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MODELING THE STABILITY OF MINING EXCAVATIONS

Abstract. The study focuses on modeling the stress-strain state of mine workings with anchor support under various seam dip angles and excavation shapes. The conditions of seam K10 at the «Abayskaya» mine of Qarmet's mining division are considered. Numerical simulations were conducted using the ANSYS software package. The research examines the influence of excavation geometry and coal seam dip angle on stress distribution within the rock mass. The objective is to optimize support parameters to ensure the stability and safety of mine workings. The results highlight the importance of accounting for geological factors and excavation geometry in the design of supports under complex mining and geological conditions.

Key words: *mine workings, stress-strain state of anchor support, excavation shape stability, mining safety, stress modeling, near-contour rock mass, geomechanics.*

Тау-кен жұмыстарының тұрақтылығын модельдеу

Аңдатпа. Зерттеу әртүрлі құлау бұрыштары мен қазба пішіндеріндегі анкерлік бекітпемен тау-кен қазбаларының кернеулі-деформацияланған күйін модельдеуге арналған. Qarmet тау-кен бөлімшесінің «Абайская» шахтасының К10 қабат жағдайлары қарастырылған. Талдау үшін ANSYS бағдарламалық кешенін пайдаланып, сандық модельдеу жүргізілді. Зерттеуде қазбаның геометриясы мен көмір қабатының құлау бұрышының кернеулердің таралуына әсері қарастырылады. Зерттеудің мақсаты – қазбалардың тұрақтылығын қамтамасыз ету және қауіпсіздігін арттыру үшін бекіту параметрлерін оңтайландыру. Алынған нәтижелер күрделі тау-геологиялық жағдайларда бекітуді жобалау кезінде геологиялық факторлар мен қазба пішінін ескеру маңыздылығын көрсетеді .

Түйінді сөздер: *тау-кен қазбалары, анкерлік бекітпедегі кернеулі-деформацияланған күй, қазба пішінінің тұрақтылығы, тау-кен жұмыстарының қауіпсіздігі, кернеулерді модельдеу, контур маңы массиві, геомеханика.*

Моделирование устойчивости горных выработок

Аннотация. Исследование посвящено моделированию напряженно-деформированного состояния горных выработок с анкерным креплением при различных углах падения пласта и формах выработки. Рассмотрены условия пласта К10 шахты «Абайская» горнорудного дивизиона Qarmet. Для анализа использовано численное моделирование с применением программного комплекса ANSYS. В работе изучается влияние геометрии выработки и угла падения угольного пласта на распределение напряжений в породах. Целью исследования является оптимизация параметров крепления для обеспечения устойчивости и повышения безопасности выработок. Полученные результаты демонстрируют значимость учета геологических факторов и формы выработок при проектировании крепей в сложных горно-геологических условиях.

Ключевые слова: *горные выработки, напряженно-деформированное состояние анкерной крепи, стабильность формы выемки, безопасность горных работ, моделирование напряжений, горные выработки, приконтурный массив пород, геомеханика.*

Introduction

One of the key issues in mining is ensuring the stability of underground excavations, which directly impacts the safety of workers and the efficiency of mining operations. In a study dedicated to modeling the stress-strain state of mining workings, the Finite Element Method (FEM) was employed using the ANSYS software package to analyze the rock mass. The primary focus was on modeling the conditions of the «Abayskaya» mine, where different dip angles of layers and shapes of excavations were considered. The obtained results showed that the geometry of the excavations significantly affects the stress distribution, with the rectangular shape of the excavation with anchor support being preferred in complex geotechnical conditions.

A similar study was conducted by Dimitrienko Y.I. and Yurin Y.V. in their work «Finite Element Modeling of the Stress-Strain State of Rocks Considering Creep» [1]. This work used a finite element algorithm to solve the three-dimensional problem of rock creep. The primary focus was on creating a 3D computer model to analyze stresses under varying exposure times. These results highlight the importance of considering temporal factors when designing supports.

An interesting addition is the work performed at the Don State Technical University, titled «Stability of Rock Exposures in Mining Workings» [2]. The study focuses on assessing the stability of rock exposures at the contours of mining workings, as well as proposing engineering methods for calculating stability. These methods can be useful when developing support parameters for complex geotechnical conditions.

Furthermore, a study conducted at the Kuzbass State Technical University is dedicated to the influence of geomechanical factors on the stability of rock masses and methods for their optimization [3]. The authors proposed improved methods for designing support systems, emphasizing the interaction between geomechanical parameters and reinforcement technologies.

Thus, the research on modeling the stress-strain state of mining workings complements the existing scientific literature, confirming the importance of excavation geometry and support systems for enhancing the stability of mining workings. A comparison with similar studies shows that the use of numerical modeling methods such as FEM allows for detailed analysis and optimization of support parameters in complex geological conditions.

Research Methods

The study utilized the Finite Element Method (FEM) in the ANSYS software suite for numerical modeling of the stress-strain state of the rock mass. The initial data for the modeling consists of the geometric parameters of the K10 seam at the «Abayskaya» mine, including the depth (400 m), thickness of the coal seam (3.8 m), and the physical-mechanical properties of the enclosing rocks obtained from geological and engineering surveys.

The model takes into account the behavior of the rock mass in the conditions of the given excavation geometry (arch-shaped and rectangular) and various dip angles of the seam (from 10° to 50°). Two-dimensional elasticity theory was used for modeling, which is due to the relatively short deformation period of the rock mass during the advancement of the excavation.

Previously, the authors conducted a series of studies on the modeling of rock mass behavior in Kazakhstani mines using similar approaches, the results of which were published in the work by Zhakypova A.B. «Geomechanics in the Mining Industry» [4]. This study further develops these approaches, with particular attention to the influence of excavation geometry and dip angles on stress distribution.

Results and Discussion

Numerical modeling showed that the shape of the excavation and the dip angle of the seam significantly influence the stress distribution within the rock mass. The main focus was on analyzing normal, longitudinal, and shear stresses for both arch-shaped and rectangular excavation profiles at dip angles ranging from 10° to 50°.

For the arch-shaped cross-section of the excavation, normal stresses increase exponentially with the rise in dip angle, reaching 13.5 MPa at the maximum dip angle (50°) (Figure 1a). This is explained by the concentration of stresses at the upper part of the excavation due to its curved shape, which intensifies the localized load on the support system. In contrast, the rectangular cross-section demonstrates a more uniform distribution of normal stresses: values increase from 1.2 to 3.5 MPa as the dip angle rises, then stabilize (Figure 1b). This uniformity is explained by the absence of bends and the even distribution of load across the flat surfaces. The rectangular shape reduces the concentration of normal stresses and decreases the load on the support system, making it more stable under complex geo-mining conditions.

Longitudinal stresses (σ) depend on the dip angle and the shape of the excavation. For the arch-shaped profile, values increase from 63.2 to 64.1 MPa as the dip angle rises, then stabilize (Figure 2a). In the rectangular profile, stresses vary from 49 to 53.4 MPa, and then decrease to 52 MPa with further increases in the dip angle (Figure 2b). This indicates lower stress levels in the rectangular section, which is associated with a simpler stress distribution across the flat surfaces of the excavation. The rectangular shape ensures lower longitudinal stresses, contributing to its overall stability.

Shear stresses (τ) show a complex dependence on the dip angle. For the arch-shaped profile, they initially decrease from 50° to 33 MPa but then increase again to 37 MPa at higher angles (Figure 3a). In the rectangular profile, the values remain lower and more stable (Figure 3b), due to the absence of curved sections that would create additional loads. Despite the advantages of the rectangular shape, its stability may decrease in the presence of geological disturbances such as cracks or uneven load distribution on the support system.

Comparative analysis shows that the rectangular shape of the excavation is preferable in terms of reducing the concentration of normal, longitudinal, and shear stresses. This confirms its suitability for complex geo-mining conditions, such as the K10 seam at the «Abayskaya» mine. The results can be explained by the specific stress distribution within the rock mass. The arch-shaped profile creates zones of concentration due to the curvature of the excavation, which increases local loads. In contrast, the rectangular shape allows for a more even distribution of loads across the entire surface, reducing the likelihood of structural failure. However, its effectiveness may decrease if cracks or other defects in the rock mass occur.

The obtained results emphasize the importance of selecting the correct excavation geometry and support parameters to increase the stability and safety of mining operations. The rectangular excavation shape not only reduces the load on the support system but also lowers the costs associated with its design and operation. This is of significant importance for the planning and optimization of mining activities in areas with complex geological sections.

The findings of this study are in agreement with the conclusions made by Zhakypova [4], which highlighted the importance of selecting the excavation geometry to manage the stress state of the rock. Furthermore, the data showing the reduction in stress concentration for the rectangular shape align with the results of Zhang et al. (2021) and Lee et al. (2018). This underscores the universality of the conclusions and confirms the practical applicability of the proposed approach. However, the modeling was based on a two-dimensional analysis, which is a limitation of the study. For a deeper understanding, three-dimensional modeling is recommended, along with the inclusion of temporal factors such as rock creep, and investigations in fractured rock mass conditions.

Theoretical Foundations of the Problem

The theoretical basis of this study is grounded in the principles of geomechanics and the mechanics of rock masses, particularly in the theories of elasticity and the analysis of the stress-strain state of rock masses under various loading conditions. These aspects are comprehensively discussed in the work of Ryl'nikova M.V. and Zoteev O.V. «Geomechanics», which describes the mechanical properties of rock masses and approaches to assessing the stress state of rock formations [5].

To model the complex distribution of stresses in mine workings, the Finite Element Method (FEM) is used, which has been successfully applied in the work of Dimitrienko Y.I. and Yuriev Y.V. for the analysis of three-dimensional stresses and deformations in rock masses [6].

Figure 1 illustrates the distribution of normal stresses (Figure 1a) and longitudinal stresses (Figure 1b) for the arch-shaped excavation profile at various seam dip angles. The results of the analysis show that normal stresses (Figure 1a) increase exponentially with the rise in dip angle, reaching a maximum value of 13.5 MPa. Meanwhile, longitudinal stresses (Figure 1b) increase to 64.1 MPa before stabilizing. These results emphasize the necessity of considering the impact of the dip angle when designing the support system.

Figure 2 presents a more comprehensive analysis of stress distribution for different excavation profiles (arch-shaped, rectangular, and polygonal). The following data are shown in Figure 2:

- *Figure 2a: Distribution of normal stresses*
- *Figure 2b: Longitudinal stresses*
- *Figure 2c: Shear stresses*
- *Figure 2d: Stress distribution in the contour zone*
- *Figures 2e and 2f: Stress maps in the surrounding rock mass*

The analysis shows that the rectangular shape of the excavation leads to lower concentrations of normal and longitudinal stresses (Figures 2a, 2b), as well as more even distribution of shear stresses (Figure 2c). In the stress maps (Figures 2e, 2f), it is evident that the rectangular shape ensures a more stable rock mass state compared to the arch-shaped and polygonal profiles.

Thus, the study confirms the importance of selecting the appropriate geometry of the excavation and the support parameters to reduce the risks of rock failure and improve the stability of mine workings. The results are a significant contribution to the theory and practice of designing support systems in complex geo-mining conditions.

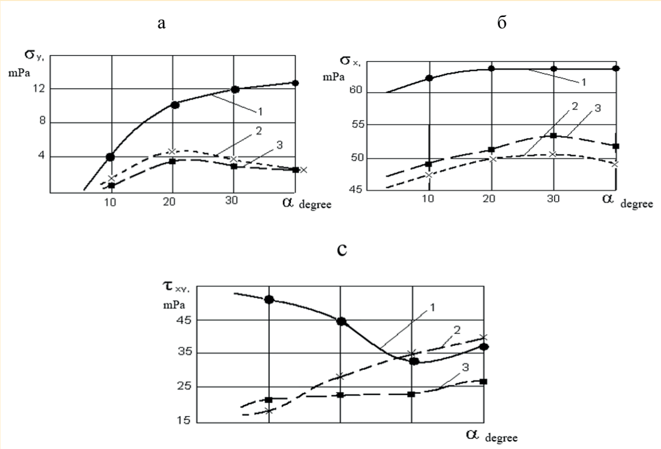

Figure 1. Influence of Roadway Shape and Seam Dip Angle on Maximum Stress Magnitudes in the Rock Mass with Anchor Support: *(a) Normal stresses, (b) Longitudinal stresses, (c) Shear stresses; 1 – Arched, 2 – Polygonal, 3 – Rectangular.*
Сурет 1. Кен қазбасының пішіні мен қабаттың еңіс бұрышының әсері: *максималды қалыпты (а), бойлық (б), жанама (в) кернеулердің мәніне тау жыныстары массивінде анкерлік бекітуді қолдану кезінде; 1 – аркалық, 2 – көпбұрышты, 3 – тікбұрышты.*
Рис. 1. Влияние вида формы выработки и угла падения пласта на величину: *максимальных нормальных (а), продольных (б), касательных (в) напряжений в массиве пород при анкерном креплении выработки; 1 – арочная, 2 – полигональная, 3 – прямоугольная.*

Analysis of Stress Distribution for Arch-Shaped Excavation Profile

For the arch-shaped cross-section of the mine working, normal stresses increase with the rise in the dip angle of the seam, following an exponential function, ranging from 10 MPa to 13.5 MPa (Figure 1). These results demonstrate that the dip angle of the seam has a significant impact on the distribution of normal stresses, creating stress concentration zones in the surrounding rock mass, particularly in the contour zone.

Thus, the arch-shaped excavation profile leads to an increase in normal stresses, necessitating additional measures to ensure the stability of the mine working. Further analysis of the stress distribution is conducted by considering longitudinal and shear stresses (Figure 2).

Figure 2 presents the results of the analysis of longitudinal and shear stresses at different dip angles of the seam for the arch-shaped excavation profile. The analysis of longitudinal stresses (σ) shows that their values increase with the increase in the dip angle of the seam but stabilize after reaching a certain threshold. In contrast, shear stresses (τ) exhibit more complex dynamics: their values first decrease and then increase again as the dip angle increases.

This behavior of stress components emphasizes the need for careful consideration of the seam's dip angle in the design and planning of mine workings, as changes in stress distribution can affect the stability and safety of the excavation. The results suggest that while the arch-shaped profile may be advantageous in some cases, it may also require more rigorous support systems to manage increased stress concentrations effectively.

The analysis of the stress distribution, presented in Figure 2, shows that the shape of the excavation has a significant impact on the mechanical behavior of the rock mass. Figure 2a demonstrates that normal stresses in the rectangular excavation shape are distributed more evenly compared to the arch shape, which reduces local stress concentrations. Figure 2b confirms that longitudinal stresses in the rectangular shape reach lower values than in the arch shape, especially at higher dip angles, improving the overall stability of the structure. Figure 2c presents the distribution of shear stresses, where it is evident that the arch shape is more prone to local concentrations, while the rectangular shape provides a more stable distribution. Figure 2d shows the stress distribution in the surrounding zone of the rock mass, highlighting that higher local stresses occur with the arch shape, which may require additional engineering solutions. The stress contour plots in Figures 2e and 2f confirm that the surrounding rocks experience less stress with the rectangular excavation shape, making it more preferable in complex geological conditions. Thus, the analysis of Figure 2 leads to the conclusion that the rectangular excavation shape reduces the risk of failure, ensures a more uniform load distribution, and is the optimal solution for ensuring the stability of underground workings. For the polygonal excavation shape, the trends in the stress-strain state are similar to those observed for the rectangular shape. The stresses in the polygonal shape are 1.5 times higher, while the pressure is lower by 2–3 MPa and the stress is 1.5–2.0 times higher. The change and distribution of stresses in the zones surrounding the excavation are shown in Figures 2e and 2f. The studies conducted allow us to conclude that the rectangular excavation shape with anchor support in the host rocks is preferable for the conditions of the K10 seam at the «Abayskaya» mine of the Qarmet mining division.

Conclusion

The conducted study demonstrates the importance of selecting the geometry of underground workings and support parameters to ensure stability and safety under complex geological conditions. Using numerical modeling with the finite element method (FEM) in the ANSYS software, the distributions of normal, longitudinal, and shear stresses in the rock mass were analyzed for different dip angles and excavation shapes.

The obtained results showed that the rectangular excavation shape provides a more uniform distribution of stresses compared to the arch shape. The rectangular shape reduces the concentration of normal, longitudinal, and shear stresses, making it preferable for the stability of underground workings.

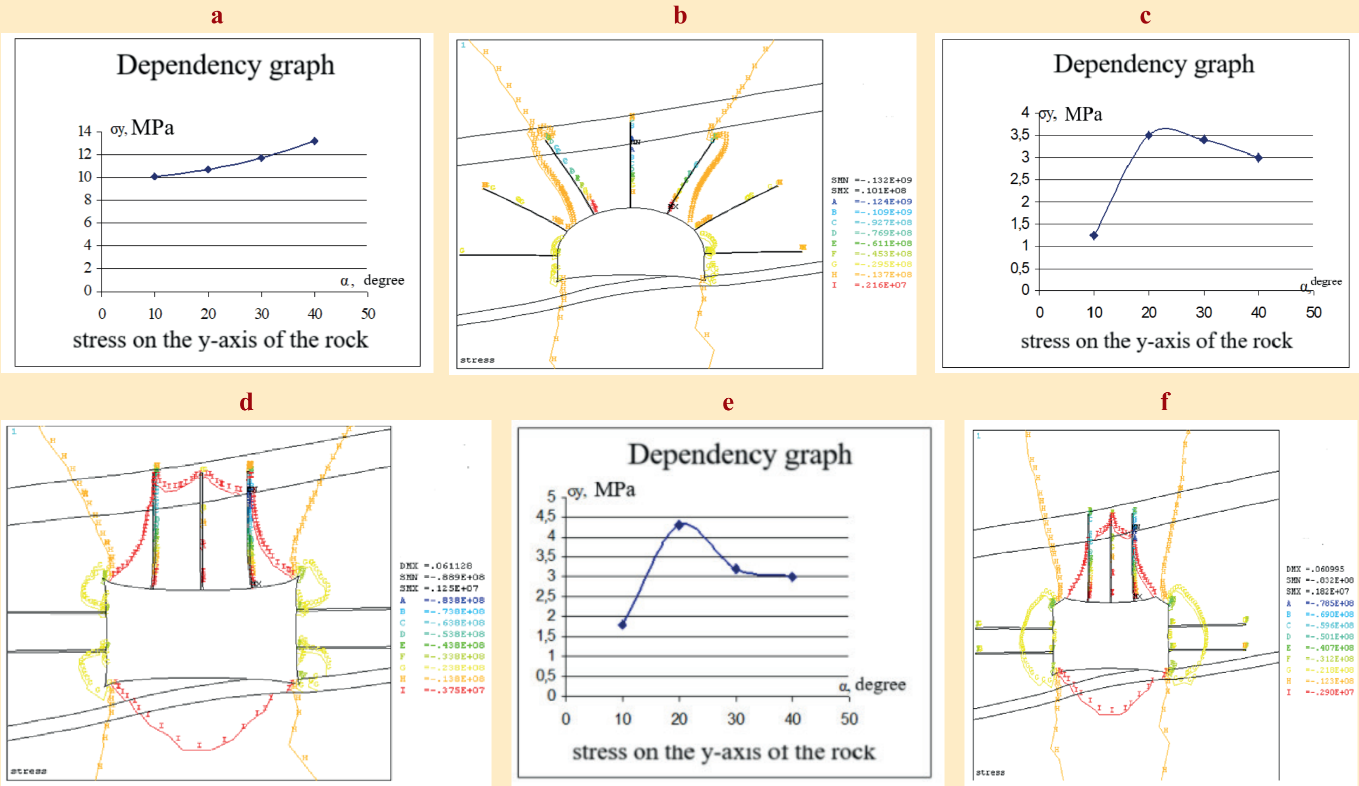

Figure 2. Distribution of Maximum Stresses in the Surrounding Rock Mass of the Roadway with Shape.
Сурет 2. Кен қазбасының айналасындағы бүйірлік тау жыныстарындағы максималды кернеулердің таралуыр.
Рис. 2. Распределение максимальных напряжений в боковых породах, окружающих выработку с формой.

In contrast, the arch shape creates higher local stresses, which require additional measures to ensure stability.

The practical significance of the study lies in the potential application of the results for designing support systems, which can increase the stability of underground workings and reduce operational costs. The conclusions align with data from previous studies, including works by Zhakypov, Zhang et al., Lee et al., Seryakov V.V., Pytel U., Parchanovich J., Pytel V., Mertushka P., Jones T., and Paprocki H. [1-10], highlighting the universality of the proposed approach.

However, the study has its limitations. The analysis was based on a two-dimensional model, which does not account for three-dimensional effects and the influence of time (e.g., rock creep). For further development of the topic, it is recommended to conduct three-dimensional modeling, study the influence of rock fracturing, and explore long-term characteristics of the support system.

This research contributes to the development of approaches for designing support systems for underground workings, offering optimal engineering solutions to enhance the stability and safety of mining operations.

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