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Research Article

Investigation of Stress Redistribution Within the Host Rock Mass During Underground Mining Operations

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Abstract

The article presents the results of a systematic investigation of stress redistribution and the formation of stress concentration and relaxation zones in the rock mass surrounding underground mine workings under the influence of mining operations. The study was conducted considering the geological and geomechanical conditions of an underground mining operation, with particular emphasis on the changes in the stress–strain state of the rock mass caused by excavation. A mathematical model was developed to describe the stress–strain behavior of the rock mass, with mining depth, vertical and horizontal in-situ stresses, Young's modulus, and Poisson's ratio adopted as the principal input parameters. The research methodology is based on analytical calculations, geomechanical modeling, and comparative analysis of the obtained results. The proposed approach makes it possible to quantitatively evaluate the spatial redistribution of stresses and identify areas characterized by increased stress concentration and stress relaxation. The modeling results demonstrate that mining operations cause significant redistribution of the initial stress field, resulting in the formation of localized zones of increased compressive stress around the excavation boundaries. Particular attention was given to the development of tensile-stress-affected zones above the excavation roof. A zone extending approximately 20–30 m above the roof was identified, indicating a potential area of increased rock fracturing and activation of pre-existing discontinuities. The values of the relaxation coefficient were determined and justified based on the specific geological and geomechanical conditions of the mine. The proposed model also allows the regularities governing the formation and spatial development of stress concentration and relaxation zones to be assessed. The obtained results provide a scientific and practical basis for quantitatively assessing mining-induced stress redistribution and improving the geomechanical justification of underground excavation stability and support parameters

Keywords

Rock Mass, Stress Concentration, Stress-strain State, Mathematical Model, Relaxed Zone, Stress Redistribution, Geomechanical Monitoring

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1. Introduction

At present, the increasing depth and intensity of mineral extraction are contributing to the formation of complex stress states within rock masses under the influence of both natural and anthropogenic factors. Under these conditions, improving methods for effective ground pressure management and quantitatively assessing the impact of mining operations on the rock mass surrounding underground mine workings constitute an important scientific and practical challenge [1].

Furthermore, ensuring the long-term stability of underground mine workings under elevated stress conditions requires the advancement of existing mining technologies and the implementation of scientifically substantiated geotechnological solutions. From this perspective, key priorities include the accurate assessment of the geomechanical state of the rock mass, the development of comprehensive engineering measures to ensure the stability of underground workings, and the consideration of spatial and temporal changes in tectonic stresses [2].

The geological faults present within the area of the Razvedochnaya ore mine further complicate the geodynamic conditions of the deposit. The Kyzylalmasay Fault, located in the central part of the mine, has a thickness of up to 200-250 m and extends for approximately 1000-1200 m. The ore body located in the central part of the deposit has a relatively simple morphology. Its thickness varies from 40-50 m to 200-250 m, while its strike length reaches approximately 1200 m. The distance from the upper boundary of the ore body to the ground surface ranges from 300 to 450 m, whereas the distance from the ground surface to the lower boundary of the ore body reaches approximately 800 m. The dip angle of the ore body is 50 °-70 °[3].

The strength coefficient of the ore, according to the M. M. Protodyakonov scale, ranges from f = 8.53 to f = 12.8. In zones characterized by intense fracturing and significant hydrothermal alteration, the strength coefficient decreases to f = 6-8. The gold-bearing ore consists predominantly of quartz. In addition to quartz, the ore contains carbonates (up to 1%), pyrite as the principal sulfide mineral, as well as chalcopyrite and sphalerite, which occur in minor quantities within the ore body. The surrounding rock mass is composed mainly of siltstones, with a strength coefficient of f = 10-14 [4].

To assess the reliability of the results obtained from the current research and to improve the accuracy of the analysis, it is necessary to develop an appropriate mathematical model. The mathematical model developed for this study serves as the principal theoretical tool for the quantitative assessment of the stress-strain state of the rock mass during mining operations and for predicting its spatial evolution over time [5].

2. Methodology

For the geological and geomechanical conditions of the Razvedochnaya mine, the proposed model describes the relationships among the following principal geomechanical parameters:

1) H - depth below the ground surface, m;
2) σ_v - vertical stress;
3) σ_g - horizontal compressive tectonic stress; in the calculations, its average value was assumed to be 1.8γH. The value σ_g = 1.8γH was determined based on reports incorporating the results of scientific studies conducted to date under the conditions of the Razvedochnaya Mine;
4) E - elastic modulus;
5) kq - coefficient accounting for the redistribution of stresses in the rock mass resulting from mining operations;
6) ν - Poisson's ratio.

The proposed mathematical model provides a basis not only for performing theoretical and practical calculations, but also for analyzing the results of physical and geomechanical modeling. Within the framework of this mathematical model, the initial stress field is expressed as follows.

Vertical stress

$$\sigma_v = \gamma H \ \text{[MPa]}$$

where: γ — unit weight of the rock mass, typically γ=0.023 *MPa/m*

$$\sigma_v = 0.023 \ H \ \text{[MPa]}$$

Horizontal stress

$$\sigma_g = k\sigma_v = 1{,}8\gamma\mathrm{H} = 0{,}0414 \ H \ \text{[MPa]}$$

Determination of principal stresses under plane-strain conditions

$$\sigma 1{,}2 = \sigma v + \sigma g 2 + (\sigma v - \sigma g 2) 2 + k_q 2 \ \text{[MPa]}$$

Stresses in the rock mass surrounding the underground opening after mining operations.

$$\sigma_{max} = \max(\sigma_v, \sigma_g)$$

$$\sigma_{min} = \min(\sigma_v, \sigma_g)$$

Elastic deformation modulus for assessing the development of the relaxation zone

According to the Hoek-Brown criterion

$$\varepsilon = \frac{1}{E}(\sigma, k_q\sigma')$$

For plane-strain conditions:

$$\varepsilon_x = \frac{\sigma_g - k_q\sigma_v}{E}$$

$$\varepsilon_y = \frac{\sigma_v - k_q \sigma_g}{E}$$

The main advantages of the proposed model are as follows: it accounts for the effect of depth (*H*) through the initial geostatic stress; jointly evaluates the ratio between the natural vertical and horizontal stresses; incorporates the deformability of the rock mass through the elastic modulus (*E*) and Poisson's ratio (ν); and establishes a unified mathematical relationship between the stress concentration coefficient (*Kk*) and the relaxation coefficient (K_{rel}) [6].

The model enables the prediction of the development of stress concentration and the formation patterns of relaxed zones under various mining conditions. This provides a basis for assessing the stability of underground mine workings, identifying potentially hazardous geomechanical zones in advance, and scientifically substantiating safe mining parameters.

Computer modeling of geomechanical processes is an important scientific and practical tool for the safe and efficient development of underground mines. As mining operations progress to greater depths, the natural stress state of the rock mass is disturbed, resulting in stress redistribution, deformation, the formation of plastic zones, abutment pressure, and relaxed areas. Since it is difficult to fully assess these processes solely through field observations, modern numerical modeling methods have become an integral part of geomechanical investigations [7].

Geomechanical modeling was performed using the *ROCSCIENCE software suite*. The software is based on the *finite element method (FEM)* and enables step-by-step modeling of the elastic-plastic deformation of rock masses under complex geological conditions. Taking into account the sequence of mining operations, the physicomechanical properties of the rock mass, and the spatial configuration of underground mine workings, the software enables the determination of the three-dimensional distribution of stresses, strains, and displacements within the rock mass. The *Mohr-Coulomb criterion* was used as the failure criterion for the rock mass. This model is widely applied in mining practice and provides reliable results for identifying zones of plastic deformation and areas in which the strength limit of the rock mass is exceeded [8-9].

Stress-state modeling was also performed for several mining sections of the *Razvedochnaya mine*. The following mechanical properties of the ore body and surrounding rock mass were adopted in the modeling: the unit weight of the rock mass was taken as $\gamma = 0.025\ MN/m^3$; the Young's modulus of the ore body was $E = 5600\ MPa$, while that of the surrounding rock mass was $E = 5300\ MPa$; Poisson's ratio of the ore was $\nu = 0.25$; and the unit weight of the surrounding rock mass was $0.026\ MN/m^3$ [9].

3. Results and Discussion

The results of modeling the stress state around the excavation formed during mining operations at the *+745 m level of the Razvedochnaya mine* are presented in Figures 1 and 2 as individual components of the tangential stress field. The obtained results indicate the presence of the following principal regularities in the redistribution of horizontal stresses within the rock mass:

1) *Zones of compressive stress concentration in the horizontal direction* are formed along the side boundary of the excavation where the underground working is located, as well as in the vicinity of the sidewalls of the level drift (Figure 3). This phenomenon can be attributed to the redistribution of the load caused by the excavated void and the development of additional compressive stress fields within the load-bearing sections of the rock mass.
2) An increase in the *secondary principal stresses* is observed on the left side of the roof of the underground working. The increase in stress intensity within these zones directly affects the stability of structural elements and may contribute to the formation of geomechanically unfavorable sections.
3) The *maximum values of tangential stresses* are recorded in the corner area of the excavation adjacent to the hanging-wall side of the ore body (Figure 1). This section represents a localized source of stress concentration and can be considered a zone with a high potential for the development of deformation processes.
4) Within the roof of the excavation, the zone affected by *tensile stresses* extends to an approximate height of *20-30 m*. This may create favorable conditions for the development of fracturing and activation of existing fracture systems in the overlying strata.
5) According to the modeling results, the magnitudes of the *tensile and compressive stresses* developing around the sidewalls of the stope remain below the corresponding strength limits of the rock mass. This indicates that the risk of abrupt loss of stability in these sections is relatively limited.

Thus, under the conditions of the *+745 m level*, the mining process produces a complex, multicomponent stress field within the rock mass. The identified zones of stress concentration are of significant scientific and practical importance for ensuring the stability of underground mine workings, substantiating support parameters, and forecasting geodynamically hazardous sections of the mine [10].

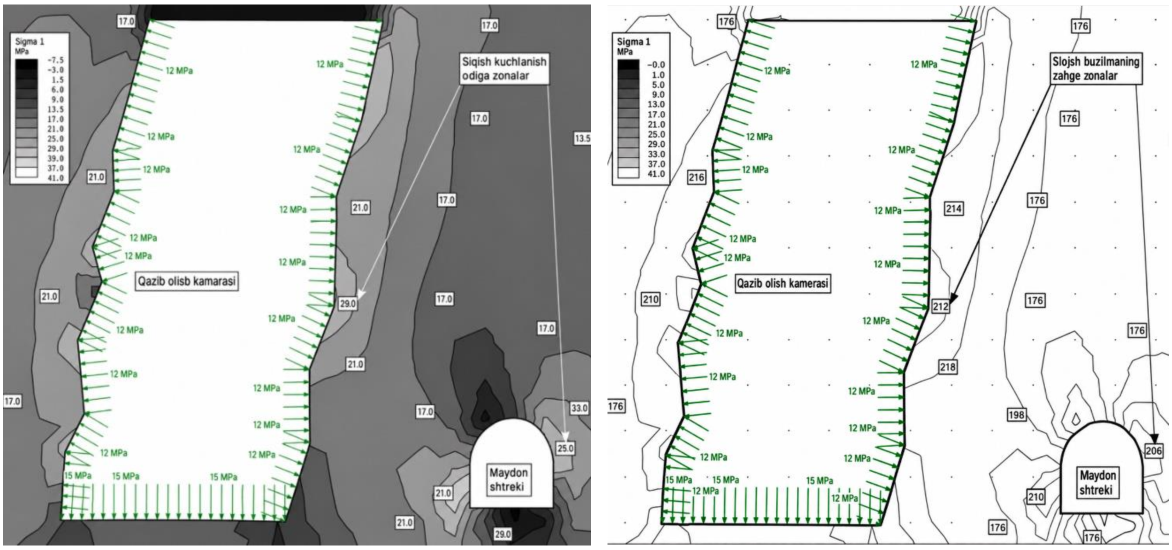

Figure 1. Distribution pattern of horizontal stresses (σ_1) in the rock mass after mining operations at the +745 m level of the Razvedochnaya mine.

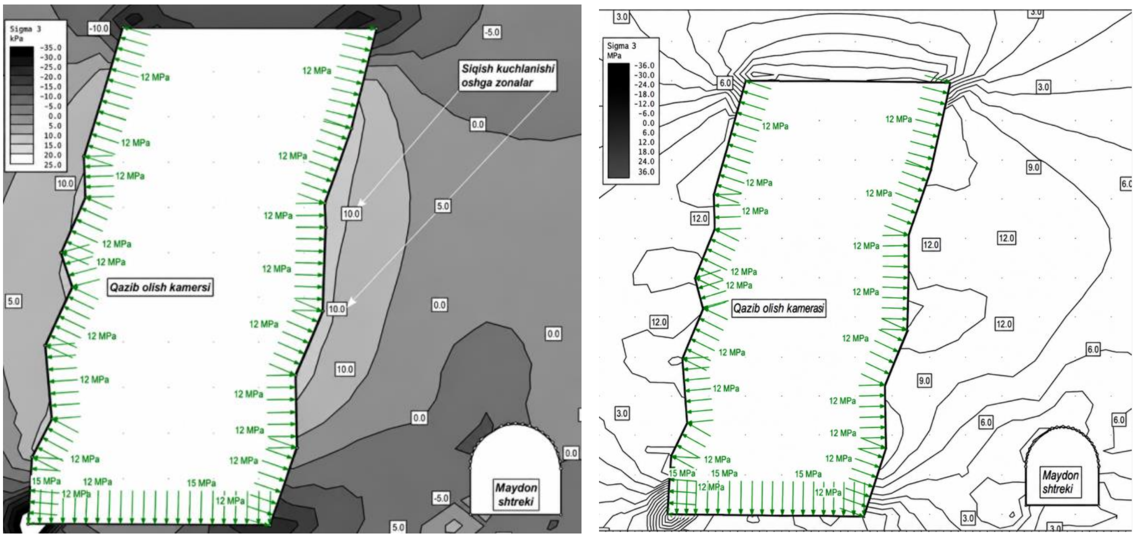

Figure 2. Distribution pattern of the second horizontal stress component (σ_3) in the rock mass after mining operations at the +745 m level of the Razvedochnaya mine.

According to the mathematical modeling results presented above, the compressive stress values (σ_1) predominantly develop within the rock mass surrounding the excavation chamber. The qualitative pattern of stress-field distribution remains generally consistent [11].

For the geomechanical models presented above, the following generalized analytical equation is recommended. It can subsequently be transformed into a specific form adapted to each individual mining level and sublevel, as well as into a multicomponent analytical expression [12].

$$\boldsymbol{\tau}_m = \sigma_t + \sum_{i=1}^{n} A_1 \ln x_i \left[\frac{(x-x_i)^2}{r_i^2}\right] - \sum_{i=1}^{n} B_1 \ln x_i \left[\frac{(x-x_i)^2}{y_i^2}\right] + kx; \text{ [MPa]}$$

where:

1) τ_m - normal or tangential stress in the rock mass, MPa;
2) σ_t - natural geostatic stress;
3) A_1 - maximum stress amplitude in the abutment-pressure zone;
4) x_i - coordinate of the stress-concentration center;
5) r_i - radius of propagation of the stress-concentration zone;
6) B_1 - stress-reduction amplitude within the relaxation (destressed) zone;
7) y_i - width of influence of the relaxation zone;
8) k - depth or mining-front influence coefficient;
9) x - coordinate or distance, m.

Figure 3 presents the distribution curve of compressive stresses (σ_1) along the contour of the 2D ore body. The compressive stress values range from 0 to 65 MPa. Along the horizontal OX axis, the length of the excavation contour formed as a result of mining the 2D ore body is represented.

The graph presented above illustrates the redistribution dynamics of compressive stresses (σ_1) along the contour of the excavation formed in the rock mass after mining. The following geomechanical features can be identified from the graph: high initial geostatic and tectonic stresses in the initial section; a relaxed zone extending from 10 to 90 m; a very sharp localized stress-concentration zone between 105 and 112 m; a relaxed state of the rock mass within the 115-180 m interval; and a subsequent increase in abutment pressure beyond 185 m.

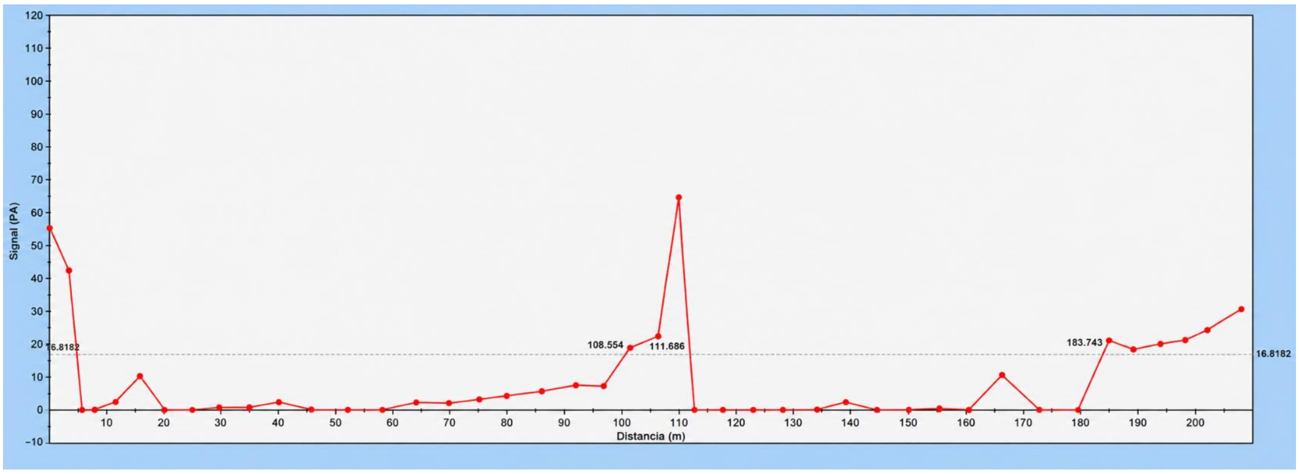

Figure 3. *Distribution curve of compressive stresses (σ1) along the contour of the excavation formed after mining the 2D ore body.*

Such a stress distribution is generally formed as a result of the interaction between the collapse of the surrounding rock mass into the excavated void, tectonic fractures, abutment-pressure zones, and elastic-plastic deformation zones.

Following the extraction of the ore bodies located in the central section of the Razvedochnaya mine at the +745 m level, new characteristics of the redistribution of compressive stresses within the rock mass surrounding the excavation are observed:

A decrease in the values of compressive stresses and maximum tangential stresses is observed in the roof and floor of the excavation (Figure 1).

A wide zone of tensile stresses develops in the areas of the excavation floor located on the hanging-wall side of the ore body (Figure 1).

Zones characterized by increased values of compressive and maximum tangential stresses are formed in the floor of the excavation (Figure 2).

In the roof and floor of the excavation, the levels of tensile and compressive stresses remain below the corresponding strength limits of the surrounding rocks.

Thus, under the conditions of the Razvedochnaya mine, under the influence of high tectonic stresses, when the height of the ore extraction zone in the central section does not exceed the height of three sublevels, failure of the rock mass along the sidewalls of the excavation does not affect the zone containing underground workings driven through barren rock. If the height of the excavation exceeds the critical value, failure of the rock mass along the sidewalls may extend over a considerable distance.

Based on the identified patterns governing the formation of high-stress zones, it becomes possible to develop appropriate geotechnological schemes and mining parameters for the commencement of mining operations within zones characterized by a high concentration of dynamic events.

The relaxed-zone development coefficient (K_r) is an important geomechanical parameter characterizing the degree of stress redistribution within the rock mass induced by underground mining operations. An increase in the value of this coefficient indicates a reduction in stresses and an increase in deformation within the rock mass, resulting in the expansion of the relaxed zone. Therefore, K_r serves as an important criterion not only for assessing the geomechanical state around the excavation, but also for predicting the long-term stability of underground mine workings and determining the likelihood of secondary deformation processes.

Within the framework of this study, the proposed mathematical model makes it possible to evaluate the development coefficient of the relaxed zone in relation to mining depth, in-situ stresses, and the elastic properties of the rock mass. Calibration and validation of the model using numerical modeling results and mine monitoring data improve the reliability of the estimated K_r values and expand the applicability of the model under different geological conditions.

Consequently, the use of this coefficient provides an effective tool for the early identification of hazardous relaxed zones, optimization of the mining sequence, scientific justification of support parameters, and improvement of underground mining safety. In this regard, the K_r parameter should be considered an integral component of a geomechanical monitoring system and should preferably be applied in an integrated manner with modern numerical modeling methods.

Abbreviations

τ_m Normal or Tangential Stress in the Rock Mass
σ_t Natural Geostatic Stress
A_1 Maximum Stress Amplitude in the Abutment-pressure Zone

Author Contributions

Salyamova Klara Djabbarovna: Methodology, Project administration, Supervision, Writing – review & editing

Bakirov Gayrat Kholikberdiyevich: Methodology, Resources, Validation, Writing – review & editing

Nurkhonov Khusan Almirza Ugli: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft

Boriyev Feruz Mansur Ogli: Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

Salyamova Klara Djabbarovna is a prominent Uzbek scientist, Doctor of Technical Sciences, and professor. Her scientific research focuses mainly on the mechanics of deformable solid bodies, the strength and stability of earth dams, and the seismic safety and dynamic behavior of hydraulic structures. She currently works as a chief research scientist at the M.T. Urazbaev Institute of Mechanics and Seismic Stability of Structures of the Academy of Sciences of Uzbekistan. She continues to contribute to scientific research and the training of young researchers.

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Research Field

Salyamova Klara Djabbarovna: Mechanics of Deformable Solids, Strength and Stability of Earth Dams, Seismic Safety of Hydraulic Structures, Dynamic and Static Loads; Soil Mechanics

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Nurkhonov Khusan Almirza Ugli: Mining Engineering; Underground Mining Technologies, Rock Mechanics; Blasting and Drilling Technology, Contour Blasting; Mine Ventilation, Gas-Dynamic Processes in Mine Workings, Mathematical Modeling of Mining Processes, and Mining Safety

Boriyev Feruz Mansur Ogli: Mining Engineering, Mining Safety, Industrial Training, Occupational Safety, Mining Technologies, Professional Development of Mining Personnel