

Research and Improvement of Methods for Predicting Hidden Fracturing in a Rock Mass at a Polymetallic Mine

Bakhtybayev N.B., *Abil O.A., Bakhtybayeva A.S.

Mining Research Group LLP, Karaganda, Kazakhstan

*Corresponding author email: orazabil@minrg.com

Received: April 15, 2026
Peer-reviewed: April 25, 2026
Accepted: May 28, 2026

ABSTRACT

This paper presents the results of a study aimed at improving the reliability of predicting hidden fracturing in the near-contour rock mass adjacent to underground mine workings at a polymetallic mine. The relevance of the study is associated with the fact that hidden discontinuities are not always identified during conventional visual inspection of the rock mass, which increases the risk of local collapses and complicates the selection of support parameters. The work aimed to improve methods for predicting hidden fracturing through the integrated application of ground-penetrating radar profiling, three-dimensional surveying, spatial fracture mapping, and geomechanical modeling. The study included analysis of the mining and geological conditions of the deposit, laser scanning of mine working sections, spatial fracture analysis in ShapeMetriX, numerical modeling in RocTunnel3, and GPR profiling using the GROT 12N system. It was established that the highest reliability of hidden fracturing prediction is achieved through the sequential integration of 3D survey data, spatial fracture analysis, and GPR investigation. The practical effect of the proposed approach lies in improving the validity of selecting existing support schemes rather than introducing new support types.

Keywords: hidden fracturing, rock mass, underground mine workings, ground-penetrating radar profiling, laser scanning, fracture mapping, geomechanical modeling, mine support.

Information about authors:

Bakhtybayev N.B.

Candidate of Technical Sciences, Director of the Mining Research Group LLP, Karaganda, Kazakhstan. E-mail: bakhtybayev@minrg.com; ORCID ID: <https://orcid.org/0000-0002-9816-9765>

Abil O.A.

Executive Director of the Mining Research Group LLP, Karaganda, Kazakhstan. E-mail: orazabil@minrg.com; ORCID ID: <https://orcid.org/0000-0001-9939-9039>

Bakhtybayeva A.S.

PhD, Senior researcher of the Mining Research Group LLP, Karaganda, Kazakhstan. E-mail: bakhtybayeva_a@minrg.com, ORCID ID: <https://orcid.org/0000-0001-7163-6274>

Introduction

The stability of underground mine workings is largely determined by the structural condition of the surrounding rock mass, primarily by the presence of fractures that form weakened zones and potential failure surfaces. Under conditions of underground mining, hidden fracturing represents a particular hazard because such discontinuities are not exposed on the contour of workings and cannot always be reliably identified by visual inspection alone [[1], [2], [3]]. This reduces the reliability of assessing the state of the sidewall rock mass and may lead to local collapses, roof slabbing, block formation, and disturbances to normal mining operations.

For a polymetallic mine, predicting hidden fracturing is of practical importance because geotechnical disturbances have been recorded in workings where hazardous discontinuity planes could

not be reliably identified by visual observations. Analysis of mining-geological and geotechnical documentation showed that manifestations of instability are most often observed near junctions, while some hazardous disturbances remain hidden.

Modern studies indicate that the most reliable results in detecting hidden fracturing are achieved by combining direct and indirect methods, including structural mapping, seismic and electrical tomography, ground-penetrating radar, and numerical modeling [[1], [2], [3], [4], [5], [6]]. At the same time, the quantitative prediction of fracture parameters and the spatial localization of hidden weakened zones remain the most challenging aspects [[4], [5], [6]].

Recent studies show that the prediction of hidden fracturing in underground excavations is developing along four main directions: high-resolution GPR imaging, integration of geophysical

methods, digital fracture mapping from 3D data, and geomechanical interpretation for support design [[3], [7], [8], [9], [10], [11], [12], [13], [14]]. In the first direction, ground-penetrating radar has proven to be a promising tool for detecting concealed fractures, disturbed zones, moisture-related heterogeneities, and shallow structural discontinuities in rock masses [[3], [9], [10], [11], [16]]. At the same time, its efficiency strongly depends on signal attenuation, lithological contrast, moisture, metallic interference, and the correctness of radargram interpretation [[9], [10], [15], [16]]. Recent work has therefore focused not only on fracture detection itself, but also on improving image quality, interpretation robustness, and data constraints [[10], [15], [16]].

A second active direction is the integration of GPR with other geophysical methods. In fractured and heterogeneous rock masses, single-method interpretation often remains ambiguous because similar anomalies may be caused by fracturing, water saturation, lithological contacts, or altered zones [[2], [7], [8]]. For this reason, recent studies increasingly combine GPR with electrical resistivity tomography, borehole logging, seismic methods, or joint inversion strategies [[7], [8]]. Hasan et al. showed that non-invasive geophysical data can be linked to rock mass quality indicators [[2], [7]], while Huayllazo et al. demonstrated that ERT-supported interpretation can improve the identification of fractured zones and geomechanical inferences [8]. Yuan et al. proposed a GPR workflow constrained by logging data for fractured rock mass detection [10]. These developments are especially relevant for underground mining, where local geological complexity and limited access often make single-method diagnosis insufficient [[3], [8], [10]].

The third major trend concerns the transition from conventional visual mapping to digital characterization of discontinuities using LiDAR, photogrammetry, and point-cloud-based analysis [6]. This is highly relevant for mine workings where access is restricted, exposure conditions are incomplete, and shotcrete masks part of the structural pattern [[6], [12]]. Recent work has shown that semi-automatic extraction of discontinuity parameters from 3D data can significantly improve the consistency of fracture orientation analysis and the geometric basis for stability assessment [[6], [12]]. The value of such digital methods lies not only in documenting visible fracture traces, but also in building a coordinate-consistent structural model that can then be transferred into geomechanical calculations [[6], [11], [17]]. This is directly aligned

with the present study, where LiDAR and ShapeMetriX are used as the first step before geomechanical analysis and targeted GPR profiling [[18], [19], [20]].

The fourth direction is the integration of structural observations into geomechanical and probabilistic stability analysis. Recent studies indicate that the engineering effect of fracture characterization is maximized when mapped discontinuities are not treated as descriptive information only, but are further used to assess parameter inversion, stress sensitivity, and support adequacy [[12], [13], [13], [14]]. This is particularly important in underground excavations affected by intersecting fracture sets and local weakening [11]. Recent publications address stress-field selection, inversion of surrounding rock parameters, and support-related geomechanical interpretation in fractured ground [21]. These studies support the logic of the present work, in which fracture geometry obtained from 3D mapping is used to guide RocTunnel3 modeling and to prioritize GPR survey locations [[18], [22]].

This study aimed to investigate and improve methods for predicting hidden fracturing in a rock mass under conditions of a polymetallic mine through the integrated use of ground-penetrating radar profiling, three-dimensional surveying, and spatial fracture mapping, as well as to develop recommendations for refining the selection of support types and parameters for underground mine workings.

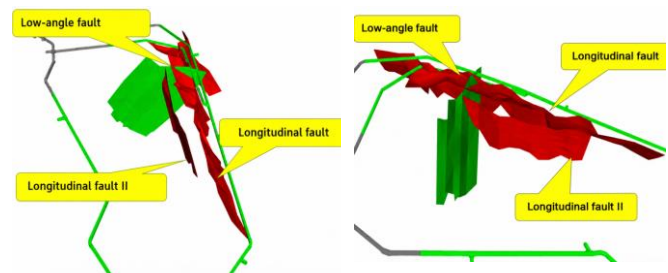


Figure 1 – Layout of faults at the polymetallic deposit

Experimental part

The study included experimental investigations using laser scanning, ground-penetrating radar profiling, and specialized software packages RocTunnel3 and ShapeMetriX. At the first stage, mine workings were visually inspected in order to identify sections suitable for instrumental investigation within the fault-controlled zone (Figure 1). It was found that a significant part of the workings had been covered with shotcrete. Therefore, six

unshotcreted sections located at the +335, +315, +295, +275, +255, and +235 m levels were selected for detailed study. An example of an investigated section is shown in Figure 2.

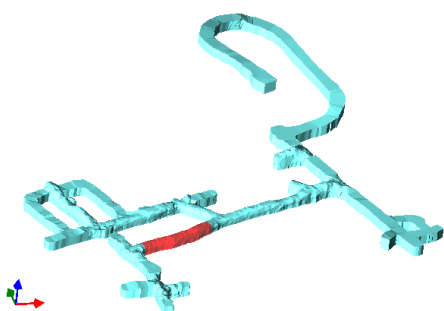


Figure 2 – Section No. 6 at the +235 m level

To obtain spatially oriented models of the workings, a Greenvalley ARTGEO LIGRIP O2 LITE (Figure 3) handheld laser scanner was used. Scanning was carried out along the contours of all selected sections, as well as at observation stations with naturally exposed fractures. Based on dense point clouds, three-dimensional models of the investigated sections (Figure 4-5) were constructed [18].



Figure 3 – Handheld LiDAR Greenvalley ARTGEO LIGRIP O2 LITE

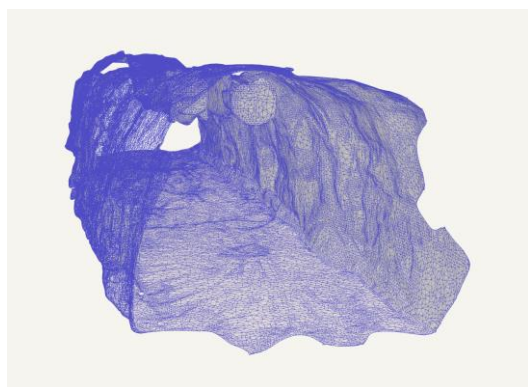


Figure 4 – Example of a 3D model of the processed section



Figure 5 – 3D model of the observation station

Spatial fracture analysis was performed in the ShapeMetriX software package (Figure 6), where fracture surfaces, strike azimuths, dip angles, and fracture sets were identified from digital models. The obtained data were then used as input for geomechanical analysis in RocTunnel3, where the formation of potentially unstable wedges and blocks was assessed. This approach made it possible to move from a generalized assessment of the rock mass to the analysis of its actual spatial fracture structure [[18], [22]].

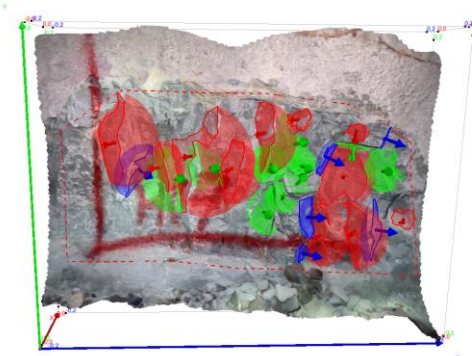


Figure 6 – Identification of fracture systems in ShapeMetriX software

Ground-penetrating radar profiling of the near-contour rock mass was carried out using the GROT 12N radar equipped with a 2 m antenna (Figure 7). Under polymetallic mine conditions, a hodograph-based measurement approach was applied, which made it possible to determine the depth of reflecting boundaries, the geometry of structural disturbances, and the electrophysical properties of the medium [[3], [4]]. According to the field program, GPR investigations were performed at four sections located at the +315, +295, +275, and +255 m levels. The interpretation quality was significantly affected by metallic support elements, wet clay-rich deposits on the surface, and the high electrical conductivity of the medium.

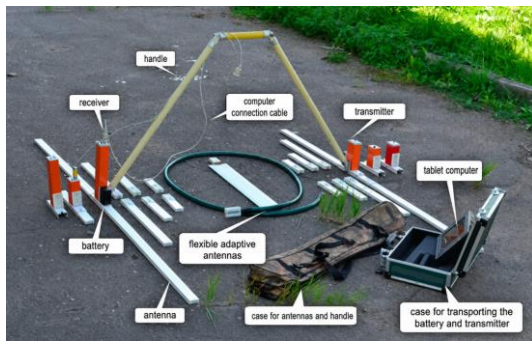


Figure 7 – General layout of the GROT 12N ground-penetrating radar

In the investigated workings, the use of alternative geophysical methods was limited by water saturation and the presence of metallic support elements, including mesh and rock bolts. Under such conditions, ERT and other resistivity-based or electromagnetic methods may be significantly distorted by conductive water and metal inclusions. Seismic methods are less suitable for rapid local near-contour investigation because they require more complex acquisition geometry under underground operating conditions. Therefore, GPR was considered the most suitable method for the selected task, while LiDAR-based fracture mapping and geomechanical modeling were used to improve the reliability of interpretation (Figure 8).



Figure 8 – Process of ground-penetrating radar survey along the floor

Results and Discussion

The performed investigations showed that visual inspection of the rock mass under polymetallic mine conditions does not provide sufficient information about the actual condition of the near-contour rock

mass. Fine wet deposits, shotcrete coverage, and secondary infill of fractures reduce the reliability of determining the number, orientation, and aperture of fractures by conventional visual mapping.

Laser scanning and subsequent processing in ShapeMetriX made it possible to identify fracture systems and obtain a spatially oriented model of the rock mass structure. This provided reliable initial data for stability assessment and for planning targeted GPR investigations.

According to the results of geomechanical modeling in RocTunnel3, the most hazardous zones are associated with intersections of fracture systems and with locally weakened sectors of the rock mass where wedge and block failure structures may form. Using Section No. 3 at the +275 m level as an example, the factors of safety for the sidewall rock mass were determined, thereby allowing the localization of zones requiring additional verification by GPR (Figure 9).

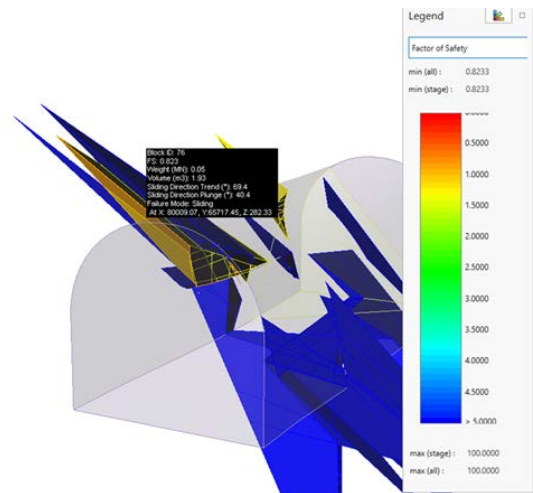


Figure 9 – Factor of safety of the side rock mass of Section No. 3 at the +275 m level in RocTunnel3 software

Ground-penetrating radar profiling confirmed the presence of hidden weakened zones that could not be detected on exposed surfaces of the workings. In addition to potentially disturbed areas, radargrams revealed zones of increased mineralization characteristic of ore bodies (Figures 10-12). Considering the combined effect of interference factors under deposit conditions, the GROT 12N radar provided an effective investigation depth of up to 18 m [[18], [22]].

As a result of the work, an integrated methodology for predicting hidden fracturing was developed, including section selection, 3D surveying, spatial fracture mapping, geomechanical modeling, and targeted GPR profiling.

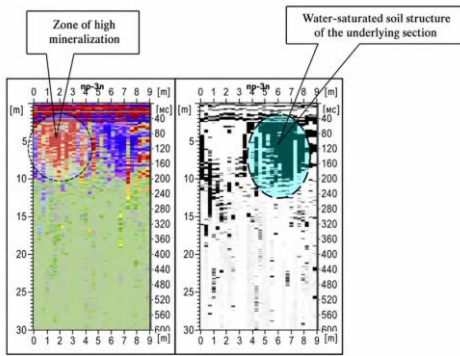


Figure 10 – Radargram of Profile 3L

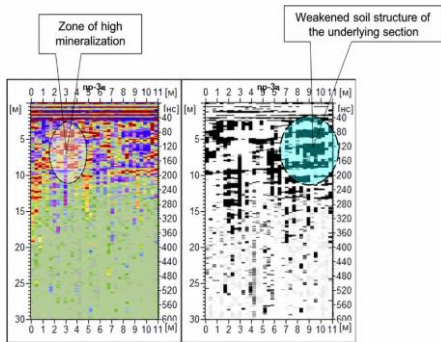


Figure 11 – Radargram of Profile 3C

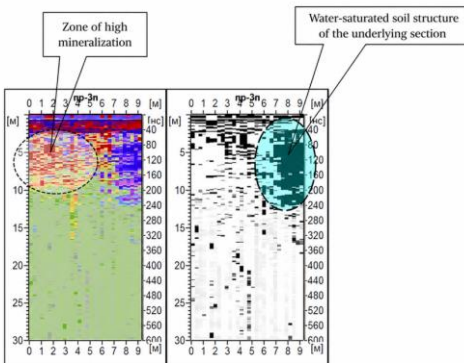


Figure 12 – Radargram of Profile 3P

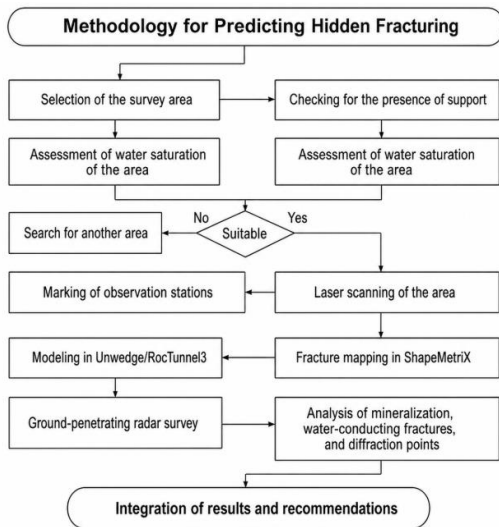


Figure 13 – Flowchart of the methodology for predicting hidden fracturing

The obtained results show that under polymetallic mine conditions, the highest reliability of predicting hidden fracturing is achieved through the integration of laser scanning, spatial fracture mapping, geomechanical modeling, and ground-penetrating radar investigation [3], [4], [5], [6], [7], [8]]. This approach makes it possible to first record the actual geometry of the working and visible fracturing, then develop a calculated scheme of possible block-type failures, and only after that perform targeted GPR profiling to identify hidden discontinuities.

The practical significance of the results lies in the possibility of a more accurate selection of support parameters. The performed analysis showed that the current mine support regulations already include a sufficient set of support methods and support types, including anchor, friction, steel-polymer, cable, and reinforced schemes. Therefore, the main direction of improvement should not be the introduction of new support types but rather the enhancement of the validity of selecting existing solutions while taking into account the actual spatial fracture structure of the rock mass [18].

The proposed methodology (Figure 13) is especially advisable when opening new levels, driving capital mine workings, working in areas with complicated geological structure, water inflows, and signs of instability in the surrounding rock mass.

The present study had an experimental and methodological character and was primarily aimed at testing the applicability of an integrated workflow for hidden fracturing prediction under actual mine conditions. For this reason, a full quantitative validation of the method, including statistical performance assessment and large-sample comparison with documented instability cases, was beyond the scope of the current work. These aspects represent an important direction for further research.

Conclusion

1. Hidden fracturing was found to be one of the key factors controlling local instability of the near-contour rock mass in underground workings of a polymetallic mine.
2. Conventional visual inspection does not provide sufficient completeness in identifying hazardous zones under conditions of shotcrete coverage, secondary fracture infill, and complex tectonic structure of the rock mass.
3. An integrated methodology for predicting

hidden fracturing was developed based on the sequential use of LiDAR surveying, spatial fracture mapping, RocTunnel3 modeling, and GPR profiling with the GROT 12N system.

4. The application of the integrated approach improves the reliability of identifying hidden weakened zones and enhances the engineering justification for selecting support parameters.

5. The main practical conclusion is that improvement of the technological regulation should be aimed at refining the conditions for applying existing support schemes rather than expanding the

range of support types.

Credit author statement: **N. Bakhtybayev, O. Abil:** Conceptualization, Methodology, Software, Data curation, Writing – original draft, Writing – review & editing; **A. Bakhtybayeva:** Investigation, Visualization, Validation, Supervision.

Funding. This study was carried out within the framework of R&D work “Research on improving methods for predicting hidden fracturing of the rock mass” (state registration No. 0126RKN0029) under Contract No. 27-01/2026-0001 dated 12 January 2026.

Cite this article as: Bakhtybayev NB, Abil OA, Bakhtybayeva AS. Research and Improvement of Methods for Predicting Hidden Fracturing in a Rock Mass at a Polymetallic Mine. *Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources*. 2028; 344(1):109-116. <https://doi.org/10.31643/2028/6445.11>

Полиметалл кенішінде тау жыныстары массивінің жасырын жарықшақтылығын болжау әдістерін зерттеу және жетілдіру

Бахтыбаев Н.Б., Әбіл О.А., Бахтыбаева А.С.

Mining Research Group ЖШС, Қарағанды, Қазақстан

Мақала келді: 15 сәуір 2026
Сараптамадан өтті: 25 сәуір 2026
Қабылданды: 28 мамыр 2026

	<p>ТҮЙІНДЕМЕ Мақалада полиметалл кенішінің жерасты тау-кен қазбаларының жапсарлас массивіндегі жасырын жарықшақтылықты болжау дәлдігін арттыруға бағытталған зерттеу нәтижелері қарастырылған. Жұмыстың өзектілігі жасырын үзілімдік бұзылыстардың бақылауға қолжетімді беттерде әрдайым байқала бермейтіндігімен және осыған байланысты тау жыныстары массивін дәстүрлі визуалды тексеру кезінде анықталмай қалуымен түсіндіріледі, бұл жергілікті опырылулар қаупін арттырып, бекіту параметрлерін таңдауды қиындатады. Зерттеудің мақсаты георадарлық профильдеу, үшөлшемді түсірілім, жарықшақтарды кеңістіктік карталау және геомеханикалық модельдеуді кешенді қолдану негізінде жасырын жарықшақтылықты болжау әдістерін жетілдіру болды. Жұмыс барысында кен орнының тау-кен-геологиялық жағдайларына талдау жасалды, қазба учаскелеріне лазерлік сканерлеу жүргізілді, ShapeMetriX бағдарламасында жарықшақтылықтың құрылымдық талдауы, RocTunnel3 бағдарламасында сандық модельдеу және «GROT 12N» георадары арқылы георадарлық профильдеу орындалды. Жасырын жарықшақтылықты болжаудың ең жоғары сенімділігіне 3D-түсірілім, құрылымдық талдау және георадарлық зерттеу деректерін дәйекті түрде біріктіру арқылы қол жеткізілетіні анықталды. Тәжірибелік нәтиже жаңа бекіту түрлерін енгізуде емес, қолданыстағы бекіту сұлбаларын таңдаудың негізділігін арттыруда екені көрсетілді.</p>
	<p>Түйін сөздер: жасырын жарықшақтылық, тау жыныстары массиві, жерасты тау-кен қазбалары, георадарлық профильдеу, лазерлік сканерлеу, жарықшақтарды кеңістіктік карталау, геомеханикалық модельдеу, қазбаларды бекіту.</p>
<p>Бахтыбаев Н.Б.</p>	<p>Авторлар туралы ақпарат: Т.ғ.к., Mining Research Group ЖШС директоры, Қарағанды, Қазақстан. E-mail: bakhtybayev@minrg.com; ORCID ID: https://orcid.org/0000-0002-9816-9765</p>
<p>Әбіл О.А.</p>	<p>Mining Research Group ЖШС атқарушы директоры, Қарағанды, Қазақстан. E-mail: orazabil@minrg.com; ORCID ID: https://orcid.org/0000-0001-9939-9039</p>
<p>Бахтыбаева А.С.</p>	<p>PhD, Жетекші ғылыми қызметкер, Mining Research Group ЖШС, Қарағанды, Қазақстан. E-mail: bakhtybayeva_a@minrg.com, ORCID ID: https://orcid.org/0000-0001-7163-6274</p>

Исследование и совершенствование методов прогноза скрытой трещиноватости горного массива на полиметаллическом руднике

Бахтыбаев Н.Б., Абиль О.А., Бахтыбаева А.С.

TOO Mining Research Group, Караганда, Казахстан

<p>Поступила: 15 апреля 2026 Рецензирование: 25 апреля 2026 Принята в печать: 28 мая 2026</p>	<p>АННОТАЦИЯ В статье рассмотрены результаты исследований, направленных на повышение достоверности прогноза скрытой трещиноватости прибортового массива вблизи подземных горных выработок полиметаллического рудника. Актуальность работы обусловлена тем, что скрытые разрывные нарушения не всегда выявляются при традиционном визуальном обследовании массива, что повышает риск локальных вывалов и осложняет выбор параметров крепления. Целью исследования являлось совершенствование методов прогноза скрытой трещиноватости на основе комплексного применения георадарного профилирования, трехмерной съемки, пространственного картирования трещин и геомеханического моделирования. В работе выполнены анализ горно-геологических условий месторождения, лазерное сканирование участков выработок, пространственный анализ трещиноватости в ShapeMetriX, численное моделирование в RocTunnel3 и георадарное профилирование георадаром «ГРОТ 12Н». Установлено, что наибольшая достоверность прогноза достигается при последовательной интеграции данных 3D-съемки, пространственного анализа трещиноватости и георадарного обследования. Показано, что практический эффект заключается в повышении обоснованности выбора уже действующих схем крепления, а не во введении новых типов крепи.</p>
	<p>Ключевые слова: скрытая трещиноватость, горный массив, подземные горные выработки, георадарное профилирование, лазерное сканирование, картирование трещин, геомеханическое моделирование, крепление выработок.</p>
<p>Бахтыбаев Н.Б.</p>	<p>Информация об авторах: Кандидат технических наук, директор ТОО Mining Research Group, Караганда, Казахстан. E-mail: bakhtybayev@minrg.com; ORCID ID: https://orcid.org/0000-0002-9816-9765</p>
<p>Абиль О.А.</p>	<p>Исполнительный директор ТОО Mining Research Group, Караганда, Казахстан. E-mail: orazabil@minrg.com; ORCID ID: https://orcid.org/0000-0001-9939-9039</p>
<p>Бахтыбаева А.С.</p>	<p>PhD, Ведущий научный сотрудник ТОО Mining Research Group, Караганда, Казахстан. E-mail: bakhtybayeva_a@minrg.com, ORCID ID: https://orcid.org/0000-0001-7163-6274</p>

References

- [1] Butchibabu B, Sandeep N, Sivaram YV, Jha PC, Khan PK. Bridge pier foundation evaluation using cross-hole seismic tomographic imaging. *Journal of Applied Geophysics*. 2017; 144:104–114. <https://doi.org/10.1016/j.jappgeo.2017.07.008>
- [2] Hasan M, Shang Y, Meng Q. Application of electrical resistivity tomography (ERT) for rock mass quality evaluation. *Scientific Reports*. 2021; 11:24529. <https://doi.org/10.1038/s41598-021-03217-8>
- [3] Song Z, Zheng J, Zhang R, Zhu A, He T, Wang J. The potential of ground penetrating radar in rock fracture detection: insights from physical model tests and numerical simulations. *Journal of Rock Mechanics and Geotechnical Engineering*. 2025. <https://doi.org/10.1016/j.jrmge.2025.04.036>
- [4] Hunziker J, Greenwood A, Minato S, Barbosa ND, Caspari E, Holliger K. Bayesian full-waveform inversion of tube waves to estimate fracture aperture and compliance. *Solid Earth*. 2020; 11:657–668. <https://doi.org/10.5194/se-11-657-2020>
- [5] Ringel LM, Jalali M, Bayer P. Characterization of the highly fractured zone at the Grimsel Test Site based on hydraulic tomography. *Hydrology and Earth System Sciences*. 2022; 26:6443–6455. <https://doi.org/10.5194/hess-26-6443-2022>
- [6] Pavičić I, Galić I, Kucelj M, Dragičević I. Fracture system and rock-mass characterization by borehole camera surveying: application in dimension stone investigations in geologically complex structures. *Applied Sciences*. 2021; 11(2):764. <https://doi.org/10.3390/app11020764>
- [7] Hasan M, Shang Y, Meng Q. Evaluation of rock mass units using a non-invasive geophysical approach. *Scientific Reports*. 2023; 13:14493. <https://doi.org/10.1038/s41598-023-41570-y>
- [8] Huayllazo Y, Infa M, Frodella W, et al. Using electrical resistivity tomography method to determine the inner 3D geometry and the main runoff directions of the large active landslide of Pie de Cuesta in the Vitor Valley, Peru. *Geosciences*. 2023; 13(11):342. <https://doi.org/10.3390/geosciences13110342>
- [9] Rhee J-Y, Park K-T, Cho J-W, Lee S-Y. A study of the application and the limitations of GPR investigation on underground survey of the Korean expressways. *Remote Sensing*. 2021; 13(9):1805. <https://doi.org/10.3390/rs13091805>
- [10] Yuan W, Liu S, Zhao Q, Deng L, Lu Q, Pan L, Li Z. Application of ground-penetrating radar with the logging data constraint in the detection of fractured rock mass in Dazu Rock Carvings, Chongqing, China. *Remote Sensing*. 2023. 15(18):4452. <https://doi.org/10.3390/rs15184452>
- [11] Chen N, Hao Y, Wang C, Zheng J. Semi-automatic identification of discontinuity parameters in rock masses based on unmanned aerial vehicle photography. *Geological Journal*. 2024; 59(9):2401–2415. <https://doi.org/10.1002/gj.4905>
- [12] Liu Y, Hua W, Chen Q, Liu X. Characterization of complex rock mass discontinuities from LiDAR point clouds. *Remote Sensing*. 2024; 16:3291. <https://doi.org/10.3390/rs16173291>
- [13] Tomilov A, et al. Expert system for stability assessment of underground mine workings and automatic selection of rock bolt support schemes. *Applied Sciences*. 2025; 15(16):8951. <https://doi.org/10.3390/app15168951>

- [14] Isfahani NS, et al. Optimizing rock bolt support for large underground excavations in fractured rock masses using three-dimensional DEM-DFN modeling. *Geosciences*. 2025; 15(8):293. <https://doi.org/10.3390/geosciences15080293>
- [15] Zhang X, Pei J, Sha X, Feng X, Hu X, Chen C, Song Z. Experimental co-polarimetric GPR survey on artificial vertical concrete cracks by the improved time-varying centroid frequency scheme. *Remote Sensing*. 2024; 16(12):2095. <https://doi.org/10.3390/rs16122095>
- [16] Elshaboury N, Mohammed Abdelkader E, Al-Sakkaf A, Zayed T. A critical review and bibliometric analysis on applications of ground penetrating radar in science based on Web of Science database. *Eng*. 2023; 4(1):984–1008. <https://doi.org/10.3390/eng4010059>
- [17] Wang C, Liu Z, Dong Z, Zhang F, Ma C, Xu X, Guo Q. Comprehensive application of borehole fine detection methods: a case study in Shantou Bay subsea tunnel. *Geofluids*. 2024; 2024:5546191. <https://doi.org/10.1155/2024/5546191>
- [18] Research report Study on improving methods for predicting hidden fracturing of a rock mass. Karaganda: Mining Research Group LLP. 2026.
- [19] Salvini R, Rindinella A, Brogi A, et al. Stress–strain investigation of the rock mass based on overcoring with CSIRO HI cell test and numerical modeling: a case study from an Italian underground marble quarry. *Geosciences*. 2022; 12(12):441. <https://doi.org/10.3390/geosciences12120441>
- [20] Shi C, Yan X, Yang J, Liu Y. An inversion method for surrounding rock parameters of tunnels based on a probabilistic baseline model under a constructional environment. *Geosciences*. 2024; 14(4):107. <https://doi.org/10.3390/geosciences14040107>
- [21] Liu Y, Chen J, Zhan J. Revisiting each fracture size and spatial pattern: inference from rock mass surface to interior. *Journal of Rock Mechanics and Geotechnical Engineering*. 2025; 17(3):1399–1417. <https://doi.org/10.1016/j.jrmge.2024.08.026>
- [22] Technological regulations for selecting the types and parameters of support at the Dolinnoye mine. Version 3. 2025.