста, тобто ймовірність обвалення породного моста зі збільшенням ширини дна кар'єру не підвищується.

Наукова новизна. Вперше отримано залежність розподілу горизонтальних напружень σ_3 на етапах розширення дна кар'єру на свинцево-цинковому родовищі Акжал. Це дозволяє реалістично прогнозувати зміну геомеханічного стану породного мосту залежно від ширини дна карєру.

Практична значимість. Можливість передбачити зміну напружено-деформованого стану у перехідній зоні та визначення безпечних параметрів породного мосту дозволять знизити ймовірність їх руйнування та прийняти своєчасні управлінські рішення щодо безпечних умов відпрацювання запасів.

Ключові слова: *напружено-деформований стан, запобіжний цілик, геологічний індекс міцності, чисельний аналіз*