SATBAYEV UNIVERSITY

Engineering Journal of Satbayev University

Volume 147 (2025), Issue 2, 31-39

https://doi.org/10.51301/ejsu.2025.i2.05

Geomechanical assessment of stress-strain conditions in structurally heterogeneous rock masses of Kyrgyzstan

A.R. Abdiev[1*], J. Wang[2], R.Sh. Mambetova[1], A.A. Abdiev[1], A.Sh. Abdiev[1]

[1]*Kyrgyz State Technical University named after I. Razzakov, Bishkek, Kyrgyzstan*
[2]*Northwest University, Xi'an, China*

**Corresponding author:* atsanbek.abdiev@kstu.kg

Abstract. This study focuses on assessing the stress-strain state of rock masses in structurally heterogeneous ore deposits of Kyrgyzstan. The primary objectives include identifying stress distribution patterns with depth, analyzing the impact of tectonic faults, and establishing the relationship between the elastic properties of rocks and their strength parameters. A comprehensive methodological approach is employed, including in-situ stress measurements using the overcoring technique to determine principal normal stresses at various depths, laboratory tests to evaluate elastic wave velocities, Young's and shear modulus, and statistical analysis to derive regression relationships. Furthermore, the orientation of principal stresses is reconstructed, and the influence of tectonic discontinuities on the stress field within the rock mass is evaluated. The results indicate that vertical stresses in the rock mass approximately correspond to the overburden pressure, expressed as γH. Regression models obtained for competent and moderately strong rocks confirm that the experimental data lies between the values predicted by N. Hast's relationships and those derived from hydrostatic stress distribution. The analysis of elastic properties reveals a high degree of anisotropy, where variations in P-wave velocity strongly correlate with changes in Young's and shear moduli. The practical significance of this research lies in its contribution to developing more accurate predictive models for the stress-strain behavior of ore-bearing rock masses, thereby enhancing the design of underground excavations.

Keywords: *mining, stress-strain state, elastic properties, rock mass, ore deposits.*

Received: 08 October 2024
Accepted: 15 April 2025
Available online: 30 April 2025

1. Introduction

Mining plays an important role in the economic development of the Kyrgyz Republic, serving as one of the key sources of raw materials and contributing significantly to the national budget [1-3]. The development of ore deposits not only fosters job creation and infrastructure growth but also drives technological advancement, forming the foundation for sustainable economic growth and enhancing the country's competitiveness in the global market. Furthermore, continued investment in mining innovation and rigorous safety measures ensure that the sector remains resilient and capable of meeting both domestic and international demands [4, 5].

As mining operations advance to greater depths and encounter increasingly complex geological structures, ensuring the safety and efficiency of extraction processes has become a central challenge for Kyrgyzstan's mining industry [6]. Structurally heterogeneous rock masses, characterized by complex tectonic features and numerous fault systems, exhibit unstable stress-strain behavior [7-9]. This instability is critical in hazardous dynamic events, such as rock bursts and geotectonic shocks, which pose serious risks to personnel and can lead to accidents in underground excavations [10, 11].

The challenges associated with the safe and efficient extraction of structurally complex ore deposits are largely driven by the inevitable manifestation of rock pressure at deeper mining levels [12, 13]. The geological complexity, expansion of mined-out zones, high tectonic stress levels, and heterogeneity of rock physical properties contribute to sudden structural failures in the rock mass [14-16]. Such failures often manifest as large-scale roof collapses, pillars' destruction, excavation junctions' damage, and dynamic phenomena like rock and geotectonic bursts. These events significantly impact mining productivity and may lead to the suspension of underground development projects [17-20].

Effective rock pressure management requires reliable methods for assessing and monitoring the geomechanical state of the rock mass. Contemporary methodologies advocate for an integrated approach, which considers the stress-strain state, rock properties, geodynamic processes, and the specific characteristics of deposit exploitation [21-24]. This approach forms the basis for scientifically grounded strategies to mitigate rock pressure hazards and optimize engineering decisions in the design and execution of mining operations.

This study presents the results of experimental investigations conducted at ore deposits in Kyrgyzstan using both in-situ and laboratory techniques. Special emphasis is placed on developing a methodology for assessing the stress-strain state that enables precise forecasting of the nature and extent of geodynamic phenomena. Such predictive capability is essential for minimizing the risk of hazardous events and ensuring the long-term stability of underground workings in structurally complex rock environments.

1.2. Study area

The study focuses on structurally heterogeneous ore deposits in the Kyrgyz Republic, characterized by significant geological diversity and complex structural organization. The sites investigated include the Khaydarkan, Kadamjay, Mamkala, Kumtor, and Chon-Koy deposits. These collectively provide insight into geomechanical parameters at depths ranging from 800 m to prospective levels of 900-1000 m and beyond. These ore-bearing formations exhibit pronounced tectonic activity, with localized stress concentrations reaching 35-40 MPa in areas adjacent to major fault zones [25-27].

For example, at the Uluu-Too mine of the Khaydarkan Mercury Combine, deep levels are accessed via two shafts-Deep and Central-reaching depths of 685 m and 860 m, respectively, clearly indicating increased rock pressure with depth. Deposits located near major tectonic faults display elevated localized stress levels. Mining sites at Khaydarkan, Kadamjay, Mamkala, Kumtor, and Saryjaz frequently experience manifestations of rock pressure in the form of extensive roof collapses, damage to excavation junctions, and large-scale displacements of the rock mass [28-32].

Variations in the physical properties of rocks, such as elasticity, elastic wave velocities, and anisotropy coefficients, significantly influence the stress distribution within the mass [33, 34]. These differences result in pronounced spatial variability of the stress-strain state, depending on depth and proximity to tectonic discontinuities.

One notable example is the Kumtor mine, where underground workings collapsed near the fifth transfer chamber at a depth of 3821 m and at a horizontal distance of 6100620 meters from the shaft collar. This incident led to the suspension of underground construction in June 2009 and highlights the high risk posed by both gravitational and tectonic stress. The study, therefore, aimed to evaluate stress-strain conditions, identify depth-related stress patterns, analyze the influence of rock properties on stress distribution, and inspect underground excavations operating under elevated rock pressure [35-37].

Consequently, the diversity of mining conditions ranging from deep multi-shaft operations to zones adjacent to major faults necessitates a comprehensive approach for assessing the geomechanical state of ore-bearing rock masses. The adopted methodology accounts for the internal physical properties of rocks and external geodynamic influences, which are essential for predicting hazardous dynamic events and ensuring the safety of mining operations in Kyrgyzstan.

2. Materials and methods

Field and laboratory methods were applied to investigate the in-situ stress conditions within structurally heterogeneous rock masses of ore deposits in Kyrgyzstan.

Field measurements of natural stresses were conducted at several mining sites using specialized sensors installed at various depths (e.g., 930 m and 960 m). The overcoring method directly determined principal normal stresses within the rock mass, which is crucial for assessing the influence of geodynamic processes.

Rock samples were analyzed in the laboratory to determine their elastic properties, including the velocities of longitudinal and shear waves, Young's modulus, and anisotropy coefficients. These data served as a basis for analyzing the impact of internal rock heterogeneity on stress distribution.

The experimental results were subjected to statistical processing to identify dependencies of stress on depth and tectonic activity parameters. Regression models were constructed, and correlation analysis was performed to compare experimental findings with theoretical models, including Dinnik's model and the empirical relationships proposed by N. Hast [38].

Particular attention was given to assessing the influence of fault zones on stress distribution. To this end, spatial data on fault locations were compared with measurement results to evaluate how the orientation and magnitude of stresses vary with proximity to active structural discontinuities [39].

To ensure the methodological robustness of the approach, the stress-strain state analysis was grounded in fundamental physical and mechanical principles represented by the equations. The equation defines the hydrostatic vertical stress:

$$\sigma_V = \gamma \cdot H \,, \tag{1}$$

where σ_v is the vertical stress; γ is the unit weight of the rock; H is the depth. This expression provides a basic reference for evaluating vertical stress and serves as a benchmark corresponding to the overburden pressure.

Hooke's law describes elastic deformation:

$$\sigma_V = E \cdot \varepsilon \,, \tag{2}$$

where E is the Young's modulus; ε is the strain.

Hooke's law is used to interpret laboratory data, enabling the evaluation of rock elastic properties from experimentally measured wave velocities and related parameters.

The regression model for stress as a function of depth takes the form:

$$\sigma = \sigma_0 + k \cdot H \,, \tag{3}$$

where: σ_0 is the initial stress at the surface; k is a coefficient characterizing the stress gradient with depth.

This linear model (3) provides a generalized framework for assessing the gravitational contribution to the formation of the stress-strain state.

Applying the fundamental principles (1)-(3) not only facilitates the comparison of experimental results with theoretical models but also forms the basis for developing more accurate methods for evaluating the geomechanical state of ore-bearing rock masses. Integrating gravitational and tectonic stress components within a unified analytical framework ensures methodological rigor and scientific validity of the research approach.

3. Results and discussion

Statistical processing of experimental data obtained from in-situ stress measurements in structurally heterogeneous rock masses enabled the development of regression equations describing changes in the average values of principal normal stresses with depth. For competent rocks with Young's modulus ranging from $5\text{-}6 \cdot 10^4$ to $10\text{-}11 \cdot 10^4$ MPa, the following relationships were established:

$$\sigma_x = \sigma_y = 9.5 + 2.78\gamma H \,, \tag{4}$$

$$\sigma_x = 5.0 + 2.78\gamma H \,, \tag{5}$$

$$\sigma_y = 4.5 + 1.12\gamma H \,, \tag{6}$$

For moderately strong rock masses with Young's modulus of approximately 2-3·10^4 MPa, the relationships are as follows:

$$\sigma_x + \sigma_y = 5.0 + 2.14\gamma H \, , \tag{7}$$

$$\sigma_x = 3.0 + 1.14\gamma H \, , \tag{8}$$

$$\sigma_x = 2.0 + \gamma H \, , \tag{9}$$

where: γ is the unit weight of the rock, equal to 2.7·10^{-2} MPa/m; H is the depth from the surface in meters.

In a first approximation, vertical stresses σ_y correspond to the overburden pressure γH.

Comparison with values derived from hydrostatic theory revealed that the experimental results lie below those predicted by N. Hast's empirical relationships but above those calculated under a purely hydrostatic stress assumption.

Beyond regression modeling, experimental work enabled the identification of key patterns in stress distribution within the rock mass. At the Kadamjay mine, measurements at the 930 m level revealed that in the southern limb of the fold, the maximum principal stress reached 35.1 MPa (azimuth 156°). At the same time, at the southwestern periclinal closure, it was 40.1 MPa (azimuth 282°), reflecting changes in stress axis symmetry during fold formation.

A comparison between the 930 m and 960 m levels showed that the experimental site at 960 m (located just 240 m below the surface 90 to 140 m less than at 930 m) exhibited vertical stresses 2.2-2.6 times lower and horizontal stresses 1.6-2.0 times lower than those at the 930 m level. This difference is attributed to the predominance of tectonic stresses influenced by the distribution of faults.

Analysis showed that the magnitude of maximum principal stresses depends on the depth and the distance to active fault zones. For example, in the southern drift (930 m level), the stress measured was 35.1 MPa at a depth of 330 m, whereas near the shaft of the "Novaya" mine (460 m deep, 690 m away from the fault), it was only 18.6 MPa. The tectonic component, approximately 22 MPa was highest near the fault and decreased exponentially with distance.

At the Chon-Koy deposit, significant variation was observed between zones. In the southern ore-bearing zone (depth H = 160 m), vertical stresses were around 4.2 MPa, and horizontal stresses ranged from 7.4 to 9.6 MPa. In contrast, vertical and horizontal stresses reached 21.3 MPa and 19.2-21.7 MPa in the northern zone near the flexural bend, respectively.

Principal stress orientations were reconstructed based on geomechanical data, confirming the consistency of overcoring measurements. Statistical analysis demonstrated that vertical stresses closely aligned with theoretical values, while horizontal stresses were significantly elevated due to the pronounced influence of tectonic discontinuities.

The research also revealed a strong correlation between the propagation velocity of elastic waves and rock strength. Marbled rocks and Chatbazar limestones, which are relatively homogeneous and isotropic, showed a high correlation between strength parameters and elastic wave velocity. The strength anisotropy coefficient $K = \sigma^{\perp} / \sigma^{\parallel}$, for these rocks indicates uniform mechanical properties regardless of loading direction.

In contrast, rocks from the Uluu-Too deposit (including effusive rocks, listvenites, schists, and serpentinites) exhibited substantial heterogeneity and anisotropy in their physical properties, resulting in a lower correlation coefficient between wave velocity and strength ($\rho \approx 0.64$). This suggests that in anisotropic rocks, strength characteristics depend on the magnitude of the applied load and the orientation of elastic symmetry axes relative to the compression direction.

Notably, a rise in strength anisotropy generally accompanies an increase in the elastic anisotropy coefficient, while lower elastic anisotropy is associated with greater resistance to uniaxial compression. Therefore, considering the anisotropic nature of rocks, alongside a detailed analysis of their elastic and strength properties, enables more reliable forecasting of the stress-strain state and evaluation of geotechnical risks during mining in structurally heterogeneous environments. The relationship between elastic anisotropy and strength characteristics is presented in Table 1.

Table 1. Relationship between elastic anisotropy and strength characteristics

Rock type	Wave velocity, m/s		Elastic wave velocity anisotropy, %	Uniaxial compressive strength, kg/cm²		Strength anisotropy coefficient $K = \frac{\sigma_{max}\sigma_{min}}{\sigma_{min}}$, %
	$V_{P\parallel}$	$V_{P\perp}$		σ_{max}	σ_{min}	
Basalt	4610	4410	4.5	1070	940	13.9
Marmarized limestone	5460	5100	6.8	865	830	4.1
Chlorite schist	7120	6400	11.3	3140	2400	30.8
Jasperoid	4760	4050	17.0	1290	850	51.9
Bedded limestone	4740	3280	44.6	805	610	32.0
Carbonaceous schist	5105	2715	87.5	1400	830	68.6
Mica-quartz schist	5100	2550	100.0	880	525	68.1

Figures 1 and 2 illustrate the relationships between elastic wave velocities and rock strength parameters, as well as the degree of anisotropy based on experimental data.

Figure 1 presents the measured values of both longitudinal and shear wave velocities for various rock types. The highest longitudinal wave velocities are observed in crystalline and marmarized rocks, consistent with their high strength and relative structural homogeneity. In contrast, schists and other rocks exhibiting pronounced fissuring or bedding demonstrate significant anisotropy, evident in the directional variability of elastic wave propagation.

The degree of anisotropy in longitudinal wave velocities is shown in Figure 2. It demonstrates a tendency toward increased anisotropy coefficients in rocks with complex internal structures and dominant planes of stratification, confirming that the orientation of structural elements has a considerable impact on wave velocity.

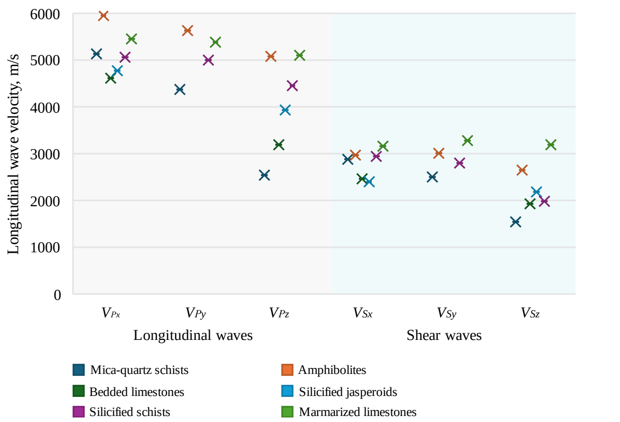

Figure 1. Variation of elastic wave velocities in the investigated rock types

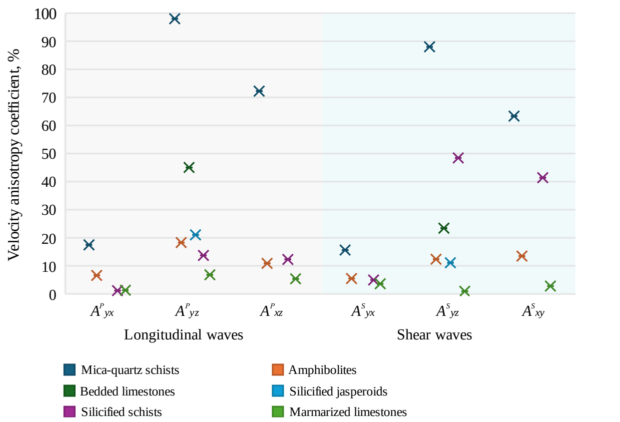

Figure 2. Variation of longitudinal wave velocity anisotropy coefficients in the investigated rock types

In addition to internal structural factors, external stress also plays a significant role. Experimental data show that when the applied load increases from zero to 50% of the rock's ultimate strength, the velocity of longitudinal waves $V\sigma^{\perp}(\rho)$, measured perpendicular to bedding or the axis of elastic symmetry, increases by 25-35%. In contrast, wave velocities measured parallel to stratification $V\sigma^{\parallel}(\rho)$ increase by only 7-15%. This effect highlights the nonlinear relationship between wave velocity and increasing compressive stress. With increasing pressure, microcracks and pores tend to close, resulting in an overall increase in wave velocity, especially in directions initially exhibiting reduced velocities due to the rock's anisotropic fabric.

For the studied rock types, elastic properties were determined using an anisotropy-based calculation scheme and equations applicable to orthotropic and transversely isotropic symmetry. Figure 3 presents the averaged values of Young's moduli (E_x, E_y, E_z), shear moduli (G_x, G_y, G_z), and Poisson's ratios (μ_{xy}, μ_{yz}, μ_{zx}) for selected anisotropic and isotropic rocks.

As shown by previous experimental data, the anisotropy of elastic wave velocities in the studied rocks can range from 5-10% in relatively isotropic marmarized limestones to 80-100% in mica-quartz schists and certain varieties of siliceous rocks. This variability is attributed to microstructural features such as bedding, fracturing, and mineral grain orientation, which create directional differences in the propagation paths of elastic waves.

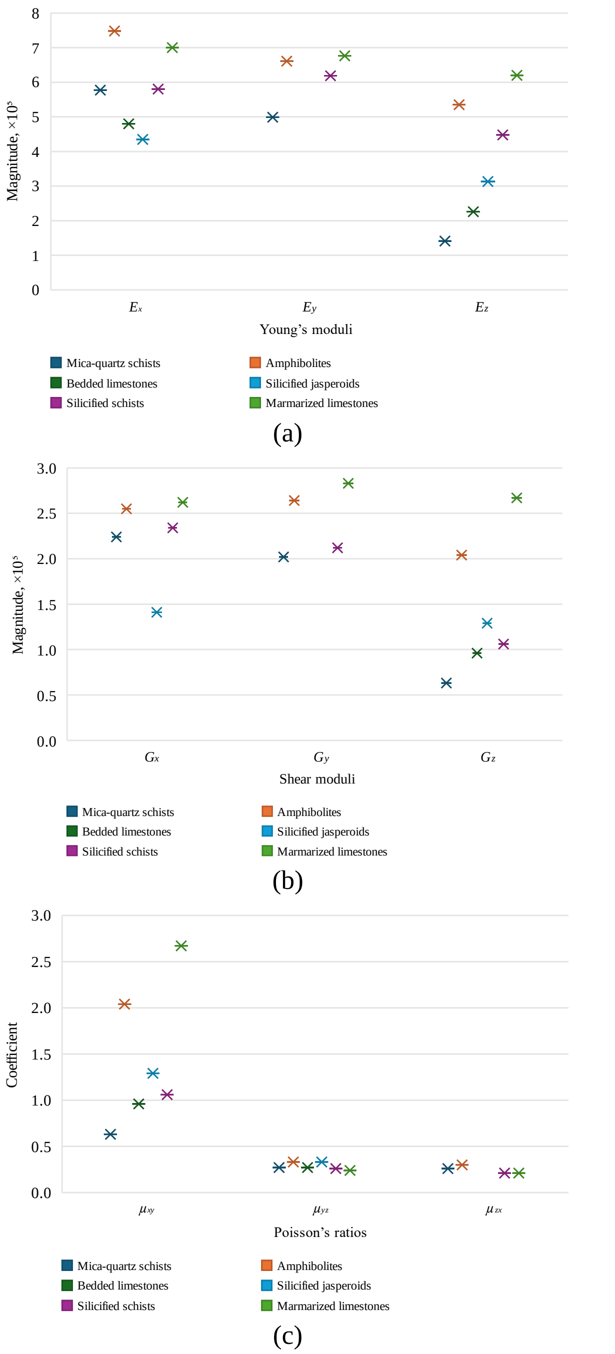

Figure 3. Comparison of elastic properties in the investigated anisotropic and isotropic rocks: (a) – distribution of Young's moduli (E_x, E_y, E_z); (b) – distribution of shear moduli (G_x, G_y, G_z); (c) – distribution of Poisson's ratios (μ_{xy}, μ_{yz}, μ_{zx})

According to the graphs in Figure 3a, the values of $E_{\parallel}$ (measured along the bedding or principal symmetry axis) often exceed those of $E_{\perp}$ (measured perpendicular to bedding). Similar patterns are observed for shear moduli ($G_{\parallel}$, $G_{\perp}$) and Poisson's ratios ($\mu_{\parallel}$, $\mu_{\perp}$), indicating higher stiffness and reduced deformability of rocks along the direction of greater structural continuity.

A comparison of the ratios $E_{\parallel} > E_{\perp}$ and $G_{\parallel} > G_{\perp}$ demonstrates that stronger elastic wave anisotropy correlates with more pronounced contrasts in elastic parameters measured in different directions. In other words, the higher the anisotropy degree of the rock, the more significant the differences in the values of *E* and *G* moduli along and across the bedding planes.

The previously observed trend of increased longitudinal wave velocity V_p several times when measured along different structural directions aligns with proportional changes in Young's and shear modulus (by a factor of n_2). Thus, the increase or decrease in wave velocity directly reflects the change in material stiffness and its capacity to resist compressive and shear deformation.

Thus, the results presented in Figure 3 confirm the pronounced anisotropy of the investigated rocks and highlight characteristic differences in their elastic properties associated with the orientation of tectonic and structural-textural elements within the rock mass. Box-and-whisker plots characterizing the elastic behavior of the studied rock types are presented in Figure 4.

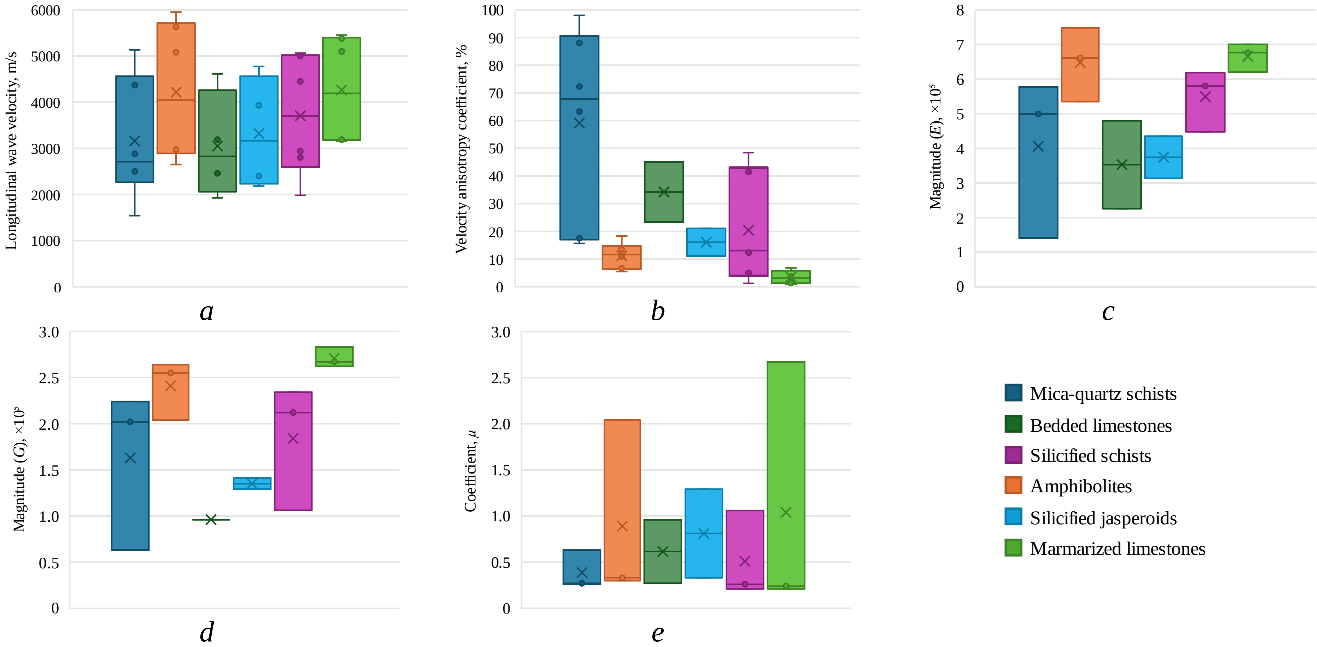

Figure 4. Box-and-whisker plots illustrating the properties of the investigated rocks: (a) – elastic wave velocities; (b) – longitudinal wave velocities; (c) – Young's moduli; (d) – shear moduli; (e) – Poisson's ratios

The range of elastic wave velocities (Figures 4a and 4b) varies significantly across rock types, indicating a high degree of anisotropy in the studied materials. Homogeneous rocks exhibit relatively narrow value intervals, while those with pronounced textural heterogeneity show a considerably wider spread.

Analysis of the box plots reveals that Young's modulus values (Figure 4c) measured parallel to bedding ($E_{||}$), are consistently higher than those measured perpendicular to bedding ($E_{\perp}$). A similar trend is observed for shear moduli, where $G_{||} > G_{\perp}$ (Figure 4d). This finding indicates stiffer mechanical behavior along the primary axis of symmetry, which is attributed to the preferential alignment of mineral grains or structural layers.

The box plot for Poisson's ratios (Figure 4e) shows a narrower spread than Young's and shear moduli but reveals noticeable differences among rock types. Poisson's ratio reflects the lateral-to-axial strain ratio and is a critical parameter in assessing the deformability of a material.

The studied rocks exhibit a high degree of anisotropy based on the analysis of all measured parameters – wave velocities, Young's moduli, shear moduli, and Poisson's ratios. Variations in longitudinal wave velocity, which proportionally reflect changes in elastic parameters (by a factor of n^2), indicate that the greater the anisotropy, the more pronounced the differences in parameters measured along and across the primary bedding direction.

Survey results, consistent with findings reported in [40-44], show that in unsupported vertical, main, and single preparatory workings, rock failures in the sidewalls are typically localized in areas where the span direction aligns with the orientation of high horizontal tectonic stresses. In horizontal excavations, failures predominantly occur in the roof and floor.

As part of the assessment of stoping chambers, the condition of over 200 active and depleted panels with varying operational lifespans was examined. The inspection included documentation of actual chamber dimensions and inter-chamber pillar widths, bedding and fracturing parameters, water saturation levels, mining depth, the collapses' area and volume, and the tectonic stresses' orientation in the examined zones. A total of 22 instances of individual roof collapses were recorded. The spans of chambers in collapse zones ranged from 6 to 50-55 meters, with depths between 20 and 300 meters. The collapsed areas covered 6 to 500 m², with volumes ranging from 0.2 to 3.0-4.0 m³. The fallen rock typically accumulated in piles along the chamber floor and rarely filled the entire excavation area. Notably, most collapses occurred after chamber stoping was completed.

Analysis of the obtained data indicates that the critical stress state in rock masses, depending on the excavation orientation, is most commonly reached on the roof and floor, where compressive stress concentrations significantly exceed those observed in undisturbed rock. When the orientation of the excavation is close to being perpendicular to the direction of the maximum tectonic stress vector, stress concentrations along the excavation boundary can exceed the ambient stress levels in the surrounding mass by a factor of 2 to 3.

The influence of tectonic stresses extends to all types of underground excavations, including main, preparatory, and stoping workings. The mechanisms of rock instability vary and range from spalling to slab detachment. Under conditions of low tectonic activity, the predominant deformation mode is spalling along planes of structural heterogeneity, resulting in the fall of discrete structural blocks, which remain relatively intact. In contrast, under high tectonic stress conditions, the blocks are crushed and destroyed, leading to the detachment of slabs parallel to the excavation contour in zones subjected to the highest compressive stresses. This progressive transition in failure mechanisms not only alters the nature and extent of damage around underground openings but also plays a crucial role in determining the design and implementation of effective support systems, excavation sequencing, and ground control strategies, particularly in deep mining conditions or regions characterized by elevated tectonic stress, where the risk of dynamic rock failure and structural collapse is substantially higher.

Thus, rock deformation around excavations under tectonic forces highly depends on the orientation of the longitudinal axis. Adjusting the alignment of an excavation relative to the direction of maximum tectonic stress makes it possible to influence stress concentrations along its boundaries and thereby control deformation and failure processes. Various engineering methods and technological solutions have been developed to minimize the adverse effects of tectonic stresses on excavation stability, considering both the magnitude and orientation of the tectonic stress vector.

4. Conclusions

Gravity and tectonic forces govern the stress-strain state of ore-bearing rock masses in Kyrgyzstan. The developed regression models for competent rocks (with Young's moduli ranging from 5-6·10⁴ and 10-11·10⁴ MPa) and moderately strong rocks (approximately 2-3·10⁴ MPa) confirm that vertical stresses σ_y are, in the first approximation, equivalent to the overburden pressure, expressed as γH.

The experimental data fall between the values predicted by N. Hast's empirical relationships and those calculated from hydrostatic theory, indicating a substantial influence of horizontal tectonic stresses.

Field measurements at the Kadamjay mine reveal that principal stress magnitudes depend on depth and the distance to fault zones. At the 930 m level, the maximum stress reaches 35.1-40.1 MPa, and a comparison between the 930 m and 960 m levels shows a 2.2-2.6-fold and 1.6-2.0-fold decrease in vertical and horizontal stresses, respectively.

The study of elastic properties revealed significant anisotropy: rocks with pronounced heterogeneity exhibit anisotropy coefficients up to 80-100%, while marmarized limestones show 5-10% values. A corresponding rise in strength anisotropy accompanies an increase in elastic anisotropy.

The inspection of underground excavations showed that rock failures most frequently occur in areas where the span direction of the excavation aligns with the vector of high horizontal tectonic stresses. These findings underscore the necessity of incorporating tectonic stress factors into the design parameters of underground workings.

Author contributions

Conceptualization: ARA, JW; Data curation: RSM, AAA; Formal analysis: AAA, ASA; Funding acquisition: ARA, RSM; Investigation: AAA, ASA; Methodology: RSM; Project administration: ARA, JW; Resources: RSM, ASA; Supervision: ARA, JW; Validation: AAA, ASA; Visualization: AAA; Writing – original draft: ARA, JW, RSM; Writing – review & editing: ARA, RSM. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Acknowledgements

The authors would like to express their sincere gratitude to the editor and the two anonymous reviewers for their constructive comments and valuable suggestions, which significantly contributed to the improvement of the manuscript.

Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

References

[1] Bogdetsky, V., Stavinskiy, V., Shukurov, E. & Suyunbaev, M. (2001). Mining industry and sustainable development in Kyrgyzstan. *Mining, Minerals and Sustainable Development, 110, 23-37*

[2] Aguirre-Unceta, R. (2024). Has Kyrgyzstan suffered from a resource curse?. *The Extractive Industries and Society*, *17*, *101427*. https://doi.org/10.1016/j.exis.2024.101427

[3] Calabrese, L. (2024). Diversifying Away from Extractives: The Belt and Road Initiative, Chinese Capital and Industrialisation in the Kyrgyz Republic. *The European Journal of Development Research*, *36*(3), *601-638*. https://doi.org/10.1057/s41287-024-00632-1

[4] Bazaluk, O., Ashcheulova, O., Mamaikin, O., Khorolskyi, A., Lozynskyi, V. & Saik, P. (2022). Innovative activities in the sphere of mining process management. *Frontiers in Environmental Science*, *(10)*, *878977*. https://doi.org/10.3389/fenvs.2022.878977

[5] Koval, V., Kryshtal, H., Udovychenko, V., Soloviova, O., Froter, O., Kokorina, V. & Veretin, L. (2023). Review of mineral resource management in a circular economy infrastructure. *Mining of Mineral Deposits*, *17*(2), *61-70*. https://doi.org/10.33271/mining17.02.061

[6] Yuldashev, F. & Sahin, B. (2016). The political economy of mineral resource use: The case of Kyrgyzstan. *Resources Policy*, *49*, 266-272. https://doi.org/10.1016/j.resourpol.2016.06.007

[7] Abdiev, A.R., Mambetova, R.Sh., Abdiev, A.A., & Abdiev, Sh. A. (2020). Studying a correlation between characteristics of rock and their conditions. *Mining of Mineral Deposits*, *14(3), 87-100*. https://doi.org/10.33271/mining14.03.087

[8] Gornostayev, S.S., Crocket, J.H., Mochalov, A.G. & Laajoki, K.V.O. (1999). The platinum-group minerals of the Baimka placer deposits, Aluchin horst. *Canadian Mineralogist, 37(5), 1117-1129*

[9] Sotskov, V. & Saleev, I. (2013). Investigation of the rock massif stress strain state in conditions of the drainage drift overworking.

Annual Scientific-Technical Colletion - Mining of Mineral Deposits, 197-201. https://doi.org/10.1201/b16354-35

[10] Umarov, T., Abdiev, A., Moldobekov, K., Mambetova, R. & Isaev, B. (2023). Creation of digital maps of land disturbed by mining operations. *E3S Web of Conferences, 420, 03023.* https://doi.org/10.1051/e3sconf/202342003023

[11] Bazaluk, O., Kuchyn, O., Saik, P., Soltabayeva, S., Brui, H., Lozynskyi, V. & Cherniaiev, O. (2023). Impact of ground surface subsidence caused by underground coal mining on natural gas pipeline. *Scientific Reports, (13), 19327.* https://doi.org/10.1038/s41598-023-46814-5

[12] Khomenko, O.Ye. (2012). Implementation of energy method in study of zonal disintegration of rocks. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, (4), 44-54*

[13] Rysbekov, K.B., Huayang, D., Nurpeisova, M.B., Lozynskyi, V.H., Kyrgyzbayeva, G.M., Kassymkanova, K. & Abenov, A.M. (2022). Modern monitoring tools – effective way to ensure safety in subsoil use. *Engineering Journal of Satbayev University, 144(3), 34-40.* https://doi.org/10.51301/ejsu.2022.i3.06

[14] Shavarskyi, Ia., Falshtynskyi, V., Dychkovskyi, R., Akimov, O., Sala, D. & Buketov, V. (2022). Management of the longwall face advance on the stress-strain state of rock mass. *Mining of Mineral Deposits, 16(3), 78-85.* https://doi.org/10.33271/mining16.03.078

[15] Song, J.F., Lu, C.P., Zang, A., Zhang, X.F., Zhou, J., Zhan, Z. W. & Zhao, L. M. (2024). Assessment of Microseismic Events via Moment Tensor Inversion and Stress Evolution to Understand the Rupture of a Hard–Thick Rock Stratum. *Rock Mechanics and Rock Engineering, 57(11), 10009-10025.* https://doi.org/10.1007/s00603-024-04066-3

[16] Zhang, H., Guo, G., Li, H., Wang, T., Ni, J. & Meng, H. (2025). A new numerical method for calculating residual deformation in mined-out areas considering water-rock interaction and its application. *Scientific Reports, 15(1), 11207.* https://doi.org/10.1038/s41598-025-94001-5

[17] Kononenko, M. & Khomenko, O. (2010). Technology of support of workings near to extraction chambers. *New Techniques and Technologies in Mining, 193-197.* https://doi.org/10.1201/b11329-31

[18] Matayev, A.K., Lozynskyi, V.H., Musin, A., Abdrashev, R.M., Kuantay, A.S. & Kuandykova, A.N. (2021). Substantiating the optimal type of mine working fastening based on mathematical modeling of the stress condition of underground structures. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, (3), 57-63.* https://doi.org/10.33271/nvngu/2021-3/057

[19] Fang, C., Yuan, Y., Chen, J., Gao, D. & Peng, J. (2024). Examination of Green Productivity in China's Mining Industry: An In-Depth Exploration of the Role and Impact of Digital Economy. *Sustainability, 16(1), 463.* https://doi.org/10.3390/su16010463

[20] Saik, P., Dychkovskyi, R., Lozynskyi, V., Falshtynskyi, V. & Ovcharenko, A. (2024). Achieving climate neutrality in coal mining regions through the underground coal gasification. *E3S Web of Conferences, 526, 01004.* https://doi.org/10.1051/e3sconf/202452601004

[21] Mussin, A., Imashev, A., Matayev, A., Abeuov, Ye., Shaike, N. & Kuttybayev, A. (2023). Reduction of ore dilution when mining low-thickness ore bodies by means of artificial maintenance of the mined-out area. *Mining of Mineral Deposits, 17(1), 35-42.* https://doi.org/10.33271/mining17.01.035

[22] An, H., & Mu, X. (2025). Contributions to Rock Fracture Induced by High Ground Stress in Deep Mining: A Review. *Rock Mechanics and Rock Engineering, 58(1), 463-511.* https://doi.org/10.1007/s00603-024-04113-z

[23] Lan, T., Liu, Y., Yuan, Y., Fang, P., Ling, X., Zhang, C. & Feng, W. (2024). Determination of mine fault activation degree and the division of tectonic stress hazard zones. *Scientific Reports, 14(1), 12419.* https://doi.org/10.1038/s41598-024-63352-w

[24] Salieiev, I., Bondarenko, V., Kovalevska, I., Malashkevych, D. & Galkov, R. (2025). Principles of mining-geological classification for maintaining mine workings in conditions of weakly metamorphosed rocks. *Mining of Mineral Deposits, 19(1), 26-36.* https://doi.org/10.33271/mining19.01.026

[25] Abdiev, A.R., Mambetova, R.Sh., Abdiev, A.A. & Abdiev, Sh.A. (2020). Development of methods assessing the mine workings stability. *E3S Web of Conferences, 201, 01040.* https://doi.org/10.1051/e3sconf/202020101040

[26] Abdiev, A.R., Mambetova, R.Sh., Abdiev, A.A. & Abdiev, Sh.A. (2020). Razvitie metodov otsenki geomekhanicheskogo sostoyaniya porodnogo massiva vokrug gornykh vyrabotok. *Nauchnye issledovaniya v Kyrgyzskoy Respublike, 1-12*

[27] Mambetov, Sh.A., Kozhogulov, K.Ch. & Abdiev, A.R. (2021). Vzaimosvyaz svoystv i sostoyaniya porod strukturno-neodnorodnykh mestorozhdeniy poleznykh iskopaemykh. *Sovremennye problemy mekhaniki, 43(1), 3-17*

[28] Abdiev, A.R., Mambetova, R.Sh. & Mambetov, Sh.A. (2017). Geomechanical assessment of Tyan-Shan's mountains structures for efficient mining and mine construction. *Gornyi Zhurnal, (4), 1-9*

[29] Mambetov, Sh.A., Abdiev, A.R. & Mambetov, A.Sh. (2002). Zonal and step-by-step evaluation of the stressed-strained state of Tyan'-Shan' rock massif. *Gornyi Zhurnal, (10), 1-12*

[30] Rahman, A., Shah, R.A., Yadava, M.G. & Kumar, S. (2024). Carbon and nitrogen biogeochemistry of a high-altitude Himalayan lake sediment: Inferences for the late Holocene climate. *Quaternary Science Advances, 14, 100199.* https://doi.org/10.1016/j.qsa.2024.100199

[31] Mambetov, Sh.A., Kozhogulov, K.Ch. & Abdiev, A.R. (2021). Kontrol svoystv i napryazhenno-deformirovannogo sostoyaniya porod strukturno-neodnorodnykh mestorozhdeniy poleznykh iskopaemykh. *Sovremennye problemy mekhaniki, 43(1), 35-49*

[32] Mambetov, Sh.A., Abdiev, A.R. & Mambetova, R.Sh. (2020). *Osnovy geomekhaniki. Klassicheskiy uchebnik. Bishkek, KRSU*

[33] Eljufout, T. & Alhomaidat, F. (2024). Utilizing waste rocks from phosphate mining in Jordan as concrete aggregates. *Results in Engineering, 22, 102350.* https://doi.org/10.1016/j.rineng.2024.102350

[34] Rezaei, M. & Mousavi, S.Z.S. (2024). Slope stability analysis of an open pit mine with considering the weathering agent: Field, laboratory and numerical studies. *Engineering Geology, 333, 107503.* https://doi.org/10.1016/j.enggeo.2024.107503

[35] Patent KR №2238. (2020). Sposob otsenki geomekhanicheskogo sostoyaniya porodnogo massiva vysokogornykh mestorozhdeniy. *Bishkek, Kyrgyzstan*

[36] Matayev, A., Abdiev, A., Kydrashov, A., Musin, A., Khvatina, N. & Kaumetova, D. (2021). Research into technology of fastening the mine workings in the conditions of unstable masses. *Mining of Mineral Deposits, 15(3), 78-86.* https://doi.org/10.33271/mining15.03.078

[37] Abdiev, A.R., Mambetova, R.Sh. & Abdiev, A.A. (2020). Izuchenie zakonomernostey izmeneniya struktury i svoystv gornykh porod v zone tektonicheskikh narusheniy. V LKhKhIII Mezhdunarodnye nauchnye chteniya. *Sbornik statey Mezhdunarodnoy nauchno-prakticheskoy konferentsii, 111-114*

[38] Khomenko, O. & Bilegsaikhan, J. (2018). Classification of theories about rock pressure. *Solid State Phenomena, 277, 157-167.* https://doi.org/10.4028/www.scientific.net/SSP.277.157

[39] Baymakhan, R.B., Muta, A.N., Tileikhan, A. & Kozhogulov, K.C. (2023). On the use of the finite element method in the study of the stress-strain state of the contour of the Annie Cave on Mount Arsia. *Engineering Journal of Satbayev University, 145(2), 31-36.* https://doi.org/10.51301/ejsu.2023.i2.05

[40] Kazatov, U., Raimbekov, B., Bekbosunov, R., Ashirbaev, B. & Orokov, A. (2023). Some results of the study of rock properties of the Sulukta deposit. *E3S Web of Conferences, 431, 03009.* https://doi.org/10.1051/e3sconf/202343103009

[41] Shakenov A., Abdiev, A.R. & Stolpovskih I. (2023). Energy potential of mining transport at mines of Kyrgyzstan located at high altitude. *IOP Conference Series: Earth and Environmental Science, 1254, 012142.* https://doi.org/10.1088/1755-1315/1254/1/012142

[42] Kozhogulov, K.Ch. & Abdiev, A.R. (2023). Napryazhenno-deformirovannoe sostoyanie neodnorodnykh strukturnykh massivov vysokogornykh rudnykh mestorozhdeniy Kyrgyzstana. *Fundamentalnye i prikladnye voprosy gornykh nauk, 10(2), 39-46.* https://doi.org/10.15372/FPVGN2023100206

[43] Zhienbayev, A., Takhanov, D., Zharaspaev, M., Kuttybayev, A., Rakhmetov, B. & Ivadilinova, D. (2025). Identifying rational locations for field mine workings in the zone influenced by mined-out space during repeated mining of pillars. *Mining of Mineral Deposits, 19(1), 1-12.* https://doi.org/10.33271/mining19.01.001

[44] Mambetova, R.Sh., Abdiev, A.A. & Abdiev, A.R. (2023). Issledovaniya gidrogeologicheskikh usloviy Sulyuktinskogo burougolnogo mestorozhdeniya dlya sozdaniya estestvennoy tsifrovoy gidrodinamicheskoy modeli. *Vestnik Kyrgyzsko-Rossiyskogo Slavyanskogo universiteta, 23(8), 150-155*

Қырғызстанның құрылымдық-гетерогенді тау жыныстарының кернеулі-деформацияланған күйін геомеханикалық бағалау

А.Р. Абдиев[1*], Ц. Ван[2], Р.Ш. Мамбетова[1], А.А. Абдиев[1], А.Ш. Абдиев[1]

[1]*И. Раззаков атындағы Қырғыз мемлекеттік техникалық университеті, Бішкек, Қырғызстан*
[2]*Солтүстік-Батыс университеті, Сиань, Қытай*

**Корреспонденция үшін автор: atsanbek.abdiev@kstu.kg*

Аңдатпа. Зерттеулер Қырғызстанның құрылымдық жағынан біртекті емес кен орындарының тау жыныстарының кернеулі-деформацияланған жай-күйін бағалауға, тектоникалық үзілістердің тереңдігі мен әсеріне байланысты кернеулердің таралу заңдылықтарын анықтауға, сондай-ақ тау жыныстарының серпімді сипаты мен олардың беріктік қасиеттері арасындағы байланысты орнатуға бағытталған. Жұмыста әртүрлі тереңдіктегі негізгі қалыпты кернеулердің мәндерін алуға мүмкіндік беретін түсіру әдісімен далалық өлшеулерді, серпімді толқындардың жылдамдығын, серпімділік модульдерін және сдысу модульдерін анықтауға арналған зертханалық сынақтарды, сондай-ақ регрессиялық тәуелділіктерді құруға арналған статистикалық талдауды қамтитын әдістер кешені пайдаланылды. Сонымен қатар, негізгі кернеулерді бағдарлауды қайта құру және тектоникалық үзілістердің масивадағы кернеулердің таралуына әсерін бағалау жүргізілді. Зерттеу нәтижелері тау жыныстарындағы тік кернеулер, бірінші жақын жерде, жоғарғы қабаттардағы γH салмағының қысымына сәйкес келетіндігін көрсетеді. Күшті тау жыныстары мен орташа беріктік массивтері үшін алынған регрессиялық модельдер эксперименттік деректер Н. Хаст тәуелділіктері бойынша есептелген мәндер мен гидростатикалық кернеудің таралуына байланысты мәндер арасында екенін растайды. Тау жыныстарының серпімді сипаттамаларын зерттеу бойлық толқын жылдамдығының өзгеруі серпімділік модульдері мен ығысу модулінің өзгеруімен тікелей байланысты болатын анизотропияның жоғары дәрежесін анықтады. Алынған нәтижелер кен массивтерінің кернеулі-деформацияланған күйін болжаудың дәлірек модельдерін жасауға және тау-кен қазбаларын жобалауды оңтайландыруға мүмкіндік береді.

Негізгі сөздер: *тау-кен ісі, кернеулі-деформацияланған күйі, серпімді сипаттамалары, тау жыныстары.*

Геомеханическая оценка напряжённо-деформированного состояния структурно-неоднородных породных массивов Кыргызстана

А.Р. Абдиев[1*], Ц. Ван[2], Р.Ш. Мамбетова[1], А.А. Абдиев[1], А.Ш. Абдиев [1]

[1]*Кыргызский Государственный Технический Университет им. И. Раззакова, Бишкек, Кыргызстан*
[2]*Северо-Западный университет, Сиань, Китай*

**Автор для корреспонденции: atsanbek.abdiev@kstu.kg*

Аннотация. Исследования направлены на оценку напряжённо-деформированного состояния породных массивов структурно неоднородных рудных месторождений Кыргызстана, выявление закономерностей распределения напряжений в зависимости от глубины и влияния тектонических разрывов, а также на установление взаимосвязи между упругими характеристиками пород и их прочностными свойствами. В работе использован комплекс методов, включающий полевые измерения методом разгрузки, позволяющие получать значения главных нормальных напряжений на различных глубинах, лабораторные испытания для определения скоростей упругих волн, модулей упругости и модулей сдвига, а также статистический анализ для построения регрессионных зависимостей. Кроме того, проведена реконструкция ориентировки главных напряжений и оценка влияния тектонических разрывов на распределение напряжений в массиве. Результаты исследования демонстрируют, что вертикальные напряжения в породном массиве, в первом приближении, соответствуют давлению веса вышележащих слоёв γH. Полученные регрессионные модели для крепких пород и массивов средней прочности подтверждают, что экспериментальные данные находятся между значениями, рассчитанными по зависимостям Н. Хаста, и значениями, обусловленными гидростатическим распределением напряжений. Исследование упругих характеристик пород выявило высокую степень анизотропии, при которой изменение скорости продольной волны непосредственно коррелирует с изменением модулей упругости и модуля сдвига. Полученные результаты позволяют разрабатывать более точные модели прогнозирования напряжённо-деформированного состояния рудных массивов и оптимизировать проектирование горных выработок.

Ключевые слова: *горное дело, напряжённо-деформированное состояние, упругие характеристики, породный массив.*

Publisher's note

All claims expressed in this manuscript are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers.