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Assessing stability of mine workings driven in stratified rock mass

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Abstract

Purpose. The research purpose is to assess the stability of mine workings driven in a stratified rock mass by studying the influence of the stratified rock bedding angle on the rock mass stress-strain state (SSS).

Methods. The research uses both experimental and numerical methods. Experimental studies are carried out using rock samples with different angles of rock layer occurrence, while numerical modeling is performed using the RS2 (Geotechnical Finite Element Analysis) software based on the generalized Hoek-Brown failure criterion. The studies are carried out on models covering the border area of the mine workings driven in the mass with the angles of rock occurrence from 0 to 75°.

Findings. Experimental and numerical studies have shown that when the rock layer inclination angle changes, significant changes occur in the stress concentration zones around the mine workings. An increased rock layer inclination angle is accompanied by a change in stress distribution, which is important for assessing the stability of mine workings. A particularly strong influence is observed at the angles of rock occurrence 30° and above.

Originality. The research novelty is in revealing the patterns in the stress distribution in the stratified rock masses depending on the rock layer inclination angle. Research results provide new data on the rock interaction mechanisms in difficult geological conditions.

Practical implications. The results obtained can be used in the planning and operation of mine workings in difficult geological conditions. By taking into account the changes in stress zones caused by the rock layer inclination angle, it is possible to improve the safety and efficiency of mining operations.

Keywords: *mine workings, stratified mass, rocks, stability, stresses, numerical modeling*

1. Introduction

The mining industry plays a key role in the economy of Kazakhstan, constituting an important link in the structure of its industrial production and export supply [1]-[3]. The country is rich in natural resources, which include coal, oil, gas, metal ores and various minerals. This rich geological potential makes Kazakhstan one of the leading producers and exporters of resources in the global market [4]-[6]. However, there are various challenges related to the stability of mine workings in rock masses during the mining of mineral deposits. A particularly important factor influencing the stability of mine workings is the structure and mechanical properties of stratified rocks [7].

Stratified rocks are widespread in the rock masses of Kazakhstan and have a significant impact on the processes of field mining. The stratified rock behavior in mine workings depends to a large extent on their bedding angle and the stress distribution around the mine working [8]. Understanding these processes is a key to ensuring the safety and effectiveness of mining operations. In most cases, the mass surrounding underground structures consists of stratified sandstone, shale and interstratified sedimentary rocks, that is, an alternation of different rocks. Anisotropic deformation and failure characteristics of stratified rocks should be taken into account when analyzing the design and stability of an underground structure [9]-[11].

According to previously conducted studies, the rock stratification has been found to significantly influence the stress-strain state of the mass surrounding the mine workings. The paper [12] indicates that for undisturbed rock without fractures, the failure zone is smaller than in the mass with bedding layers. Stratified structure reduces rock strength due to planes of weakening [13], [14]. The authors of the paper [15], based on experimental data, constructed regression relationships to assess the influence of bedding angle and lateral pressure on strength and deformation. Correlation coefficients show a direct relationship between these factors.

According to the authors in [16], there are two mechanisms of anisotropic rock failure. If additional parameters unrelated to the stratified rock structure are not considered, these are failure along bedding planes and failure along planes where critical rock strength is achieved. The authors in [17] argue that at horizontal occurrence of rocks, the failure mode is similar to that of "rock beam" and, at large rock

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layer inclination angles there is a sliding on the contacts of rock layers. However, it should be noted that the research does not take into account the rock mass gravity. The paper [12] states that at an inclination angle of 45°, the failure mechanism in the mass changes from bending to sliding.

Depending on the rock layer inclination angle, the stress zones around the mine working at horizontal and vertical occurrence of layers are distributed symmetrically relative to the vertical mine working axis, whereas with inclined rock mass stratification, the symmetry changes, but with an increase in the inclination angle, the symmetry axis shifts [18], [18]. Asymmetry of failure zones leads to unfavorable behavior of the mass around the mine working [20].

According to previous studies, the strength of stratified rocks varies depending on the direction of the acting loads. The maximum strength of the rock mass border area is achieved under the perpendicular influence of the acting loads relative to the rock layers. Minimum strengths are achieved when the angle between the layers and the direction of the acting loads is in the range of 30 to 60° [21]. Triaxial compression tests of rock samples with different layer dip angles performed by the authors of the paper [22] show that the failure mode and stratified rock strength are related to the layer inclination angles, demonstrating obvious anisotropy. However, at horizontal ($\beta = 0°$) and vertical bedding gradients ($\beta = 90°$), the rock strength varies, and this difference should be taken into account in the failure criteria.

The strength criterion is of decisive importance in determining the rock mass failure characteristics. Quite a few criteria have been proposed to describe the dependence of anisotropic rock strength on the mass SSS, such as Hoek-Brown, Mohr-Coulomb, Jaeger theory, etc. [23], [24]. Classical failure criteria for assessing the isotropic mass stability require consideration of the thickness and strength, as well as the direction (inclination angle) of individual rock layers in the geomechanical substantiation of an anisotropic mass [25]. Hoek-Brown proposed that the anisotropic rock strength parameters vary depending on the load direction. When studying the anisotropic rock strength, it has been revealed that the Hoek-Brown criterion parameters quantify the anisotropic effect [26]-[28].

Before technogenic outcrops, the rock mass is in an undisturbed stress-strain state under the influence of vertical and horizontal forces. During mining operations, the initial stress state is disturbed and stresses are redistributed [29]. De-stressing zones and stress concentration zones are formed around the mine working. If the SSS exceeds the critical strength of the rocks surrounding the mine working, then a failure process occurs. Studying the mass SSS provides valuable initial data for solving problems arising in the conditions of underground mining, construction of underground structures, and the stability of rock outcrops in mine workings.

The paper discusses the influence of the rock dip angle and the distribution of acting stresses on the failure zone around the mine working.

2. Methodology

In this paper, the assessment of rock stability is implemented using the generalized Hoek-Brown criterion, widely known in rock mechanics. The generalized Hoek-Brown criterion [30], [31] was developed as a tool to assess the rock mass strength (Fig. 1).

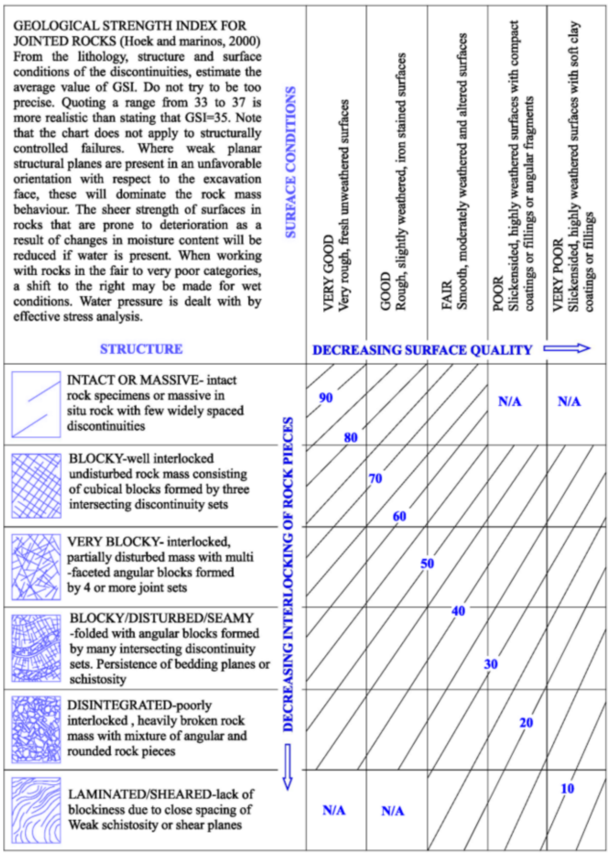

Figure 1. General diagram for GSI assessments based on geological observations

Based on the criterion, the transition from the laboratory strength of rock samples to the strength properties of rocks in the mass has been developed by introducing additional parameters that take into account structural weakening – *GSI* (Geological Strength Index) [32].

Based on the rock mass quality, the intact rock strength is reduced quantitatively to assess the rock mass strength. The generalized Hoek-Brown criterion is expressed by the following Formula:

$$\sigma_1 = \sigma_3 + \sigma_c \left(m_b \frac{\sigma_3}{\sigma_c} + s \right)^a , \quad (1)$$

where:

σ_1 and σ_3 – the principal and secondary effective stresses at failure, respectively;

σ_c – the undisturbed rock uniaxial compressive strength;

m_b, s, a – the Hoek-Brown constants, which are determined based on the *GSI* and *D* parameters (technogenic disturbance coefficient of the mass) by Formulas:

$$m_b = m_i \exp\left(\frac{GSI - 100}{28 - 14D} \right); \quad (2)$$

$$s = \exp\left(\frac{GSI - 100}{9 - 3D} \right); \quad (3)$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-\frac{GSI}{15}} + e^{-\frac{20}{3}} \right). \quad (4)$$

The technogenic disturbance coefficient *D* of the mass is a factor reflecting the technogenic influence on the studied rock and tunneling conditions. The factor D value varies from 0 (minimal technogenic impact on the rock – good rock quality) to 0.8 (poor rock quality, drilling and blasting mining method).

An important input parameter of the Hoek-Brown failure criterion is the geological strength index, developed to describe the rock structure and fracture surface conditions in a rock mass. *GSI* is determined by visual inspection of the mass, outcropped surfaces of mine workings and pieces of rock cores [33]. Using *GSI*, the mechanical behavior of the rock mass can be accurately assessed for both very poor and very good quality rocks [33].

To study the deformations and failure mode of stratified rocks, samples simulating bedding layers are made from building materials. Rock samples are filled with three layers at different angles of occurrence, which are shown in Figure 2. For different rock test methods, the ratio of the sample height to its diameter, according to the accepted methodology, is recommended to be equal to two. With this ratio of sample sizes, the accuracy of test results is significantly improved and the influence of various factors on the strength and deformation of rock samples is reduced. The sample is prepared in a cylindrical shape with a diameter of 40 cm and a height of 80 cm.

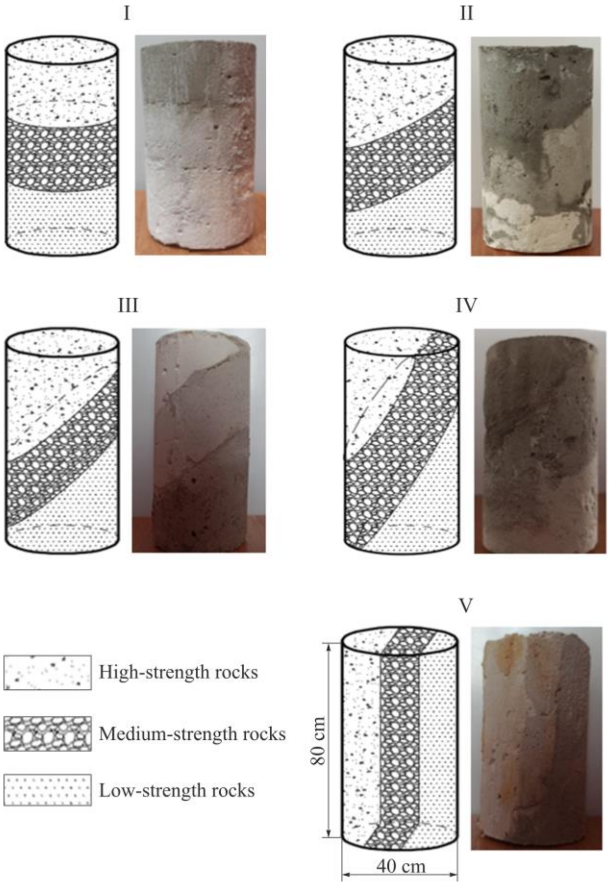

Figure 2. Formation of rock samples to be tested: I – 0°; II – 5°; III – 15°; IV – 30°; V – 45°; VI – 60°; VII – 75°

A point-load testing device GCTS PLT-2W is used to perform uniaxial compression tests on rock samples. This device provides high accuracy of load and deformation control during test process, which makes it possible to obtain reliable data on rock strength and deformation. The uniaxial compression test results are processed in the following sequence.

The uniaxial compressive strength $\sigma_{c(i)}$ is calculated using the Formula:

$$\sigma_{c(i)} = \frac{4P}{\pi D^2}, \quad (5)$$

where:

P – the maximum load achieved during sample testing, kN;

D – the sample diameter, cm;

i – the sample number in sample collection.

The average value of the rock uniaxial compressive strength $\sigma_{c(av)}$ is calculated based on the results of testing all samples:

$$\sigma_{c(av)} = \frac{\sum_{i=1}^{n} \sigma_{c(i)}}{n}, \quad (6)$$

where:

n – the number of samples tested.

The confidence interval for the deviation of test results of individual samples from the average value of $\Delta\sigma$ is determined by the Formula:

$$\Delta\sigma = \pm\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\sigma_i - \sigma_{av}\right)^2}. \quad (7)$$

Then the coefficient of variation v of the determined parameter is calculated:

$$v = \frac{\Delta\sigma}{\sigma_{av}} \cdot 100\%. \quad (8)$$

The above sequence makes it possible to systematically process and analyze the results of testing the rock samples for uniaxial compression, which helps to understand their mechanical behavior and stability under different conditions.

The pattern between the angle of rock occurrence and the acting load is studied using the mathematical modeling method, since modeling allows studying geomechanical processes in a wider range and predicting their development. The RS2 software product (Geotechnical Finite Element Analysis) is used in the study. RS2 is software for geotechnical finite element analysis developed by Rocscience.

The choice of the RS2 software is substantiated by its capabilities focused on performing geotechnical analysis using the finite element method. The RS2 software provides powerful tools for modeling complex geological structures and assessing the stability of mine workings. Its functionality allows taking into account various parameters, such as mine working geometry, rock characteristics, hydrogeological conditions and load dynamics. Thus, the use of the RS2 software provides reliable and accurate modeling of geotechnical processes, which makes it an optimal choice for studying the stability of mine workings in the rock stratum.

A 5 m wide arched cross-sectional mine working located at a depth of 600 m is chosen as the model. To study the influence of layer occurrence angle on the mine working stability, models have been constructed in a homogeneous mass with rock layer occurrence from 0 to 75°. Values of acting stresses are taken along a line drawn vertically upwards along the roof center, as well as along two lines drawn along the bedding of rock layers and perpendicular to bedding (Fig. 4).

This modeling approach takes into account complex geometrical and geomechanical rock mass parameters, which in turn contributes to a more accurate analysis of the in-fluence of the angle of rock layer occurrence on the mine working stability.

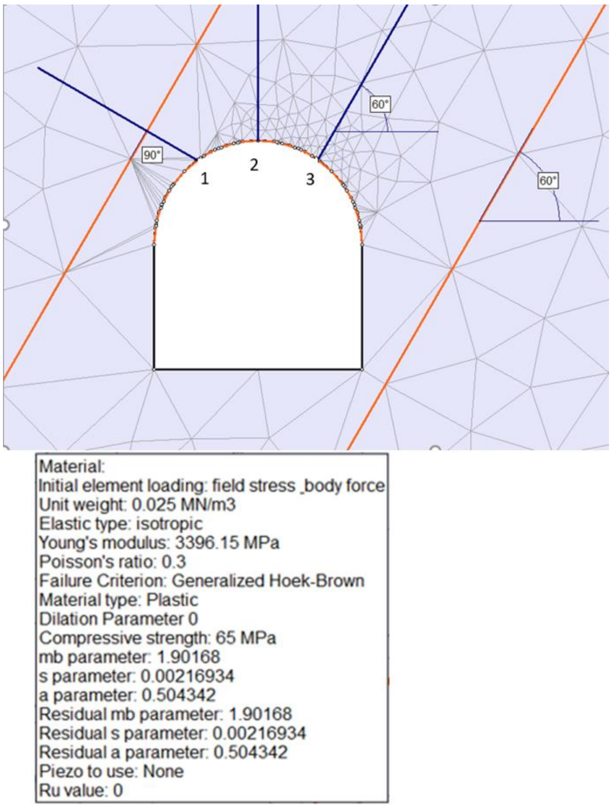

Figure 4. Numerical model layout and material properties: 1-3 – numbered measurement points

In addition, the use of the RS2 software provides reliable and accurate modeling of geotechnical processes, making it the optimal choice for studying the stability of mine workings in the rock stratum.

3. Results and discussion

This section presents the results of uniaxial compression tests on rock samples and their analyses. The results of the conducted research on mine working stability in stratified rock mass using the RS2 software and mathematical modeling method are also presented.

Based on the results of loading rock samples, a dependency graph of the rock layer strength on the inclination angle is plotted. Figure 5 shows that as the rock layer inclination angle increases, the sample strength decreases. At an inclination angle of 30°, a minimum strength is observed. As the angle is further increased, there is an increase in strength, but less than in the case of horizontal occurrence of rock layers.

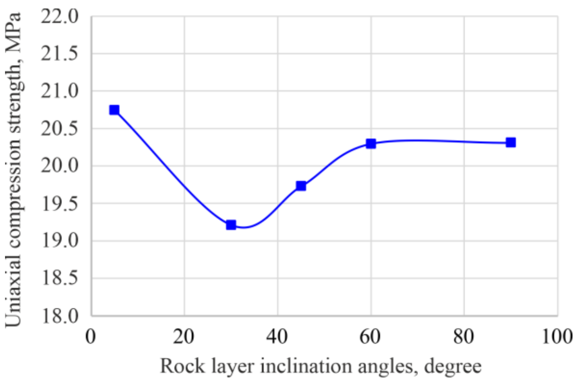

Figure 5. Dependency graph of the rock layer strength on the inclination angle

In the experiment conducted, the bulk of the rock samples are destroyed according to axial lines gravitating along the cylindrical shape. The samples are subjected to uniaxial compression tests, where axial stresses are applied parallel to the axes of the samples. It should be noted that with an increase in the rock layer inclination angle, reaching and exceeding 30°, the phenomenon of deformations along the bedding planes is observed. This phenomenon is an important indicator for understanding the rock failure mechanisms under bedding conditions, and its observation is an important element for a more in-depth analysis of the stability of mine workings in the rock stratum.

While continuing to analyze the results of experiments and laboratory tests, attention should be paid to the data obtained. Analyzing the data provides a better understanding of how stratified structure of rocks affects their stability in conditions of mining operations. Based on these data, we proceed to review the results of the numerical modeling. The obtained results of numerical modeling allow us to expand our understanding of the processes occurring in the rock mass.

The obtained results of numerical modeling show that the nature of the stress distribution around the mine working depends on the direction of the layers. Figure 6 shows that at horizontal occurrence of rock layers, a zone of increased stress concentration is located not only in the roof, but also in the sides of the mine working.

For the case of an inclined-stratified rock mass, the stress zone asymmetry gradually changes as the dip angle increases. The stress concentration zone changes towards the footwall of the seam, and this is clearly expressed at the inclination of the layers from 30° and above. It follows that the influence of rock stratification on the behavior of the rock mass surrounding the mine working is significant and should be taken into account.

This occurs due to the peculiarities of the internal structure of stratified rocks and their mechanical properties. An increase in the rock layer inclination angle leads to a change in the direction of acting forces and stress distribution in the rock mass. When rock layers are inclined at an angle directed from the horizon, stresses caused by gravity and other external factors begin to shift towards the footwall of the seam. This creates an uneven distribution of stresses around the mine working and results in a zone of increased stress concentration in this direction. Thus, the influence of rock stratification on rock mass behavior becomes more evident with an increase in rock layer inclination angle, which requires consideration in the planning and operation of mine workings.

To study the influence of inclination angle on the rock mass behavior, diagrams are constructed showing the stresses along the lines in the rock mass from the measured points. In the case, when measuring stresses along the line drawn in the direction of the rock layer strike in the concentration zone, the stress value is 22-24 MPa (Fig. 7). This indicates a high intensity of stresses in this area, which confirms previously determined tendencies of increased stress concentration with an increase in rock layer inclination angle.

Less stress concentration zones are observed when rocks occur horizontally and at 15°. This indicates that the change in the rock layer inclination angle has a significant impact on the stress distribution in the rock mass, so that with increasing inclination angle, an increase in the stress concentration intensity in the relevant areas is observed.

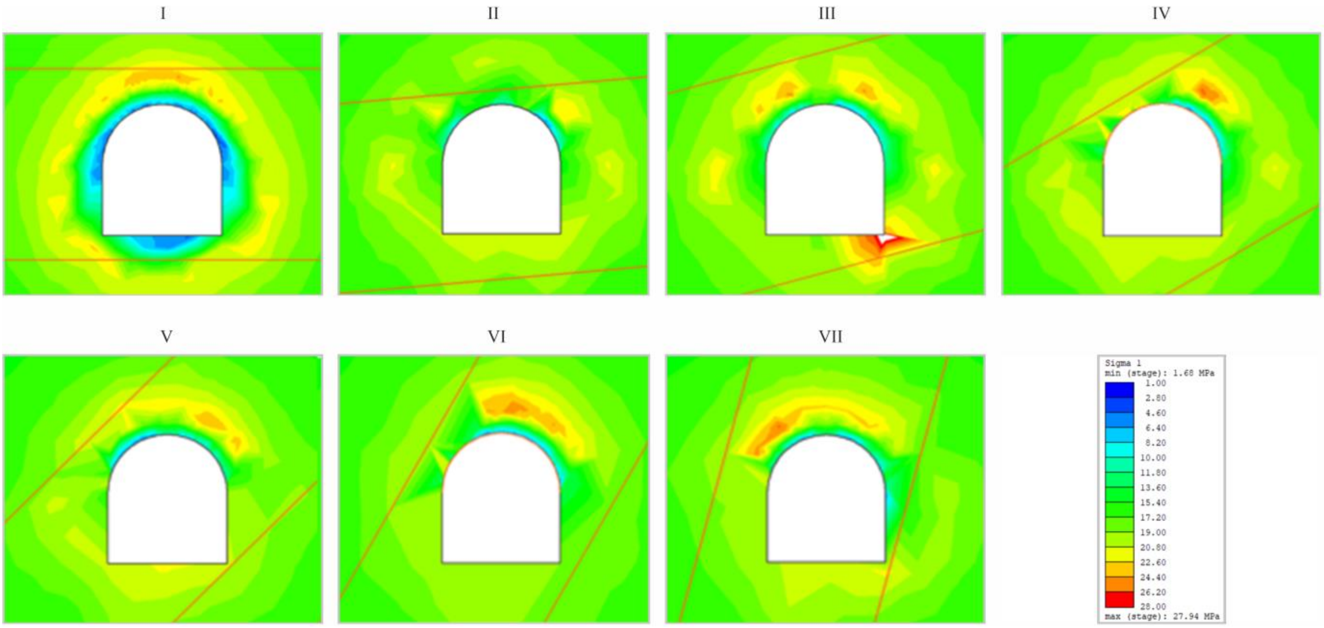

Figure 6. Stress distributions in the mass around the mine working: I – 0°; II – 5°; III – 15°; IV – 30°; V – 45°; VI – 60°; VII – 75°

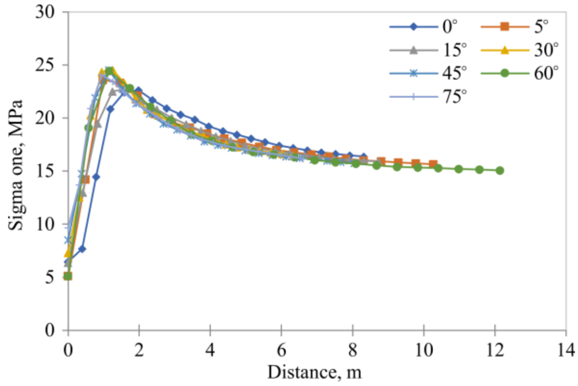

Figure 7. Patterns of stress variation in the mass depending on the angle of rock layer occurrence along the line drawn along the bedding (first measurement point)

Stress measurements in the roof show that the highest stress of 25.5 MPa is achieved at 60°, while the stress distribution is smooth and reaches up to 19 MPa when the rocks occur at an angle of 5° (Fig. 8). Figure 9 shows the dependence of stress in the rock mass on the angle of rock layer occurrence. Measurements are conducted along the line drawn transversely to bedding (third measurement point).

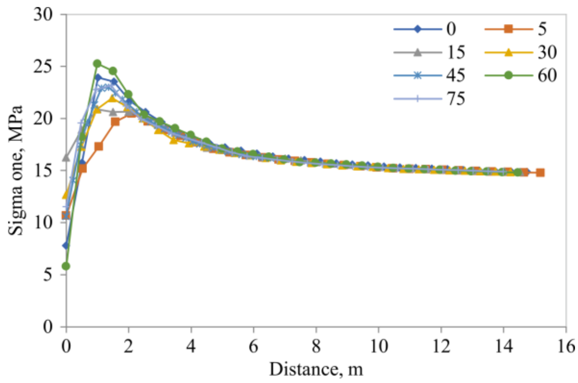

Figure 8. Patterns of stress variation in the mass depending on the angle of rock layer occurrence along the line drawn vertically upward along the roof center (second measurement point)

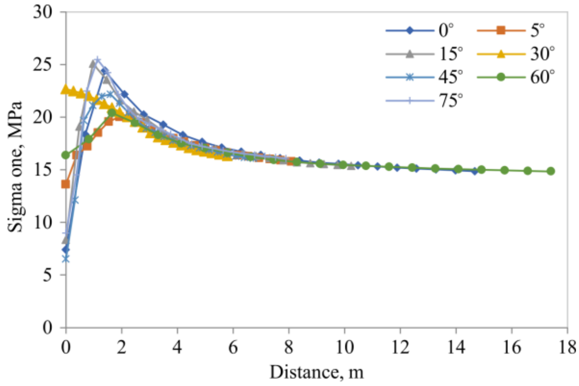

Figure 9. Patterns of stress variation in the mass depending on the angle of rock layer occurrence along the line drawn transversely to bedding (third measurement point)

Figure 9 demonstrates how the stress changes as the rock layer inclination angle changes, which makes it possible to assess the influence of this factor on the stability of mine workings. From the analysis of the graph of stress changes in the rock mass, it is evident that when rock layers are inclined at an angle of 75, 15° and at horizontal occurrence, an increased stress concentration zone is observed, reaching up to 26 MPa. A particularly high stress of 22 MPa is observed on the mine working contour at rock layer inclination angle of 30°, which may pose a threat of failure to the mine working roof.

In general, the analysis of the results shows that the change in the angle of rock layer occurrence has a significant impact on the stress distribution around the mine workings. When the rock layers occur horizontally, weakened zones are most often located in the roof and sides of the mine working, which can lead to the occurrence of stresses and deformations in these areas. However, when the layers are inclined by 5°, there is an increase in stress concentration in the roof from the side of the rock footwall, which may lead to more intense failure processes in this zone.

When the layers occur below 15°, the stress concentration is most often located along the edges of the mine working roof, which can also lead to an increased risk of failure in these areas. The mass behavior around the mine working, when the rock layers are inclined at 45 and 60° is similar and the failure zones are concentrated both in the center and along the roof edge from the side of the footwall.

A mine working, driven in a mass consisting of rock layers at 75°, has weak areas throughout the roof, which may require additional measures to ensure the safety and stability of the mine workings. Particular attention should be paid to the case when the rocks occur at an angle of 30°, since significant stresses are observed near the mine working roof, which can lead to an increased risk of failure in this area.

Based on the data obtained from numerical modeling, it is possible to vary the types of supports and apply them in those areas where maximum stress concentration zones are observed. This will optimize the process of ensuring the safety and stability of mine workings in conditions of stratified rock masses.

Further research will focus on a better understanding the relationship between the angles of occurrence of rock layers and their stability in different geological conditions. In particular, the research will include analysis of the influence of parameters such as mine working geometry, hydrogeological conditions, and anisotropic characteristics of rock layers on the distribution of stresses and deformations in the rock mass. In addition, promising research areas may also include the development of new data analysis and modeling methods that will enable more accurate prediction of mine working behavior in stratified rock masses. Such research is essential to ensure the safety and efficiency of mining operations, as well as to improve strategies for planning and operation of mine workings, taking into account their geological structure.

4. Conclusions

Based on the conducted research, the following conclusions can be drawn.

The stratified rock mass structure significantly influences the stress-strain state around mine workings. The rock layer inclination angle has a noticeable influence on the character of stress and deformation distribution in the mass. When layers occur at 30° or more, there are asymmetrical stress distribution zones, which must be taken into account when developing timbering plans.

Experimental and numerical research has confirmed that an increase in the rock layer inclination angle significantly influences the stress distribution in the rock mass. For example, when the inclination of rock layers is 30° and above, there is a significant increase in stress concentration zones, which can lead to an increased risk of mine working failure. Specific numerical values indicate an increase in stresses up to 26 MPa at a rock inclination angle of 75°, while at an angle of 15° the stresses are 22-24 MPa on the mine working contour.

Further research in this area should focus on a more in-depth study of the mechanisms of interaction between stratified rock structure and stability. This will make it possible to develop more accurate methods for predicting the behavior of rock masses and optimizing strategies for planning and exploitation of mine workings. Given the importance of this issue for the safety and efficiency of mining operations, further research in this area is important for industry and science.

Author contributions

Conceptualization: AI; Data curation: AS, GZ; Formal analysis: ACA, BI; Funding acquisition: AI; Investigation: AI, AS, ACA; Methodology: GZ; Project administration: AI; Resources: AS, BI; Software: GZ; Supervision: AI; Validation: AI, ACA; Visualization: GZ; Writing – original draft: AI, AS, ACA; Writing – review & editing: AI, GZ, BI. 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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Оцінка стійкості виробок, пройдених у шаровому масиві гірських порід

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Мета. Оцінка стійкості виробок, пройдених у шаруватому масиві гірських порід шляхом дослідження впливу кута напластування шаруватих порід на напружено-деформований стан гірського масиву.

Методика. У роботі використовувалися як експериментальні, так і чисельні методи дослідження. Експериментальні дослідження проводилися на зразках гірських порід з різними кутами залягання шарів, тоді як чисельне моделювання було виконано із використанням програмного забезпечення RS2 (Geotechnical Finite Element Analysis), що ґрунтується на узагальненому критерії руйнування Хоека-Брауна. Дослідження проводилися на моделях, що охоплюють приконтурну частину гірничих виробок, пройдених у масиві з кутами залягання порід від 0 до 75°.

Результати. Експериментальні та чисельні дослідження показали, що при зміні кута нахилу шарів порід відбуваються значні зміни у зонах концентрації напружень навколо гірничих виробок. Збільшення кута нахилу шарів порід супроводжується зміною розподілу напружень, що має важливе значення для оцінки стійкості гірничих виробок. Особливо виражений вплив спостерігається при кутах залягання порід від 30° та вище.

Наукова новизна полягає у виявленні закономірностей при розподілі напружень у шаруватих масивах гірських порід залежно від кута нахилу шарів. Результати досліджень надають нові дані щодо механізмів взаємодії гірських порід у складних геологічних умовах.

Практична значимість. Отримані результати можуть бути використані при проєктуванні та експлуатації гірничих виробок у складних геологічних умовах. Врахування змін у зонах напружень, обумовлених кутом нахилу шарів порід, допоможе підвищити безпеку та ефективність гірничих робіт.

Ключові слова: *гірські виробки, шаруватий масив, породи, стійкість, напруження, чисельне моделювання*

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