IRSTI 52.13.25 **https://doi.org/10.58805/kazutb.v.1.30-1421**

INTEGRATED GEOMECHANICAL APPROACH TO ENSURING THE SAFETY OF UNDERGROUND MINING OF ORE DEPOSITS

[1]S.N. Shaposhnik, [1]D.A. Shokarev, [1]N.V. Matvienko, [1]K.T. Zikirova, [2]Zh.T. Dauletzhanova, [3]A.I. Konurin

[1]LLP «Expert Pro», Ust-Kamenogorsk, Kazakhstan,
[2]K. Kulazhanov Kazakh university of technology and business, Astana, Kazakhstan,
[3]N.A. Chinakal Institute of Mining, Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia

Corresponding-author: Kaliyeva_zhanna@mail.ru

This scientific paper considers an integrated geomechanical approach to ensuring the stability and safety of underground mining operations, combining an assessment of the stress–strain state of the rock mass, rockburst (impact) hazard diagnostics, substantiation of support parameters, the use of backfilling technologies, and the organization of instrumental deformation monitoring. It is shown that the reliability of design solutions is achieved through the joint use of: rock mass quality assessments and empirical schemes for selecting support; computational models of the stress–strain state with an adequate description of rock mass strength; a justified determination of the initial in-situ stress state by methods including hydraulic fracturing; and deformation monitoring for early detection of hazardous trends. Practical recommendations are formulated regarding the minimum dataset and the sequence of geomechanical support throughout the life cycle of an underground facility.

Keywords: geomechanical support, excavation stability, ground pressure management, in-situ tests, deformation monitoring.

ИНТЕГРИРОВАННЫЙ ГЕОМЕХАНИЧЕСКИЙ ПОДХОД К ОБЕСПЕЧЕНИЮ БЕЗОПАСНОСТИ ПОДЗЕМНОЙ РАЗРАБОТКИ РУДНЫХ МЕСТОРОЖДЕНИЙ

[1]С.Н. Шапошник, [1]Д.А. Шокарев, [1]Н.В. Матвиенко, [1]К.Т. Зикирова, [2]Ж.Т. Даулетжанова, [3]А.И. Конурин

[1]ТОО «Expert Pro», Усть-Каменогорск, Казахстан,
[2]Казахский университет технологии и бизнеса имени К. Кулажанова, Астана, Казахстан,
[3]Федеральное Государственное Бюджетное Учреждение Науки Институт Горного Дела им. Н.А. Чинакала СО РАН, Новосибирск, Россия,
e-mail: Kaliyeva_zhanna@mail.ru

В данной научной статье рассмотрен интегрированный геомеханический подход к обеспечению устойчивости и безопасности подземных горных работ, объединяющий оценку напряжённо-деформированного состояния (НДС) массива, диагностику удароопасности, обоснование параметров крепи, применение закладочных технологий и организацию инструментального мониторинга деформаций. Показано, что надёжность проектных решений достигается при совместном использовании: оценок качества массива и эмпирических схем назначения крепи; расчётных моделей НДС с адекватным описанием прочности массива; обоснованного определения исходного напряжённого состояния методами (включая гидроразрыв); мониторинга деформаций для раннего выявления опасных тенденций. Сформулированы практические рекомендации по минимальному набору данных и последовательности геомеханического сопровождения в жизненном цикле подземного объекта.

Ключевые слова: геомеханическое сопровождение, устойчивость выработок, управление горным давлением, натурные испытания, мониторинг деформаций.

КЕН ОРЫНДАРЫН ЖЕРАСТЫ ӘДІСПЕН ИГЕРУ ҚАУІПСІЗДІГІН ҚАМТАМАСЫЗ ЕТУГЕ АРНАЛҒАН ИНТЕГРАЦИЯЛАНҒАН ГЕОМЕХАНИКАЛЫҚ ТӘСІЛ

[1]С.Н. Шапошник, [1]Д.А. Шокарев, [1]Н.В. Матвиенко, [1]К.Т. Зикирова, [2]Ж.Т. Даулетжанова✉, [3]А.И. Конурин

[1]«Expert Pro» ЖШС, Өскемен, Қазақстан,
[2]Қ.Құлажанов атындағы Қазақ технология және бизнес университеті, Астана, Қазақстан,
[3]Н.А. Ресей ғылым академиясының Сібір бөлімшесі Қытайқал тау-кен институты, Новосибирск, Ресей,
e-mail: Kaliyeva_zhanna@mail.ru

Бұл ғылыми мақалада жерасты тау-кен жұмыстарының орнықтылығы мен қауіпсіздігін қамтамасыз етуге бағытталған, тау жыныстары массивінің кернеулі-деформацияланған күйін (КДК) бағалауды, соққы қауіптілігін диагностикалауды, бекітпе параметрлерін негіздеуді, закладка (толтырма) технологияларын қолдануды және деформацияларды аспаптық мониторингтеуді біріктіретін интеграцияланған геомеханикалық тәсіл қарастырылған. Жобалық шешімдердің сенімділігі мына компоненттерді бірлесіп қолданғанда қамтамасыз етілетіні көрсетілді: массив сапасын бағалау және бекітпені тағайындаудың эмпирикалық сұлбалары; массивтің беріктігін барабар сипаттайтын кернеулі-деформацияланған күйді есептік модельдеу; бастапқы кернеулі күйді әдістемелік тұрғыдан негізделген анықтау (гидроажырау әдісін қоса алғанда); қауіпті үрдістерді ерте айқындауға арналған деформациялар мониторингі. Жерасты объектісінің өмірлік циклі бойындағы геомеханикалық сүйемелдеудің минималды деректер жиынтығы мен кезеңдік орындалу реттілігі бойынша практикалық ұсынымдар тұжырымдалды.

Түйін сөздер: геомеханикалық сүйемелдеу, тау-кен қазбаларының орнықтылығы, тау қысымын басқару, натуралық сынақтар, деформациялар мониторингі.

Introduction. As mining advances to greater depths, the stability of underground openings is increasingly determined by the combined effects of fracturing, heterogeneity, scale effects, and high levels of natural stresses. Under these conditions, a design solution based on a single method becomes vulnerable: an engineering rock mass classification provides a rapid assessment but does not describe stress redistribution; numerical modeling enables analysis of the stress–strain state but depends on the correctness of the input parameters; in-situ measurements and monitoring provide objective feedback but require interpretation within a unified framework. In practice, a reliable methodology is one in which rock mass quality assessment, determination of the stress state, computational analyses, and deformation control are integrated into a closed-loop support cycle for mining operations.

The aim of this work is to substantiate an integrated approach to ground pressure management and the stability of underground excavations, and to formulate a sequence of actions that ensures consistency between engineering assessments of the rock mass, computational models, and in-situ control data [1–3].

The scientific problem addressed in this study consists in the lack of a unified methodological framework that integrates empirical rock mass classification, numerical modeling, and in-situ monitoring into a consistent decision-making system for underground mining conditions.

The research hypothesis assumes that the reliability of geomechanical support can be significantly improved by implementing a closed-loop integrated approach, where empirical classification, stress–strain modeling, and monitoring data are consistently combined and iteratively refined.

The objectives of the study are:

- to analyze the limitations of existing geomechanical approaches;

- to develop a structured integrated methodology combining empirical, analytical and

observational methods;

- to substantiate the sequence of geomechanical support stages;

to validate the applicability of the proposed approach using comparative analysis of field and calculated data.

Scientific novelty

The scientific novelty of the study lies in:

- the formalization of an integrated geomechanical framework combining empirical, analytical and observational approaches into a unified system;

- the development of a closed-loop methodology for ground pressure management based on continuous feedback between modeling and monitoring;

- the substantiation of a sequential algorithm for geomechanical support throughout the life cycle of underground excavations;

- the integration of rockburst hazard criteria (K1, K2) into a unified interpretation scheme for engineering decision-making.

Materials and methods. The research methodology is based on the integration of three main components:

- empirical assessment of rock mass quality using RQD, RMR, Q-system and GSI for initial classification and zoning;

- analytical and numerical modeling of the stress–strain state using rock mass strength criteria (Hoek–Brown) and deformation parameters derived from empirical correlations;

- insitu measurements and monitoring including hydraulic fracturing for stress determination and instrumental monitoring (e.g., extensometry, TDR).

The methodological framework follows a closed-loop approach:

Rock mass classification → parameter estimation → numerical modeling → in-situ validation → model correction.

This ensures consistency between predicted and observed behavior.

Modern underground geomechanics evolves at the intersection of three lines: engineering classification of the rock mass, computational modeling, and observational control. Historically, empirical methods gained broad acceptance first, because they provide a formalized language for describing the rock mass and make it possible to make decisions under inevitably incomplete initial information. One of the key elements of field description became the rock quality designation index, which translates “visual” fracturing into a quantitative indicator and thereby improves comparability of assessments between sites and observers [3].

Subsequently, empirical methods developed toward rating systems that sought to account not only for the frequency of discontinuities, but also for their engineering significance: surface condition, infilling, weathering, water influence, and the orientation of discontinuities relative to the excavation. This approach enabled a transition from simple “description” to engineering interpretation, where the final rating represents an approximate measure of rock mass quality in the context of excavation stability and support selection [2,4]. A significant step was the development of systems oriented toward support design. In works on rock mass classification for tunnel support design it was shown that rock mass quality can be described as a function of several parameters reflecting blockiness, discontinuity properties, and the influence of water, and then the resulting index can be used to select the support type and intensity [1].

This logic was further developed in directions associated with the Norwegian design school, where the classification index is used as a basis for choosing a combination of rock bolts and shotcrete, with the possibility of updating the assessment as the rock mass is exposed [5]. However, empirical methods have fundamental limitations. First, the final rating depends on the quality of field description and on the consistency of criteria; therefore, methodological discipline and personnel training are required. Second, rating systems inevitably average the rock mass and poorly reflect local “weak spots”: single faults, zones of tectonic reworking, or abrupt changes in lithology. Third, as depth and stress level increase, stability becomes determined not so much by block geometry as by stress redistribution and the development of shear and tensile zones around openings. Therefore, as a rule, an empirical assessment should be treated as the first level

of analysis that defines the initial classification picture and helps rank sites by expected complexity, but does not replace computation and in-situ verification [2].

In literature it is emphasized that empirical methods should be used not as a “tabular replacement of calculations”, but as a tool for primary diagnosis and comparison of sites. In particular, an overview of empirical methods for assessing rock mass condition notes the need to correctly choose an approach for specific conditions and to recognize that any rating system is ultimately a model with a limited domain of applicability [2]. This position is consistent with international practice, where empiricism serves as an “input” for computational parameterization and for observational control.

In underground excavation design, a key problem is the transition from laboratory characteristics of intact rock to rock mass parameters. In the laboratory, the strength and deformability of a monolithic specimen are measured, whereas a rock mass is a system of blocks and discontinuities, and its behavior is determined by the joint action of the matrix and weakness surfaces. To describe rock mass strength, an empirical failure criterion is widely used that accounts for the transition from intact rock to a rock mass by means of the Geological Strength Index. In the early-2000s edition, this criterion became widespread as a unified framework enabling estimation of rock mass strength for different degrees of disturbance and the use of parameters in engineering calculations [6].

This logic was further developed in directions associated with the Norwegian design school, where the classification index is used as the basis for selecting a combination of rock bolting and shotcrete, with the possibility of updating the assessment as the rock mass is exposed [6]. A separate development line is represented by empirical methods specially adapted to mining conditions, where technological factors are present: the influence of blasting, stress changes during extraction, and effects of discontinuity orientation relative to stopes and pillars. For such tasks, a mining rating system was proposed in which the basic rock mass rating is corrected for mining factors; this makes the empirical description more “applied” for design at mining operations [7].

The Geological Strength Index is valuable in that it formally links geological description with computational parameterization. It is “geologically friendly” because it is oriented toward the observable structure and the condition of discontinuities rather than only numerical indices. In the classical work devoted to this index, it is shown that correct assessment of the structural type and the condition of discontinuity surfaces is decisive for deriving rock mass design parameters [8]. At the same time, it is important to understand that parameterization based on the Geological Strength Index and the rock mass failure criterion does not eliminate the need for calibration using in-situ manifestations. Even with careful structural assessment, there remain factors that are difficult to capture “from a picture”: the degree of unloading and damage due to blasting, residual stresses, and local tectonic zones. Therefore, in applied geomechanics, an approach is common in which rock mass damage is introduced through a separate coefficient reflecting technological influence and the quality of mining practice. This idea is methodically formalized in studies devoted to empirical estimation of the rock mass deformation modulus, where along with the Geological Strength Index a disturbance factor is used to account for technology-related effects [9].

To quantitatively describe the deformation behavior of rocks and to subsequently assess brittleness, a “stress–strain” diagram obtained under controlled conditions of uniaxial or triaxial compression is used. Below, the test mode provisions and the processing procedure for the experimental diagram are presented.

In Fig. 1, the deformation curve is shown. The test mode consists in maintaining a constant longitudinal strain rate of the rock specimen during loading, which is achieved when using a servo-controlled press operating in an automated mode of controlled longitudinal strains. Tests are carried out in uniaxial or triaxial compression with a strain-

rate range from 10^{-3} to 10^{-8} s^{-1}. From the specimen deformation curve (Fig. 1), the elastic modulus E and the post-peak modulus M, the total strain ε_{total}, and the elastic strain ε_e are determined.

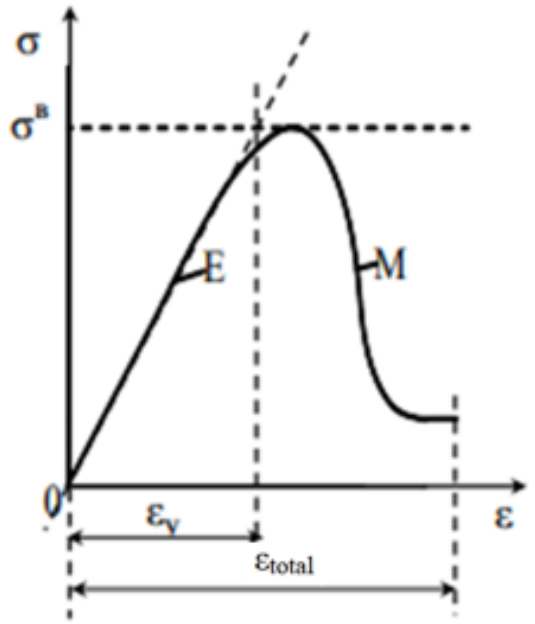


Fig.1 - Schematic "stress–strain" diagram under uniaxial compression: σ_1—axial stress on the specimen, MPa; ε_1 - longitudinal strain of the specimen; E - elastic modulus of the specimen, MPa; M-post-peak modulus of the specimen, MPa; σ_{res} - residual strength, MPa; σ_{uc} - uniaxial compressive strength, MPa

The figure is provided for the visual interpretation of the relationship discussed in the text.

To move from analysis of the diagram shape to quantitative classification, indicators are used that relate elastic properties to the character of post-peak softening. As calculation criteria, the ratio-of-moduli coefficient and the elastic-strain fraction coefficient are applied.

When assessing brittleness (rockburst hazard) of rocks, the following coefficients are considered:

$$K_1 = \frac{E}{M}$$

$$K_2 = \frac{\varepsilon_e}{\varepsilon_{total}}$$

For $K_1 < 1$ the rock is considered rockburst-prone; for $K_1 > 1$ it is considered non-rockburst-prone. For $K_2 > 0.7$ the rock is rockburst-prone; for $K_2 < 0.7$ the rock is considered non-rockburst-prone. If at least one coefficient confirms rockburst proneness, a conclusion is made that the rock is rockburst-prone.

Thus, criteria K_1 and K_2 provide a unified approach to interpreting test results and make it possible to compare rockburst proneness under different loading conditions. Below, the requirements for sample size and data processing are presented.

Rock mass deformability is one of the most sensitive parameters in stability problems. The rock mass deformation modulus largely determines the expected convergence of excavations, stress redistribution, and the tendency for the development of damaged zones around an opening. Direct estimation of the rock mass deformation modulus from in-situ tests is often constrained by cost and organizational conditions; therefore, empirical relationships are widely used in practice. A systematic discussion of such relationships and a formula proposed in the mid-2000s that accounts for the Geological Strength Index, intact rock modulus, and a disturbance factor have become one of the most cited bases for engineering estimates [9]. However, comparative studies show that different empirical methods can yield substantially different values of the rock mass deformation modulus even for identical initial rock mass characteristics. In a study based on dozens of rock mass scenarios, it is emphasized that the choice of correlation should be determined by the rock mass type and the expected deformation mechanism; otherwise, computational predictions may systematically overestimate or underestimate deformations [10]. This conclusion has a direct practical implication: it is advisable to estimate the rock mass deformation modulus by several methods and then verify consistency with in-situ observations and instrumental monitoring.

Determination of deformation properties of rocks is carried out in accordance with GOST 28985–91. The standard applies to hard rocks with uniaxial compressive strength not less than 5

MPa and establishes the method for determining their deformation characteristics. Longitudinal ε_1 and transverse ε_2 strains, axial load (P), and lateral pressure are recorded automatically by the measuring system and saved to an Excel file. The loading rate is 0.1 mm/min until specimen failure. Based on the measurements, "stress σ – strain ε" relationships are constructed (Fig.2). Stress is calculated from the expression:

$$\sigma = \frac{P}{A}$$

$$\sigma = \frac{4P}{\pi d^2}$$

The deformation modulus Ed and the Poisson's ratio ν are determined in the selected stress range (σ_start – σ_end) of the linear portion of the loading branch using the formulas: expression:

$$E_d = \frac{\sigma_{\text{end}} - \sigma_{\text{start}}}{\varepsilon_{1\text{end}} - \varepsilon_{1\text{start}}}$$

$$\nu = \frac{\epsilon_{2\text{end}} - \epsilon_{2\text{start}}}{\epsilon_{1\text{end}} - \epsilon_{1\text{start}}}$$

where σ_{end}, σ_{start} are the stress values at the end and at the beginning of the loading range; $\varepsilon_{1\text{end}}$, $\varepsilon_{1\text{start}}$ are the relative longitudinal strains at the end and at the beginning of the range; $\varepsilon_{2\text{end}}$, $\varepsilon_{2\text{start}}$ are the relative transverse strains at the end and at the beginning of the range. In the case of a nonlinear "stress–strain" relationship, a linear approximation method is applied.

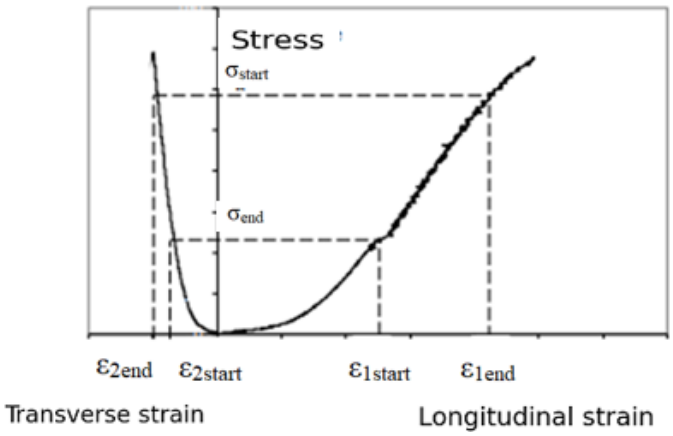


Fig.2 - "stress σ – strain ε" relationships for determining deformation properties of rocks

As depth and geological complexity increase, the role of natural stresses becomes decisive. Under such conditions, an engineering rock mass classification focused on fracturing and discontinuity quality does not provide sufficient information for predicting stress-controlled manifestations: slabbing, spalling, bursting, and dynamic failure. Therefore, in-situ methods for stress determination are applied in stressed areas. One of the most common is hydraulic fracturing, as well as hydraulic testing of pre-existing fractures. The methodological bases and limitations of these methods are described in detail in the recommended methods of the International Society for Rock Mechanics. It is emphasized that results are sensitive to borehole orientation, the presence and nature of natural fractures, borehole wall condition, and the correctness of interpreting breakdown and shut-in pressures. It is especially important that a reliable assessment requires a series of tests and comparison of results, because the rock mass is generally heterogeneous and single tests may reflect a local feature rather than the regional stress field [11]. The stress–strain relationships presented in Figures 1 and 2 correspond to generalized deformation behavior of rocks, including crack closure, elastic deformation, stable crack propagation and post-peak failure

stages, which are widely confirmed in recent studies [12,13]. Modern experimental and numerical studies also demonstrate that rock behavior under loading is nonlinear and includes distinct deformation stages reflected in stress–strain curves [14,15].

A separate layer of literature is devoted to the fact that the stress state and deformation mechanism of rock masses under complex natural–technogenic processes depend on the combined influence of geology and technogenic impact. Using karst sinkholes as an example, it is shown that deformation development is staged and requires an integrated approach in which in-situ observations are linked to a model representation of stress redistribution [16]. This result is important for underground mines as well: it confirms that stress-related manifestations rarely have a single cause, and correct interpretation requires systematic comparison of data.

For underground ore mining, methods oriented toward stope and excavation stability play an important role. A special place is occupied by the stability graph method, which relates a "modified stability number" of the rock mass to excavation geometry and allows prediction of the likelihood of collapse or the need for enhanced support. Contemporary publications emphasize that this method is widely used in underground polymetallic mines and is continuously refined as practical data accumulate [17]. Crucially, such methods are observational by nature: they work well when an operation can collect and classify actual stability data and correctly relate them to rock mass parameters. Therefore, in engineering practice it is rational to apply stability graphs in combination with rock mass classification, stress–strain modeling, and deformation monitoring. In that case, the empirical graph is not a "replacement" but part of a comprehensive toolkit.

Support of underground openings in mines has evolved from simple "load bearing" solutions to systems where not only static strength matters, but also deformation compatibility with the rock mass, the ability to hold blocks, accommodate movements, and under certain conditions resist dynamic impacts. Classical works on rock mechanics for underground operations emphasize that the support design must correspond to the failure mechanism and be part of the overall stability design concept [18]. A significant contribution to support practice was made by manuals on cable bolting, which describe design principles, installation technology, quality control, and observational adjustment based on instrumentation data. These works emphasize that support should be designed iteratively: the initial design is refined based on actual rock mass behavior and the characteristics of installed support [19].

For conditions prone to dynamic manifestations, the literature separately considers principles of designing support capable of withstanding dynamic loads and large displacements. It is shown that support selection under such conditions should be iterative and must include verification based on observational data, since static approaches do not reflect the real system behavior under dynamic failure [20]. In domestic studies devoted to assessing rock mass condition at large mines, it is also emphasized that classification assessments and observations should be combined with consideration of real manifestations and technological factors [11]. In works on integrated high-productivity extraction technologies, emphasis is placed on the fact that stability and safety must be considered as part of the technological mining scheme, and geomechanical support becomes a key factor in ensuring productivity [21].

The observational concept in geomechanics is that the design decision is treated as a hypothesis that is refined as data on rock mass behavior are obtained. Therefore, monitoring should not be limited to recording "consequences"; its task is early detection of deformation trends and localization of active zones. In this context, instrumental methods are important that make it possible to obtain information on the depth and position of shear zones. For underground conditions, it is essential that instrumental data become meaningful only when interpreted jointly with a stress–strain model and with

an understanding of rock mass structure. In other words, monitoring is the “language of feedback”, but the decision is formed based on reconciliation of: classification description, stress model, computed rock mass parameters, and actual measurements.

Time domain reflectometry is a method in which the reflection of an electromagnetic pulse in a cable line is used to determine the location of damage or local change corresponding to shear or deformation in the rock mass. The methodology and examples of its use to determine the depth of a shear zone are described in detail in the classic work on slope monitoring; the key part of the approach transfers well to the tasks of localizing deformations in geotechnical systems provided correct installation and interpretation of signals [22].

Summarizing the literature, a stable pattern can be identified: each individual approach solves only part of the problem. Empirical methods rank the rock mass well by quality and help select support type, but they reflect stress-controlled failure mechanisms less effectively. Rock mass parameterization through the Geological Strength Index and a rock mass failure criterion creates a bridge to computations but requires correct structural assessment and calibration. In-situ stress determination methods provide fundamentally important information but are sensitive to heterogeneity and require a series of tests. Monitoring and support testing provide feedback but need interpretation. Therefore, an integrated approach in which these elements are combined into a closed support procedure represents the most substantiated methodology for underground ore mines, especially under high stresses, variable rock mass structure, and increased productivity requirements [23-25].

Results and discussion. Generalization of in-situ observations and computational interpretations shows that the stability of underground excavations is most correctly described by a consistent set of characteristics including rock mass quality, stress state parameters, and confirmation of support effectiveness by in-situ data.

Empirical methods for assessing rock mass condition provide a reproducible engineering language for comparing sites and make it possible to identify zones where stability reduction is expected when excavation geometry or mining technology changes. Their strength lies in speed and applicability under limited initial data. However, for stressed and structurally heterogeneous rock masses, empirical indices should be treated as a preliminary assessment that requires confirmation by computational analysis and in-situ stress measurements.

In-situ determination of the stress state is especially important for areas where instability manifestations are stress-controlled or associated with stress redistribution due to mining. Studies of the stress state and deformation mechanisms of rock masses under complex conditions, including natural–technogenic sinkhole zones, show that deformation processes depend on the combination of geological heterogeneity and technogenic factors, and interpretation requires linking field data and modeling. In this context, in-situ stress determination methods should be applied in series, and design solutions should be checked against the range of admissible initial parameters, which is consistent with recommended methods and reduces the risk of errors caused by local rock mass variability.

Quantitative results and relationships obtained from processing in-situ data and empirical parameterization are presented below. An example of quantitative assessment of rock mass quality and the associated expected deformability for two ore bodies is then provided.

Parameterization of rock mass strength and deformability for computational analyses should be based on geologically justified indices and should account for scale effects. The use of a rock mass failure criterion and empirical estimates of the deformation modulus makes it possible to form design parameters consistent with the observed structural state. Comparative studies show that discrepancies between empirical deformability estimates can be significant; therefore, the correctness of the correlation choice should be confirmed by comparison with in-situ deformation

observations and excavation behavior.

In-situ verification of support and deformation monitoring closes the support cycle. Support testing makes it possible to assess actual load-bearing capacity and technological reproducibility, while monitoring records the transition from quasi-static behavior to the development of local deformation zones. Practice in applying domain reflectometry shows its effectiveness for identifying the position and depth of active shear zones, which increases the information content of geomechanical control and allows decisions to be made before hazardous deformations develop. As a result, the integrated approach enables a transition from reacting to consequences to risk management based on data and their consistent interpretation, which is particularly important for high-productivity underground mining technologies.

Table 1 - Rock mass quality indicators and deformability assessment

Site	Ore body	Rock Quality Designation (RQD), %	Geological Strength Index (GSI)	Rock Mass Rating (RMR)	Q-system index (Q)	Rock mass deformation modulus, GPa
Quartzite Hills	1	55.8	50	54	4.5	16.51
Quartzite Hills	4	35.1	44	49	3.3	14.89

To interpret rock mass behavior, it is important to consider mechanical properties of the main lithological varieties; summary values are provided below.

Table 2 - Averaged mechanical properties of the main lithological varieties

Lithology	Tensile strength, MPa	Uniaxial compressive strength, MPa	Hoek–Brown parameter mi	Intact rock deformation modulus, GPa	Young's modulus of specimen, GPa	Poisson's ratio
Tuffs	6.7	76.5	11	11.45	51.14	0.25
Sedimentary rocks	8.1	48.1	7	10.95	40.13	0.25
Metasomatites	11.1	45.6	7	9.00	89.2	0.25

Below are the results of a series of in-situ tests illustrating the variability of the first loading pressure under similar conditions.

Table 3 - In-situ stress testing: first loading pressure and distance

Interval	Distance, m	First loading pressure, MPa
1	10	29.9
1	9	23.3
2	10	24.2

2	9	23.7
3	8	29.1
3	7	16.5

The plot makes it possible to visually assess the scatter of first loading pressures and its relationship with the distance to the opening zone in the test series (Figure 3).

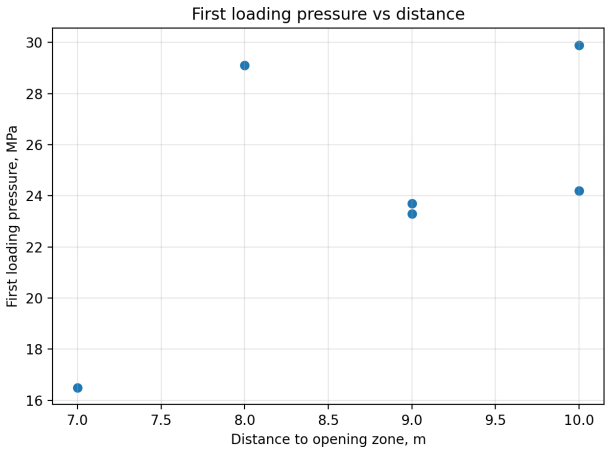


Fig.3 - First loading pressure and distance to the opening zone

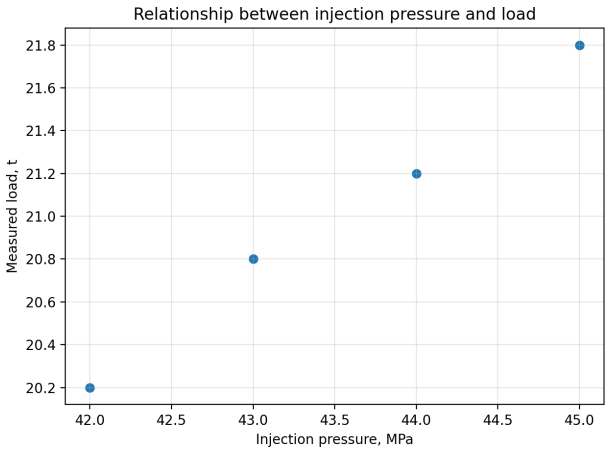


Fig.4 - Relationship between pressure and load in rock-bolt testing

To verify support reliability, the results of roof rock-bolt testing from several measurements are provided.

Table 4 - Rock-bolt tests

Location	Pressure, MPa	Load, t
Roof rock	42	20.2
Roof rock	45	21.8
Roof rock	43	20.8
Roof rock	44	21.2

The plot shows the relationship between injection pressure and measured load, which is used to check reproducibility of the test results.

Figure 4 is provided as a visual representation of the relationship used in interpretation and discussion of results.

The results obtained demonstrate that:

- discrepancies between empirical deformation modulus estimation methods can reach significant values, confirming the need for multi-method validation;

- integrated interpretation of in-situ stress measurements and monitoring data reduces uncertainty in geomechanical predictions;

- the application of the proposed integrated framework improves the reliability of support design decisions under complex geomechanical conditions.

Conclusions. The integrated approach that combines empirical rock mass assessment, selection of strength and deformation parameters for calculations, and in-situ stress determination and monitoring-based verification of decisions is a justified basis for geomechanical support of underground operations. Empirical methods are useful for ranking sites and for preliminary selection of excavation support. However, under high stress levels and rock mass heterogeneity, they should be supplemented by in-situ stress measurements and computational verification of the stability of the adopted decisions. Design parameters of the rock mass must be checked against actual observations: deformations and the real behavior of excavations. This is important because different empirical relationships can produce noticeably different deformability estimates for the same initial information. Deformation monitoring and in-situ verification of support performance should be a mandatory part of ground pressure management. They provide feedback and make it possible to adjust design and technological decisions in time. The proposed integrated approach can be considered as a methodological basis for modern geomechanical support systems, particularly under conditions of increasing mining depth and stress levels.

Литература

1. Макаров А.Б. Управление горным давлением при подземной разработке месторождений. Системы разработки/SRK, Москва. -2021. -73 с.

2. Абрамкин Н.И., Ефимов В.И., Мансуров П.А. Эмпирические методики оценки состояния массива горных пород// Известия УГГУ. -2021. -Т.4(64). -С. 109–115. DOI 10.21440/2307-2091-2021-4-109-115.

3. Deere D.U., Deere D.W. The Rock Quality Designation (RQD) Index in Practice/Rock Classification Systems for Engineering Purposes. ASTM STP 984. -1988. ISBN 0-8031-0988-1.

4. Bieniawski Z.T. Engineering Rock Mass Classifications: A Complete Manual for Engineers and Geologists in Mining, Civil, and Petroleum Engineering// New York: Wiley. -1989. ISBN: 9780471601722, 0471601721.

5. Grimstad E., Barton N. Updating of the Q-system for the Norwegian Method of Tunnelling// Engineering Classification of Rock Masses for the Design of Tunnel Support. Rock Mech. -1993. -P.189-239.

6. Hoek E., Carranza-Torres C., Corkum B., et al. Hoek–Brown Failure Criterion - 2002 Edition // Proceedings of NARMS-TAC conference. -2002. -P.267–273.

7. Laubscher D.H. A Geomechanics Classification System for the Rating of Rock Mass in Mine Design// Journal of the South African Institute of Mining and Metallurgy. -1990. -Vol.90(10). -P.257-273. DOI 10.10520/AJA0038223X_1954.

8. Marinos P., Hoek E. Geological Strength Index: A Geologically Friendly Tool for Rock Mass Strength Estimation// Proceedings of GeoEng 2000. -2000. -P.1422-1446.

9. Hoek E., Diederichs M.S. Empirical Estimation of Rock Mass Modulus // International Journal of Rock Mechanics and Mining Sciences. -2006. -Vol.43(2). -P.203-215. DOI 10.1016/j.ijrmms.2005.06.005.

10. Polemis Júnior K., Chagas da Silva Filho F., Pinheiro Lima-Filho F. Estimating the Rock Mass Deformation Modulus: A Comparative Study of Empirical Methods Based on 48 Rock Mass Scenarios// REM - International Engineering Journal. -2021. -Vol.74(1). -P.39-49. DOI 10.1590/0370-44672019740150.

11. Еременко В.А., Айнбиндер И.И., Пацкевич П.Г., Бабкин Е.А. Оценка состояния массива горных

пород на рудниках ЗФ ОАО ”ГМК ”Норильский никель” // Горный информационно-аналитический бюллетень. -2017. -№1. -С.5-17. ISSN 0236–1493.

12. Feng X.T., Gong B., Liang Z., *et al*. tudy of the Dynamic Failure Characteristics of Anisotropic Shales Under Impact Brazilian Splitting // Rock Mechanics and Rock Engineering. -2024. -Vol.57. -P. 2213-2230. DOI 10.1007/s00603-023-03673-w.

13. Wen S., et al. Mechanical behavior of layered rocks under dynamic loading // International Journal of Rock Mechanics and Mining Sciences. -2023. -Vol.170:105533. DOI 10.1016/j.ijrmms.2023.105533.

14. Qiang Y., et al. Study on closing and cracking stress calculation method of fractured rock //Frontiers in Earth Science. -2023. -Vol. 10:839304. DOI 10.3389/feart.2022.839304.

15. Huang L., et al. Mathematical problems in rock mechanics and stress–strain evolution under thermal effects // Mathematics. -2023. -Vol.11(1):67. DOI 10.3390/math11010067.

16. Мамаев Ю.А., Власов А.Н., Мнушкин М.Г., Ястребов А.А. Изучение напряженного состояния и механизма деформирования массивов горных пород при образовании природно-техногенных карстовых провалов// Геоэкология. Инженерная геология. Гидрогеология. Геокриология. -2019. -Т.1. -Р.46-59. DOI 10.31857/S0869-78092019146-59.

17. Potvin Y. Empirical Open Stope Design in Canada//The University of British Columbia. - 1988. DOI 10.14288/1.0081130.

18. Brady B.H.G., Brown E.T. Rock Mechanics for Underground Mining.3rd ed./ Dordrecht: Springer. -2006. DOI 10.1007/978-1-4020-2116-9.

19. Hutchinson D.J., Diederichs M.S. Cablebolting in Underground Mines/ BiTech Publishers. -1996. -406 p. ISBN 9780921095378.

20. Kaiser P.K., Cai M. Design of Rock Support System under Rockburst Condition// Journal of Rock Mechanics and Geotechnical Engineering. -2012. -4(3). -P.215-227. DOI 10.3724/SP.J.1235.2012.00215.

21. Абрамкин Н.И., Дородний А.В., Бухарбаев И.У.Анализ интегрированной технологии высокопроизводительной отработки запасов выемочных участков угольных шахт//Уголь. -2019. -№1(1114). -С.40-45. DOI 10.18796/0041-5790-2019-1-40-45.

22. Kane W.F. Monitoring Slope Movement with Time Domain Reflectometry// Engineering, Environmental Science, Geology. -2000.

23. Sarr D., Sall O., Ndiaye M., Lompo N. Comparative Analysis of the Hard Hillsides Stability by Empirical Methods and Limit Equilibrium: Case of Ultra Basic and Andesites of Mako and Marbles of Bandafassi (Senegal)// Geomaterials. -2019. -Vol.9(3). -P.67-79. DOI 10.4236/gm.2019.93006.

24. Haimson B.C., Cornet F.H. ISRM Suggested Methods for Rock Stress Estimation - Part 3: Hydraulic Fracturing (HF) and/or Hydraulic Testing of Pre-existing Fractures (HTPF)// International Journal of Rock Mechanics and Mining Sciences. -2003. -Vol.40(7-8). -P.1011-1020. DOI 10.1016/j.ijrmms.2003.08.002.

25. Kuranov A.D., Bagautdinov I.I. Experience of Geomechanical Research and Calculations toward Ore Deposit Development in Complex Mining Conditions// ISRM European Rock Mechanics Symposium - EUROCK 2018. -2018.

References

1. Makarov A.B. Upravlenie gornym davleniem pri podzemnoj razrabotke mestorozhdenij. Sistemy razrabotki/SRK, Moskva. -2021. -73 s. [in Russian]

2. Abramkin N.I., Efimov V.I., Mansurov P.A. Jempiricheskie metodiki ocenki sostojanija massiva gornyh

porod// Izvestija UGGU. -2021. -T. 4(64). -S.109-115. DOI 10.21440/2307–2091-2021-4-109-115. [in Russian]

3. Deere D.U., Deere D.W. The Rock Quality Designation (RQD) Index in Practice/Rock Classification Systems for Engineering Purposes. ASTM STP 984. -1988. ISBN 0-8031-0988-1.

4. Bieniawski Z.T. Engineering Rock Mass Classifications: A Complete Manual for Engineers and Geologists in Mining, Civil, and Petroleum Engineering// New York: Wiley. -1989. ISBN: 9780471601722, 0471601721.

5. Grimstad E., Barton N. Updating of the Q-system for the Norwegian Method of Tunnelling// Engineering Classification of Rock Masses for the Design of Tunnel Support. Rock Mech. -1993. -P.189-239.

6. Hoek E., Carranza-Torres C., Corkum B., et al. Hoek–Brown Failure Criterion - 2002 Edition // Proceedings of NARMS-TAC conference. -2002. -P.267–273.

7. Laubscher D.H. A Geomechanics Classification System for the Rating of Rock Mass in Mine Design// Journal of the South African Institute of Mining and Metallurgy. -1990. -Vol.90(10). -P.257-273. DOI 10.10520/AJA0038223X_1954.

8. Marinos P., Hoek E. Geological Strength Index: A Geologically Friendly Tool for Rock Mass Strength Estimation// Proceedings of GeoEng 2000. -2000. -P.1422-1446.

9. Hoek E., Diederichs M.S. Empirical Estimation of Rock Mass Modulus // International Journal of Rock Mechanics and Mining Sciences. -2006. -Vol.43(2). -P.203-215. DOI 10.1016/j.ijrmms.2005.06.005.

10. Polemis Júnior K., Chagas da Silva Filho F., Pinheiro Lima-Filho F. Estimating the Rock Mass Deformation Modulus: A Comparative Study of Empirical Methods Based on 48 Rock Mass Scenarios// REM - International Engineering Journal. -2021. -Vol.74(1). -P.39-49. DOI 10.1590/0370-44672019740150.

11. Eremenko V.A., Ajnbinder I.I., Packevich P.G., Babkin E.A. Ocenka sostojanija massiva gornyh porod na rudnikah ZF OAO ”GMK ”Noril’ skij nikel’” // Gornyj informacionno-analiticheskij bjulleten’. -2017. -№1. -C.5-17. ISSN 0236-1493. [in Russian]

12. Feng X.T., Gong B., Liang Z., *et al*. tudy of the Dynamic Failure Characteristics of Anisotropic Shales Under Impact Brazilian Splitting // Rock Mechanics and Rock Engineering. -2024. -Vol.57. -P. 2213-2230. DOI 10.1007/s00603-023-03673-w.

13. Wen S., et al. Mechanical behavior of layered rocks under dynamic loading // International Journal of Rock Mechanics and Mining Sciences. -2023. -Vol.170:105533. DOI 10.1016/j.ijrmms.2023.105533.

14. Qiang Y., et al. Study on closing and cracking stress calculation method of fractured rock //Frontiers in Earth Science. -2023. -Vol. 10:839304. DOI 10.3389/feart.2022.839304.

15. Huang L., et al. Mathematical problems in rock mechanics and stress–strain evolution under thermal effects // Mathematics. -2023. -Vol.11(1):67. DOI 10.3390/math11010067.

16. Mamaev Ju.A., Vlasov A.N., Mnushkin M.G., Jastrebov A.A. Izuchenie naprjazhennogo sostojanija i mehanizma deformirovanija massivov gornyh porod pri obrazovanii prirodno-tehnogennyh karstovyh provalov// Geojekologija. Inzhenernaja geologija. Gidrogeologija. Geokriologija. -2019. -T.1. -P.46-59. DOI 10.31857/S0869-78092019146-59. [in Russian]

17. Potvin Y. Empirical Open Stope Design in Canada//The University of British Columbia. - 1988. DOI 10.14288/1.0081130.

18. Brady B.H.G., Brown E.T. Rock Mechanics for Underground Mining.3rd ed./ Dordrecht: Springer. -2006. DOI 10.1007/978-1-4020-2116-9.

19. Hutchinson D.J., Diederichs M.S. Cablebolting in Underground Mines/ BiTech Publishers. -1996. -406 p. ISBN 9780921095378.

20. Kaiser P.K., Cai M. Design of Rock Support System under Rockburst Condition// Journal of Rock Mechanics and Geotechnical Engineering. -2012. -4(3). -P.215-227. DOI 10.3724/SP.J.1235.2012.00215.

21. Abramkin N.I., Dorodnij A.V., Buharbaev I.U.Analiz integrirovannoj tehnologii vysokoproizvoditel' noj otrabotki zapasov vyemochnyh uchastkov ugol' nyh shaht//Ugol'. -2019. -№1(1114). -S.40-45. DOI 10.18796/0041-5790-2019-1-40-45. [in Russian]

22. Kane W.F. Monitoring Slope Movement with Time Domain Reflectometry// Engineering, Environmental Science, Geology. -2000.

23. Sarr D., Sall O., Ndiaye M., Lompo N. Comparative Analysis of the Hard Hillsides Stability by Empirical Methods and Limit Equilibrium: Case of Ultra Basic and Andesites of Mako and Marbles of Bandafassi (Senegal)// Geomaterials. -2019. -Vol.9(3). -P.67-79. DOI 10.4236/gm.2019.93006.

24. Haimson B.C., Cornet F.H. ISRM Suggested Methods for Rock Stress Estimation - Part 3: Hydraulic Fracturing (HF) and/or Hydraulic Testing of Pre-existing Fractures (HTPF)// International Journal of Rock Mechanics and Mining Sciences. -2003. -Vol.40(7-8). -P.1011-1020. DOI 10.1016/j.ijrmms.2003.08.002.

25. Kuranov A.D., Bagautdinov I.I. Experience of Geomechanical Research and Calculations toward Ore Deposit Development in Complex Mining Conditions// ISRM European Rock Mechanics Symposium - EUROCK 2018. -2018.

Information about the authors

Shaposhnik S. N. - Scientific Supervisor, Limited Liability Partnership "EXPERT PRO", Ust-Kamenogorsk, Kazakhstan, e-mail: shaposhniksergey@mail.ru;

Shokarev D. A. - Advisor to the Director for Strategic Affairs, Limited Liability Partnership "EXPERT PRO", Ust-Kamenogorsk, Kazakhstan, e-mail: D.Shokarev@expertpro.kz

Matvienko N.V. - Head of R&D, Limited Liability Partnership "EXPERT PRO", Ust-Kamenogorsk, Kazakhstan, e-mail: n.matvienko@expertpro.kz;

Zikirova K. T. - Mineral Processing Engineer, Limited Liability Partnership "EXPERT PRO", Ust-Kamenogorsk, Kazakhstan, e-mail: k.zikirova@expertpro.kz;

Dauletzhanova Zh. T. - PhD Mining Engineering, Technology, Leading Researcher of LLP "Institute of Coal Chemistry and Technology", K. Kulazhanov Kazakh University of Technology and Business, Astana, Kazakhstan, e-mail: kaliyeva_zhanna@mail.ru;

Konurin A. I. - Senior Researcher, Federal State Budgetary Institution of Science, N.A. Chinakal Institute of Mining, Siberian Branch of the Russian Academy of Sciences (SB RAS), Novosibirsk, Russia, e-mail: Konurin@misd.ru.

Сведения об авторах

Шапошник С. Н. - научный руководитель, ТОО «EXPERT PRO», Астана, Казахстан, e-mail: shaposhniksergey@mail.ru;

Шокарев Д. А. - советник директора по стратегическим вопросам, ТОО «EXPERT PRO», Астана, Казахстан, e-mail: D.Shokarev@expertpro.kz;

Матвиенко Н. В. - руководитель отдела НИОКР, ТОО «EXPERT PRO», Астана, Казахстан, e-mail: n.matvienko@expertpro.kz;

Зикирова К.Т. - инженер по обогащению полезных ископаемых, ТОО «EXPERT PRO», Астана, Казахстан, e-mail: k.zikirova@expertpro.kz;

Даулетжанова Ж.Т. - PhD, горное дело и технологии, ведущий научный сотрудник ТОО «Институт химии угля и технологии», Казахский университет технологии и бизнеса им/ К. Кулажанова, Астана, Казахстан, e-mail: kaliyeva_zhanna@mail.ru;

Конурин А. И. - старший научный сотрудник, ФГБУН «Институт горного дела им. Н.А. Чинакала» СО РАН, Новосибирск, Россия, e-mail: Konurin@misd.ru.