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GEOMECHANICAL JUSTIFICATION OF THE STABILITY OF DEVELOPMENT WORKINGS UNDER FLOOR HEAVE CONDITIONS

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The paper examines the geomechanical patterns governing the loss of stability of development workings affected by floor heave at deep levels of coal mines. The aim of the study was to establish the relationship between the physical and mechanical properties of the near-contour rock mass, stress redistribution after excavation, and the development of plastic deformation in the floor of the roadway. The ventilation roadway $47K_2$-W at the Kostenko mine of the Karaganda Coal Basin was selected as the study object.

The research combined laboratory testing of rocks, instrumental assessment of strength characteristics, acoustic monitoring, and numerical modeling of the stress-strain state in the RS2 environment.

It was found that floor heave is primarily controlled by the low strength of the floor argillites, the reduction of lateral confinement in the near-contour zone, and the formation of a destressed region where weak bedded rocks pass into a plastic state.

The results show that roadway stability increases when the entire system “roof - ribs - floor” is stabilized rather than a single element being reinforced. The highest efficiency was demonstrated by combined rock-bolting schemes incorporating side and floor bolts.

The obtained results can be used to substantiate support parameters for development workings driven in similar mining and geological conditions.

Keywords: floor heave, development workings, near-contour rock mass, stress-strain state, geomechanical modeling, roadway stability, rock bolt support, Karaganda Coal Basin.

ГЕОМЕХАНИЧЕСКОЕ ОБОСНОВАНИЕ УСТОЙЧИВОСТИ ПОДГОТОВИТЕЛЬНЫХ ВЫРАБОТОК ПРИ ПУЧЕНИИ ПОРОД ПОЧВЫ

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В статье рассмотрены геомеханические закономерности потери устойчивости подготовительных выработок при пучении пород почвы на глубоких горизонтах угольных шахт. Цель исследования состояла в том, чтобы установить связь между физико-механическими свойствами пород приконтурного массива, перераспределением напряжений после проведения выработки и развитием пластических деформаций в ее почве. Объектом исследования принят вентиляционный штрек $47K_2$-З шахты имени Костенко Карагандинского угольного бассейна.

В работе использованы лабораторные испытания пород, инструментальные методы оценки прочностных характеристик, акустический мониторинг и численное моделирование напряженно-деформированного состояния массива в среде RS2.

Установлено, что ключевыми причинами пучения являются низкая прочность аргиллитов почвы, снижение бокового обжатия в приконтурной зоне и развитие разгруженной области, в которой слабые слоистые породы переходят в пластическое состояние. Показано, что устойчивость выработки возрастает при комплексном воздействии на систему «кровля - бока - почва», а наибольший эффект обеспечивают комбинированные схемы анкерного крепления с боковыми и припочвенными анкерами.

Полученные результаты могут быть использованы при обосновании параметров крепления подготовительных выработок в сходных горно-геологических условиях.

Ключевые слова: пучение пород почвы, подготовительные выработки, приконтурный массив, напряженно-деформированное состояние, геомеханическое моделирование, устойчивость выработок, анкерная крепь, Карагандинский угольный бассейн.

ТАБАН ЖЫНЫСТАРЫНЫҢ КӨТЕРІЛУІ КЕЗІНДЕ ДАЙЫНДАУ ҚАЗБАЛАРЫ ТҰРАҚТЫЛЫҒЫНЫҢ ГЕОМЕХАНИКАЛЫҚ НЕГІЗДЕМЕСІ

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Мақалада көмір шахталарының терең горизонттарында табан жыныстары көтерілген кезде дайындық қазбалары тұрақтылығының бұзылу геомеханикалық заңдылықтары қарастырылған. Зерттеудің мақсаты қазба контуры маңындағы жыныстардың физика-механикалық қасиеттері, қазба жүргізілгеннен кейінгі кернеулердің қайта бөлінуі және қазба табанының пластикалық деформациялары арасындағы байланысты анықтау болды.

Зерттеу нысаны ретінде Қарағанды көмір бассейніндегі Костенко атындағы шахтаның 47К2-з желдеткіш штрегі алынды. Жұмыста жыныстарға зертханалық сынақтар, беріктік сипаттамаларын аспаптық бағалау, акустикалық мониторинг және RS2 бағдарламалық ортасында массивтің кернеулі-деформациялық күйін сандық модельдеу қолданылды.

Табан жыныстарының көтерілуі негізінен әлсіз аргиллиттердің төмен беріктігімен, контур маңындағы аймақта бүйірлік қыспақтың азаюымен және қабаттасқан жыныстар пластикалық күйге өтетін босаңсыған аймақтың қалыптасуымен түсіндірілетіні анықталды. «Төбе - бүйір - табан» жүйесіне кешенді әсер ету қазбаның орнықтылығын арттыратыны, ал ең жоғары нәтиже бүйірлік және табандық анкерлері бар құрама анкерлік бекітуде байқалатыны көрсетілді.

Алынған нәтижелер ұқсас тау-геологиялық жағдайларда дайындық қазбаларын бекіту параметрлерін негіздеуге пайдаланылуы мүмкін.

Түйін сөздер: табан жыныстарының көтерілуі, дайындық қазбалары, контур маңындағы массив, кернеулі-деформациялық күй, геомеханикалық модельдеу, қазба тұрақтылығы, анкерлік бекіту, Қарағанды көмір бассейні.

Introduction. Ensuring the stability of development workings at deep horizons is one of the most challenging tasks in underground coal mining, since the condition of the near-contour rock mass determines operational safety, support integrity, and the эксплуатационная reliability of the excavation [1-3]. With increasing mining depth, the level of natural and technogenically redistributed stresses rises, the influence of weak lithological variations and structural disturbances intensifies, and the «rock mass–excavation–support» system begins to operate in a clearly nonlinear regime [4].

One of the most unfavorable manifestations of rock pressure is floor heave. Unlike local roof collapses or sidewall failures, this process develops gradually but leads to a persistent reduction in the cross-section of the excavation, deformation of the support system, deterioration of transport and ventilation conditions, and, consequently, the need for continuous maintenance and repair works. Floor heave is most intensive in workings driven through weak argillites and siltstones prone to plastic deformation and shear under reduced lateral confinement [3, 6].

For the conditions of the Karaganda coal basin, this problem is particularly relevant due to the significant mining depth, complex geological structure of coal-bearing strata, and pronounced lithological and structural heterogeneity of the rock mass. Under such conditions, the stability of development workings is governed not by a single parameter, but by a combination of rock strength, fracturing, bedding, stress-strain state parameters, and characteristics of the applied support system. Therefore, reliable assessment of excavation stability must be based on an integrated approach combining experimental investigations and numerical geomechanical modeling [4, 7].

Despite the large number of studies devoted to underground excavation stability, the issues of geomechanical substantiation of floor heave under specific deep mining conditions remain insufficiently explored, especially for weak layered floor rocks and their interaction with the destressed near-contour zone [5, 8]. In practice, this often leads to the use of

standard support schemes without considering the actual deformation mechanisms of the rock mass, which reduces the effectiveness of stabilization measures [6, 9].

The objective of this study was to provide a geomechanical justification for the stability of development workings under floor heave conditions based on the analysis of physical and mechanical properties of the near-contour rock mass, numerical modeling of the stress-strain state, and assessment of the influence of support parameters on deformation processes. To achieve this objective, the following tasks were addressed: determination of rock strength characteristics, identification of stress redistribution patterns in the near-contour zone, evaluation of floor rock stability, and substantiation of rational support parameters [7, 10].

Materials and Methods. The study was carried out for the conditions of ventilation roadway $47K_{2\text{-}Z}$ of the Kostenko mine, Karaganda Komir LLP. The excavation was driven at a depth of 683–691 m under complex geological conditions. The floor consists of argillites prone to heaving; the immediate and main roof are composed of argillites, sandstones, and siltstones, while the interlayer thickness K_3–K_2 varies from 2.65 to 4.5 m, forming a highly heterogeneous stress-strain state of the rock mass.

The experimental part included sampling and testing of coal and host rocks from seams K_1, K_2, and K_3. Strength characteristics were determined using a combination of laboratory and instrumental methods: Schmidt hammer rebound testing, impact-impulse testing using IPS-MG4.04 device, and uniaxial compression tests on a PSN-0.16.10 testing machine. This combination allowed obtaining comparable strength data for argillites, siltstones, sandstones, and coal, as well as assessing the influence of structural heterogeneity on mechanical behavior.

Numerical modeling of the stress-strain state of the near-contour rock mass was performed using the RS2 software based on the finite element method. The model included the coal seam, roof and floor rocks, the destressed near-contour zone, and the influence zone of the longwall face. The rock mass behavior was described using an elastoplastic model with the Mohr–Coulomb failure criterion. The initial state corresponded to a gravitational stress field. Boundary conditions included fixation of the lower boundary in vertical displacement, lateral boundaries in horizontal displacement, and application of vertical load at the top boundary corresponding to the overburden weight. Additional calculations were carried out for different unloading coefficients to track stress evolution, development of the destressed zone, and transition of floor rocks into the plastic state.

To analyze structural discontinuities and assess local stability, Dips and Unwedge software were used. Based on fracture orientation measurements, the main discontinuity systems were identified, potential wedge blocks in the roof, ribs, and floor were evaluated, and anchor support parameters were selected considering the size and stability of weakened zones. This approach allowed correlating fracture geometry with possible mechanisms of local instability [7, 11].

Field assessment of the rock mass condition was carried out using acoustic monitoring with the «RIPAS» system along the ventilation roadway 47K2-Z in section PK 10-110 m. The method is based on recording and analyzing acoustic signals reflecting changes in fracturing, stress state, and deformability of the rock mass. The use of «RIPAS» enabled comparison of calculated stress-strain conditions with actual geomechanical manifestations in the excavation.

Experimental and numerical data were analyzed jointly, which made it possible to assess the conditions of floor heave development, determine the stability coefficient of the near-contour rock mass, and justify rational support parameters.

Results and Discussion. The obtained results show that the stability of development workings under the considered conditions is determined by the combined influence of strength heterogeneity of the near-contour rock mass, stress redistribution near the excavation boundary, and the efficiency of the applied support system.

Laboratory and instrumental tests revealed significant differentiation in the physical and mechanical properties of the studied rocks. Sandstones exhibit the highest strength: estimated uniaxial compressive strength reaches 78 MPa according to Schmidt hammer data and 70 MPa according to impact-impulse testing. Siltstones occupy an intermediate position with strength values of about 50–55 MPa. The least stable materials are argillites and coal from seams K_1–K_3. For argillites, the estimated strength is 35–42 MPa (Schmidt hammer) and 32–38 MPa (IPS-MG4.04), while for coal it decreases to 12–16 MPa. Uniaxial compression tests showed failure loads ranging from 3.07 to 24.92 kN, confirming significant heterogeneity of the rock mass in terms of strength and deformability.

These results help explain the mechanism of floor heave. Argillites forming the floor are characterized

by relatively low strength, pronounced layering, and a tendency to delaminate along planes of weakness. Under reduced lateral confinement, they are the first to enter a plastic deformation state, creating conditions for extrusion of rocks into the excavation void. Numerical modeling demonstrated that after excavation, a characteristic stress redistribution pattern is formed. In the face area and roof, a zone of maximum principal stress concentration σ_1 develops, reaching 29–31 MPa. At the same time, stress reduction to 8–12 MPa is observed in the floor, indicating the formation of a destressed near-contour zone. This stress combination is geomechanically unfavorable, since the reduction in normal stress increases the role of shear stresses, which is particularly dangerous for weak layered argillites of the floor.

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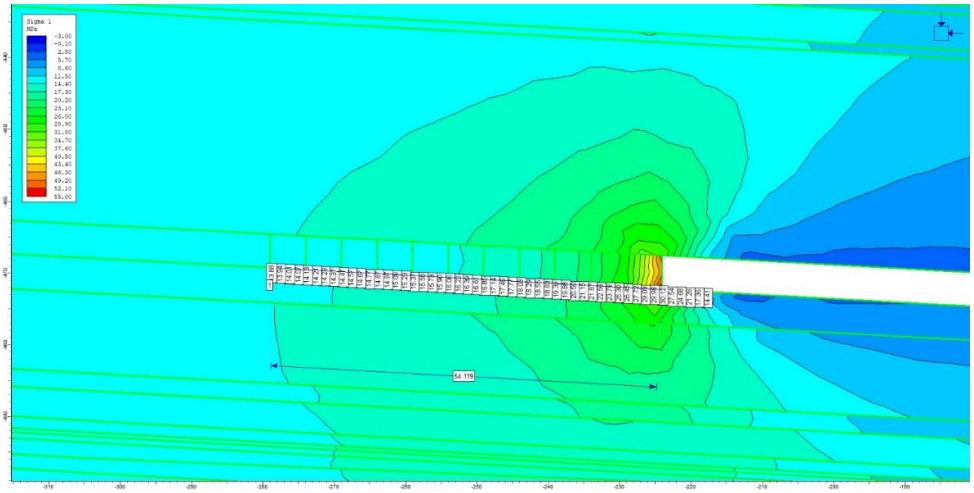


Fig. 1 - Variation of maximum principal stresses along the axis of ventilation roadway 47K2-Z

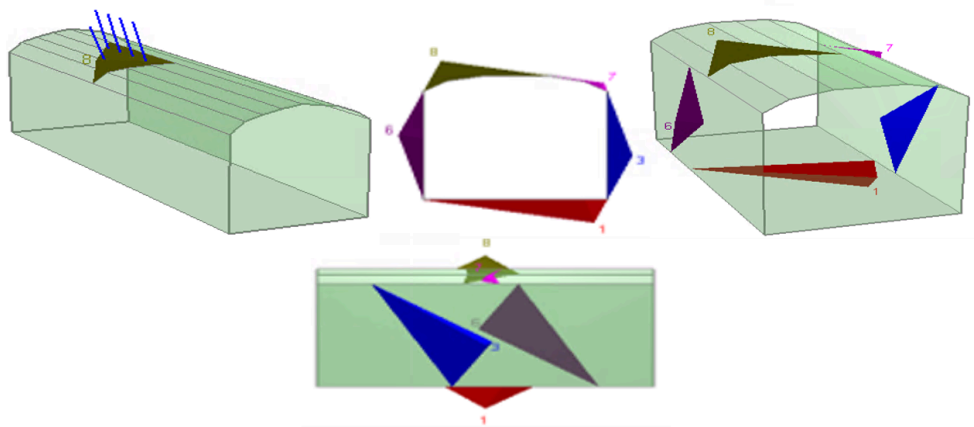


Fig. 2 - Weakened zones of the rock mass and their stability assessment based on Unwedge modeling results

The calculation of the floor rock stability factor confirmed the presence of conditions for the development of floor heave. At normal stresses of 8–12 MPa, shear stresses of 4.5–6.0 MPa, argillite cohesion of 1.2–1.8 MPa, and an internal friction angle of 18–22°, the stability factor Fs in the near-contour zone ranges from 0.80 to 0.95. Values below unity indicate a transition of the rock mass into an unstable state and the development of plastic deformation. Therefore, floor heave in the considered excavation is a natural consequence of stress redistribution under conditions of a weak argillite floor, rather than a random local manifestation of rock pressure.

Analysis of the structural disturbance of the rock mass showed that an additional factor contributing to instability is the presence of fracture systems and

weakened surfaces forming potential wedge-shaped blocks in the roof, ribs, and floor. According to modeling results obtained using Dips and Unwedge, depending on fracture orientation and excavation direction, roof and sidewall blocks of significant mass may form. For certain weakened roof wedges, the initial safety factor is equal to zero, indicating the necessity of mandatory rock bolting. After bolt installation, the safety factor increases to 1.8–2.0, and the weakened zone transitions into a stable state.

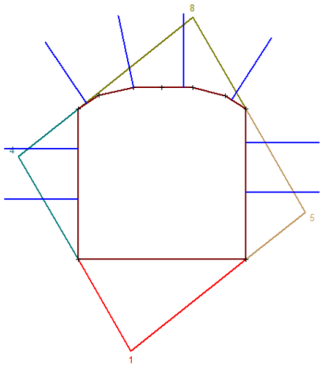
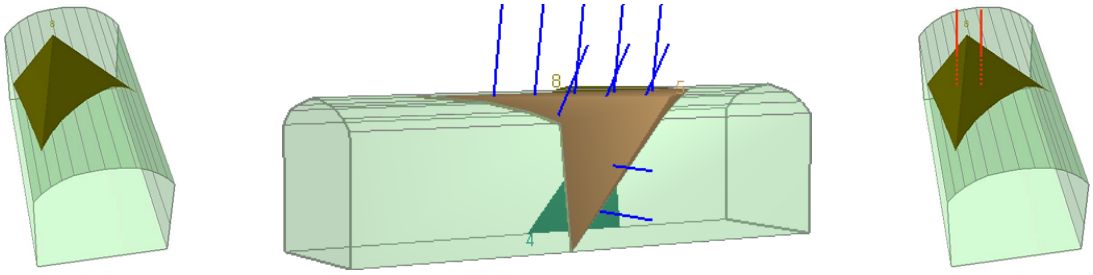


Fig. 3 - Fracture development zones under rock bolt support in disturbed areas in the Unwedge software interface (a - rock bolt support; b - factor of safety of rock blocks) In the floor (1) FS: Stable Weight: 89.8 tonnes; Left wedge (4) FS: 12.823 Weight: 59.3 tonnes; Right wedge (5) FS: 28.4 Weight: 59.3 tonnes; Roof wedge (8) FS: 11.2 Weight: 48.8 tonnes

To determine the factor of safety of the supported weakened zone, the ratio of the support capacity to the weight of the weakened wedge was used:

$$FS = \frac{support\ capacity}{weight\ of\ the\ weakened\ zone} \quad (1)$$

Figure 4 shows the calculation of the factor of safety for unsupported and supported excavations.



А **Б** **В**

Fig. 4 – Determination of the factor of safety for unsupported (A) and supported (B) geomechanical models in the Unwedge program; (C) excavation layout and support scheme

$$FS = \frac{support\ capacity}{wedgeweight}$$

Support capacity = 0 t
Wedge weight = 44 t
FS = 0 / 44 = 0

Support capacity = 80 t
Wedge weight = 44 t
FS = 80 / 44 = 1.8

The assessment of the influence of support parameters showed that the most effective scheme is the one that ensures not only roof support but also limits deformation of the ribs and floor. Modeling results indicate that a two-level rock bolting system reduces the development of inelastic deformations compared to a single-level scheme, while the use of side bolts decreases the load on the ribs and reduces pressure from the floor rocks. Increasing the length of side bolts to 3.5 m is accompanied by an increase in the rock mass safety factor, a reduction in lateral stresses from 20 to 15 MPa, and a decrease in the depth of failure in the roof and ribs. The use of floor bolting reduces floor deformations by 40–50%, which is especially important under conditions of argillites prone to heaving.

Comparison of calculated and field data shows that deformation development in the excavation has a pronounced geomechanical nature and is governed by the interaction of weak floor rocks with the redistributed stress state of the near-contour rock mass. Stability improvement is achieved not by strengthening a single element, but through a комплексное воздействие on the "floor–ribs–roof" system, where rock bolting and combined support limit the development of the plastic zone and contribute to rock mass stabilization. The summarized results of laboratory and instrumental determination of physical and mechanical properties of the studied near-contour rocks are presented in Table 1.

Table 1 - Physical and mechanical properties of the studied rocks of the near-contour rock mass

Rock Type	Average Schmidt Rebound Index (R)	Estimated Strength by Schmidt Hammer, MPa	Estimated Strength by IPS-MG4.04, MPa
Argillite	29.1	42	38
Carbonaceous argillite	25.7	35	32
Siltstone	35.5	55	50
Sandstone	43.5	78	70
Coal seam K1	19.1	16	15
Coal seam K2	17.9	14	13
Coal seam K3	16.9	13	12

The main calculated parameters of the stress state of the near-contour zone and the stability factor of the floor rocks obtained from numerical modeling are presented in Table 2.

Table 2 - Calculated parameters of the stress state and the stability factor of floor rocks

Parameter	Value	Interpretation
Maximum principal stresses in the zone ahead of the face, MPa	29–31	Formation of a stress concentration zone
Normal stresses in the floor, MPa	8–12	Development of a destressed near-contour zone
Shear stresses in the floor, MPa	4.5–6.0	Increased probability of shear deformation
Extent of the active stress redistribution zone, m	30–35	Geomechanically disturbed near-contour zone
Cohesion of floor argillites, MPa	1.2–1.8	Low shear strength
Internal friction angle of argillites, degrees	18–22	Limited shear resistance
Stability factor of floor rocks, Fs	0.80–0.95	Unstable condition, prerequisites for heave
Plastic deformation zone	3.5 m from the excavation contour	Support reinforcement required

The obtained results indicate that the development of floor heave in development workings at deep horizons is not caused by a single factor, but by their combined action. The key role is played by the interaction of the low strength of argillite floor rocks, pronounced structural heterogeneity of the rock mass, and stress redistribution after excavation. Under the considered conditions, it is the reduction of lateral confinement in the near-contour zone, combined with the action of shear stresses, that creates a geomechanical situation in which weak floor rocks transition into a plastic state and begin to heave into the excavation void.

It is fundamentally important that laboratory tests and numerical modeling do not contradict each other but rather complement one another. The experimentally

determined low strength of argillites explains their increased susceptibility to deformation, while RS2 modeling demonstrates how this weakness is manifested in the near-contour zone. Therefore, floor heave should be considered as the result of the superposition of two processes: intrinsic rock weakness and external stress redistribution.

From an engineering perspective, this implies that the conventional approach, which focuses primarily on roof support, does not ensure sufficient stabilization of the excavation. Under such conditions, an effective support system must simultaneously limit roof delamination, restrain sidewall displacement, and prevent floor heave. This explains why combined support systems with side and floor bolts, as well as two-level bolting schemes that redistribute loads to more stable zones of the rock mass, have shown the greatest effectiveness.

Comparison of the obtained results with general concepts of modern rock mechanics indicates that for deep horizons, the decisive factor is not the absolute stress level but the configuration of stress redistribution around the excavation. A stress concentration zone forms ahead of the face, while a destressed zone develops in the floor. When designing development workings under similar conditions, it is necessary to consider not only rock strength but also the potential formation of destressed near-contour zones, which are most critical in terms of floor heave.

The advantage of this study lies in its integrated approach, combining laboratory determination of rock properties, numerical modeling of the stress-strain state, and analysis of support parameters. This made it possible to move from qualitative descriptions of floor heave to its quantitative geomechanical interpretation. However, the limitations of the study include consideration of a single excavation and the use of a two-dimensional modeling approach. Further research should focus on expanding the field observation base, accounting for spatial variability of interburden layers, and applying three-dimensional modeling of the near-contour rock mass.

Conclusion. It has been established that the stability of development workings at deep horizons is largely determined by the condition of floor rocks composed of weak argillites prone to plastic deformation. Laboratory studies confirmed significant heterogeneity in the physical and mechanical properties of the near-contour rock mass, while numerical modeling revealed the pattern of stress redistribution within the excavation influence zone. It was shown that a zone of maximum principal stress concentration forms ahead of the face, while a destressed zone with reduced lateral confinement develops in the floor, creating conditions for rock extrusion into the excavation.

It is demonstrated that stability improvement is achieved by transitioning from local reinforcement of individual zones to integrated stabilization of the “roof–ribs–floor” system. The most effective solutions were combined two-level rock bolting schemes, which reduce inelastic deformation, limit the development of the plastic zone, and increase the safety factor of the near-contour rock mass. The obtained results can be used for geomechanical justification of support parameters for development workings under similar geological and mining conditions of the Karaganda coal basin.

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