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Integrated geophysical assessment of coal mass structural weakening zones for optimization of drilling-blasting operations and coal size control

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Abstract

Purpose. The purpose of this research is to develop a scientifically sound system for managing the coarse-grained raw coal at JSC Shubarkol Komir enterprise based on comprehensive geophysical diagnostics of structural weakening and fracturing zones in coal seams. The research aims at improving the efficiency of drilling-blasting operations, reducing the proportion of fines and ensuring the stability of quarry benches through the use of geophysical rock mass state indicators.

Methods. The research was performed using a set of geophysical methods, including electrical resistivity prospecting using the Electrical Tomography (ERT) method, electrical prospecting using the Mean Gradient (MG) installation, seismic prospecting using refracted waves (Refraction Seismic, RS) method, Spectral Seismic Profiling (SSP), ground-penetrating radar (GPR) surveying and radonometry (emanation surveying). Complex data interpretation was performed using 3D modeling of the specific electrical resistance (ρ) and longitudinal wave velocity (V_p) distributions, as well as statistical analysis of correlations between ρ, V_p and C(Rn) parameters.

Findings. It has been found that a decrease in specific electrical resistance below 60-100 Ohm·m and a decrease in longitudinal wave velocities below 1500-1800 m/s reliably reflect the development of fracturing and loosening of the rock mass. Radon concentration increases by 1.5-2 times in the same zones, confirming their tectonic activity. ERT and MG methods are recognized as basic for diagnosing weakened zones, RS method – as a calibration method, radonometry – as a verification method, and SSP and GPR methods – as methods that are limited in their applicability in conditions of high water content.

Originality. For the first time for the Shubarkol deposit, a comprehensive methodology for cross-spectrum analysis of electrical, seismic and radiation parameters has been developed and tested, providing a quantitative assessment of the geomechanical state of the mass and a prediction of its structural changes.

Practical implications. The implementation of the proposed methodology allows for the identification of weakening zones with an accuracy of ±5 m in depth and ±10 m along the strike, the adjustment of parameters of drilling-blasting operations, a 3-5% reduction in the proportion of fine material (< 6 mm), and an increase in the stability of quarry benches.

Keywords: *fracturing, coal, geophysical assessment, deposit, weakening, stability*

1. Introduction

1.1. Problem statement

The mining industry in Kazakhstan remains one of the key pillars of the national economy, providing a significant contribution to the fuel and energy balance, the export of mineral raw materials and the development of the country's industrial infrastructure [1]-[4]. In the context of global energy transition and the increasing requirements for the rational use of mineral resource base, the role of efficient and environmentally safe coal mining is growing, as emphasized in recent studies on the sustainable development of mining regions [5]-[9]. Recent research also underlines the growing need for energy-efficient and resource-saving industrial processes within Kazakhstan's mining sector, including the optimization of chemical and pyrometallurgical technologies [10], [11].

Coal remains a strategically important resource for Kazakhstan, both for the energy sector and for the metallurgical industry, making issues of accurate modeling of mineral reserves and geotechnical assessment of deposits particularly relevant [12], [13]. However, complex engineering-geological conditions, the presence of erosion-active rocks, water-saturated layers and technogenic impacts require a comprehensive analysis of the rock mass properties and continuous improvement of geophysical and geomechanical monitoring methods [14], [15]. Similar technological and geomechanical

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challenges have been reported in studies devoted to the cleaning of deep pit zones and stability monitoring during open-pit operations in Kazakhstan [16], [17]. Under such conditions, the efficiency of drilling-blasting and mining processes, as well as the reliability of mining equipment operation, directly depend on an accurate understanding of the structural continuity of coal seams and the spatial localization of their weakening zones [18]-[21].

Modern open-pit coal mining technologies require continuous improvement in the efficiency of drilling-blasting preparation, excavation and processing of coal mass, while simultaneously ensuring the stable quality of the mined raw materials. One of the key factors determining the technological and quality indicators of coal is the structural state of the rock mass – the degree of its fracturing, loosening and waterlogging, since it is these parameters that largely control the slope stability and the safety of mining operations [13], [22].

Structural weakening zones are spatially elongated areas of the rock mass, characterized by a specific complex of structural-tectonic, petrographic, hydrogeological and geomechanical peculiarities. Within such zones, there is a significant decrease in the strength and deformation properties of rocks compared to the surrounding mass. Similar phenomena of blockiness, strength reduction and structural loosening are discussed in detail in studies devoted to geomechanical modeling and assessment of the state of rock masses [23]-[25]. Environmental and geotechnical instability factors related to soil and mass degradation processes in Kazakhstan have also been highlighted in recent regional assessments [26], which further emphasizes the need for reliable diagnostic tools.

The occurrence and development of such zones is associated with long-term exposure to tectonic stresses, as well as with weathering, hydration and leaching processes that penetrate the rock thicknesses through a system of fractures [27], [28]. These processes alter the mineral composition and texture of rocks, increase fracture porosity and, as a result, reduce the rock mass strength characteristics. Similar patterns are noted when observing rock masses under conditions of active deformation and hydrogeological impact [29]-[31].

In zones of structural weakening, increased filtration and gas permeability, intense water ingress, high radon concentration and reduced elastic wave propagation velocities are also observed [32]. The need to integrate these factors is noted in contemporary research on the application of geophysics and monitoring methods in assessing the rock mass state [33], [34]. Modern diagnostic approaches increasingly rely on the integration of satellite remote sensing data with geological and geophysical measurements, demonstrating high efficiency in detecting deformation precursors, structural discontinuities and dynamic changes of the Earth's surface [35], [36].

The development of fracture-pore space has a serious influence on the geomechanical state of the quarry: reduces the stability of benches, complicates the management of drilling-blasting operations, contributes to the formation of an excess fraction of 0-6 mm and deteriorates the quality of commercial coal. Similar trends are described in studies on modeling geomechanical processes [37], [38]. In a broader industrial safety context, recent research also emphasizes the importance of early detection of hazardous processes affecting mining infrastructure, including hydrogen leakage control in transport and fuel supply systems, which further demonstrates the need for advanced monitoring technologies in the mining sector [39], [40].

Thus, diagnosis and spatial localization of structural weakening zones are essential elements in the design of technological open-pit mining schemes. The formation of scientifically-based geophysical criteria for assessing rock mass fracturing will improve the accuracy of geomechanical risk prediction, optimize the parameters of drilling-blasting operations, and ensure effective management of coarse-grained coal, which is directly related to the technological and economic sustainability of mining operations [41]-[43].

1.2. Analysis of recent research and publications

A significant number of domestic and foreign publications are devoted to the study of structural disturbances in coal seams, their influence on the geomechanical state of the rock mass, and the application of geophysical methods to identify them [44]-[46]. In recent decades, scientific research has actively developed approaches based on the use of non-destructive geophysical monitoring methods, which allow obtaining detailed information about fracturing, degree of loosening and water saturation of rocks without interfering with the natural mass structure [47]-[52].

Electrical tomography (ERT), ground-penetrating radar (GPR) surveying and seismic prospecting using refracted waves (Refraction Seismic, RS) methods have become the most widely used methods, which proved to be effective for assessing the spatial distribution of physical properties of coal and host rocks [53]-[55]. Electrical tomography provides high vertical and horizontal resolution, allowing the identification of areas with reduced specific electrical resistance (ρ) associated with increased fracturing and water saturation [56], [57]. Refraction Seismic (RS) method, in turn, is used to refine the boundaries of loosening zones, estimate longitudinal wave velocities (V_p) and determine the depth of tectonic disturbances [58], [59]. Ground-penetrating radar surveying has shown effectiveness in dry and weakly mineralized areas, where the reflected signal allows small-scale heterogeneities to be detected within the first few meters from the surface [60], [61].

Recent studies have focused particularly on integrating various geophysical methods, which improves the reliability of interpretation. A number of authors [54], [62]-[64] have shown that combined analysis of ρ and V_p distributions allows for more reliable mapping of fracture zones than the use of separate methods. The use of correlation and statistical models, as well as 3D data inversion, facilitates the quantitative assessment of parameters of weakened areas, the formation of spatial diagnostic models, and the prediction of changes in the mass state over time.

At the same time, radon measurement studies based on measuring radon concentrations in soil air are actively developing. Radon, as a product of radioactive decay of uranium and radium, accumulates and migrates through the fracture system, making it a reliable indicator of tectonic activity, gas permeability, and structural disturbance in the mass [65], [66]. Radonometry is successfully used to clarify the geometry of faults, monitor stress state and assess the filtration properties of rocks. A number of publications have determined stable spatial correlations between C(Rn) anomalies and zones of reduced ρ and V_p, confirming the unified nature of processes associated with the development of fracture-pore space [67].

Despite significant advances, most existing studies are fragmentary in nature. As a rule, individual physical parameters (electrical, seismic or radiation) are analysed without their associated consideration within a single interpretation model. Practical issues of interrelation of geophysical characteristics with coal fractional composition, influence of fracturing on the mined mass quality, as well as the possibility to manage the technological parameters of drilling-blasting operations based on geophysical indicators remain insufficiently studied.

In addition, a number of methods, such as spectral seismic profiling (SSP) and ground-penetrating radar (GPR) surveying, demonstrate unstable results in conditions of high water content and groundwater mineralization, thus limiting their application on an industrial scale [68]-[71]. For coal deposits in Kazakhstan, including Shubarkol, there is still no comprehensive quantitative assessment of structural weakening zones based on the integration of electrical, seismic and radon parameters, which determines the scientific novelty and relevance of this research.

1.3. Identification of unresolved common problem parts

Despite significant progress in the field of geophysical research of coal deposits, to date there is no comprehensive methodology for the quantitative diagnosis of structural weakening zones based on cross-spectrum analysis of electrical, seismic and radon parameters. Most existing works consider these methods separately, which limits the possibility of constructing a unified interpretative mass state model.

Quantitative relationships between fracturing, gas permeability and the physical-mechanical properties of rocks, as well as their influence on the formation of coarse-grained composition of coal mass, are not sufficiently studied. To date, no threshold values reflecting the degree of loosening and geomechanical stability of the rock mass have been found for the Shubarkol deposit. As a result, the task of creating an integrated geophysical diagnostic methodology that would allow quantitative assessment of weakening zones and ensure coal quality prediction remains unresolved.

1.4. Purpose of the paper and setting of objectives

The purpose of this research is to develop and test a scientifically sound system for managing coarse-grained coal based on comprehensive geophysical diagnostics of structural weakening and fracturing zones in the coal seams of the Shubarkol deposit.

To achieve the purpose set, the following tasks were addressed:

– conduct field research using a full range of methods: electrical prospecting using the resistance method based on the electrical tomography (ERT), electrical prospecting using the mean gradient (MG) installation, seismic prospecting using refracted waves (Refraction Seismic, RS) method, spectral seismic profiling (SSP), ground-penetrating radar (GPR) surveying and radonometry (emanation surveying);

– develop 3D distribution models of specific electrical resistance (ρ) and longitudinal wave velocities (V_p), while performing localization of structural weakening zones with assessment of depth, thickness and strike directions;

– determine quantitative correlation dependences between the parameters ρ, V_p and C(Rn), to form an integral diagnostic model and to identify threshold geophysical criteria for fracturing in the conditions of the Shubarkol deposit;

– assess the informative value, reliability and applicability of the methods used in production conditions, to perform their ranking for practical geophysical diagnosis of weakening zones.

2. Study area

Currently, the economic importance of the region is growing due to the exploitation of the Shubarkol coal deposit and mining of quarries at the Tur and Bogach iron-manganese deposits. The nearest railway station, Kyzylzhar, is about 100 km from the deposit; a new railway has been built connecting it with the city of Arkalyk.

The deposit area is located within the Kazakh hummocky terrain, with absolute surface elevations ranging from 450 to 556 m. The relative height differences are 10-15 m. The relief is represented by residual forms, closely related to the lithological composition of rocks, and the nature of the tectonic structures of the Palaeozoic basement.

In the geological structure of the deposit, terrigenous-carbonate formations of the Upper Devonian and Lower Carboniferous, terrigenous rocks of the Middle-Upper Carboniferous, coal-bearing terrigenous deposits of the Lower Jurassic, as well as loose weathering products of the Mesozoic and Cenozoic sediments are involved. The Mesozoic rocks unconformably overlie the Paleozoic units and are developed in the central part of the Shubarkol graben-syncline, forming a small basin of the same name.

The deposits are represented by fine- and coarse-grained sandstones, siltstones, argillites, loamy rocks and coals. Among them, argillites, siltstones and coals predominate. The total thickness of the sedimentary sequence is 250-280 m. The bedding of the rocks is predominantly horizontal. The coloration of the rocks varies from grey to dark grey.

The dip angles of the coal-bearing stratum at the coal horizon outcrops vary from 10-25 to 35-50°, increasing from the upper to the lower horizon. The steepest angles are observed in the northwestern and southeastern parts of the trough, while the western and eastern wings occur at a lower angle (10-20°). The inner part of the trough has a simple structure with gentle dip angles of 3-5°.

The coal-bearing stratum consists of Lower and Middle Jurassic deposits composed of argillites, aleurolites, fine-grained sandstones and coal seams. Directly beneath the Jurassic deposits, there are conglomerates, sandstones, aleurolites and argillites of varied colors from the Zhezkazgan Formation of the Upper Carboniferous period.

The upper coal horizon is the thickest and has a relatively simple structure. It consists of two thick seams – 2B and $1B_2$. The 2B seam covers approximately 60% of the deposit area and is represented by 3-7 coal bands with a thickness of 0.2-15.0 m, separated by 0.10-0.80 m thick rock interlayers. The working thickness of the seam is 15-22 m. The 1B seam is composed of 2-10 coal bands with a thickness of 0.15-8.3 m, separated by interlayers with a thickness of 0.03-0.40 m, with a working thickness of 4-9 m. The physical-mechanical characteristics of coal from seams 2B and 1B are presented in Table 1.

The interlayers are predominantly represented by argillites and siltstones, and less frequently by sandstones and carbonaceous argillites. At a distance of 10-12 m from the floor of the upper coal horizon lies seam B_0, which is characterized by a small thickness and typically a single-bench structure. It is distributed over almost the entire area of the basin.

The middle coal horizon is the least thick within the deposit and is represented by a coal seam with a thickness of 3-7 m and a variable internal structure. The working thickness of the seam ranges between 3.7 and 4.1 m.

Table 1. Initial physical-mechanical parameters of coal from 2B and $1B_2$ seams

Parameters	2B seam coal	$1B_2$ seam coal
Ultimate compressive strength (σ_c), MPa	18.8	17.0
Uniaxial tensile strength (σ_t), MPa	0.65	0.71
Natural moisture content (W), %	7.55	7.81
Average density (ρ) t/m^3	1.5	
Adhesion in monolith (C), MPa	3.11	3.07
Internal friction angle, φ	27	
Rock category by fracturing	Medium- and large- block	
Class by drillability	Easily drilled	
Explosibility class	Easy to explode	
Rock excavation index	Up to 3	

The lower coal horizon is the most structurally complex and is represented by a coal seam with a thickness of 25-40 m. Its constituent coal beds are generally thin and highly variable in both thickness and internal structure, reflecting the heterogeneity of sedimentation conditions and the tectonic features that controlled the formation of the coal-bearing sequence.

The industrial coal-bearing capacity of the Shubarkol deposit is confined to the lower part of the Jurassic sequence and is represented by three coal horizons: the Upper, Middle, and Lower. The Upper horizon is of the greatest interest for open-pit mining, as it is the thickest, most stable, and has a comparatively simple structure.

The zone with a simple structure extends as a narrow strip, 1.5-2.0 km long, from the northwestern closure of the basin along the northern limb of the fold to exploration line 10 and is associated with the coal-accumulation zone. Here, a center of coal accumulation is identified, where the horizon forms a single monolithic deposit subdivided into two seams: 2B (upper) and $1B_2$ (lower).

The thickness of the overburden varies from 0 to 110 m. The fracturing of the overburden rock mass plays a key role, determining its strength and deformation properties. Two types of fractures are distinguished at the deposit – tectonic and non-tectonic.

3. Research methods

3.1. General characteristics and organization of geophysical surveys

With the aim of developing a methodology for differentiating and ranking coal blocks according to the degree of structural weakening and increased fracturing in natural and technological conditions at the JSC Shubarkol Komir sections, the possibilities of using a set of geophysical methods were explored:

– electrical resistivity prospecting using the electrical tomography method (ERT);

– electrical resistivity prospecting using the mean gradient installation (MG);

– seismic prospecting using refracted waves (refraction seismic, RS) method;

– spectral seismic profiling (SSP);

– ground-penetrating radar surveying;

– radonometry (emanation surveying).

During the course of the study, based on theoretical analysis and experimental data, an integrated methodology was developed, and the optimal equipment and field survey parameters were determined for identifying structural weakening zones and areas of increased fracturing under the specific geological conditions of the Shubarkol coal deposit.

At the parametric site, instrumental measurements were carried out using a Schmidt hammer in order to establish correlations between the measured geophysical parameters of coal and its uniaxial compressive strength.

The main objective of the geophysical surveys is to identify, determine the spatial position, and quantitatively assess the zones of structural weakening and increased fracturing based on the analysis of a combination of measured physical fields.

In accordance with the geophysical survey program aimed at identifying and determining the spatial parameters of structural weakening zones and areas of increased fracturing in the coal mass, a comprehensive suite of methods was applied, providing a multiparametric assessment of the physical state of the rocks and reliable delineation of weakened areas. The methodological approach was based on electrical, seismic, radiation, and radar methods, which complement each other in terms of investigation depth, sensitivity, and resolution.

Within the framework of the field investigations, the following surveys were carried out:

1. Electrical resistivity prospecting using the electrical tomography (ERT) method, which provides detailed vertical and horizontal sections of the specific electrical resistance distribution, sensitive to changes in moisture content and fracturing of the rock mass. The surveys were conducted along two profile lines, each 200 m long, as well as along one 300-m line on the 2B seam block ("Centre Pure", safety berm).

2. Electrical resistivity prospecting using the mean gradient (MG) installation, aimed at refining the spatial position and strike azimuths of fracture zones. The work was performed along two 200-m profile lines and two 300-m lines on the 2B seam block ("Centre Pure").

3. Seismic prospecting using the refraction seismic (RS) method, which made it possible to determine longitudinal wave velocities and assess the degree of loosening of the coal mass. Measurements were conducted along two 200-m profiles and one 300-m profile on the 2B seam block ("Centre Pure", safety berm).

4. Spectral seismic profiling (SSP), used for diagnosing the upper part of the section and determining the relative fracturing of rocks based on the amplitude-frequency characteristics of reflected waves. Field measurements were carried out along two 200-m profile lines and two 300-m lines on the same block.

5. Ground-penetrating radar (GPR) surveying, intended for identifying dielectric contrasts and detecting heterogeneities in the near-surface part of the rock mass. The surveys were conducted along two 200-m profile lines and two 300-m lines on the 2B seam block ("Centre Pure").

6. Radonometry (emanation surveying), applied as a verification method to confirm the results obtained by other geophysical techniques and to identify active tectonic zones. In total, three near-bench areas (I, II, III) located within the alignment of the experimental extraction blocks were examined.

Each method had its own network of profile lines (Fig. 1), aligned in terms of coordinates and directions, which made it possible to compare the results between different physical fields. Small discrepancies in profile tracing are due to different sensitivities of methods and equipment placement requirements.

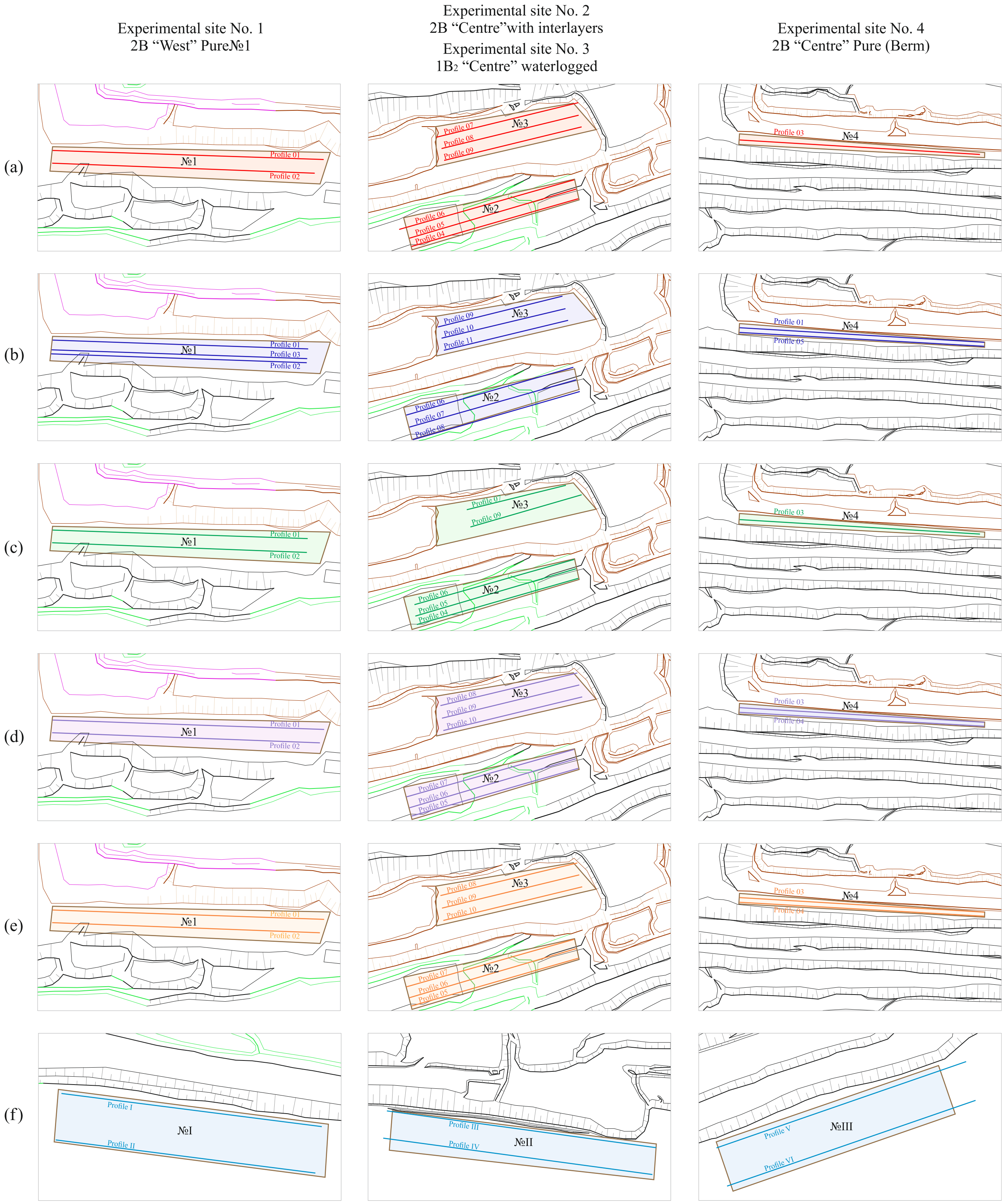

Figure 1. Layout of geophysical survey profile lines at the experimental sites of JSC Shubarkol Komir (a) electrical resistivity prospecting using the electrical tomography (ERT) method; (b) electrical resistivity prospecting using the mean gradient (MG) installation; (c) seismic prospecting using refracted waves (Refraction Seismic, RS) method; (d) spectral seismic profiling (SSP); (e) ground-penetrating radar surveying; (f) radonometry (emanation surveying)

3.2. Electrical resistivity prospecting using the electrical tomography method

Electrical resistivity prospecting remains one of the principal methods of near-surface geophysical investigations. The classical technique is vertical electrical sounding, aimed at studying horizontally layered sections.

The development of this direction has led to the emergence of the electrical tomography method, which is oriented toward the investigation of complex geological media and provides the possibility of interpreting data within the framework of two-dimensional geo-electrical models.

The basis of the resistivity method lies in the principle that the electrical field observed at the surface (ΔU_{MN}) when electric current (I_{AB}) is injected through grounded electrodes depends on the distribution of specific electrical resistance in the subsurface zone adjacent to the array. The integral nature of the observed field allows the resistivity method to be effectively applied in conditions of complex geological structures, typical of industrial and mining areas.

The electrical tomography technique, due to its high density of observations, provides enhanced resolution of results, particularly in the horizontal direction, which significantly increases the accuracy of interpretation.

During electrical resistivity surveys using the electrical tomography method, an electrical tomography system was employed, consisting of the VP-1000 and ASTRA-100 generators, as well as the MERI-24 measuring unit. When studying geoelectrical sections whose structure significantly deviates from a horizontally layered model, the use of electrical tomography becomes a necessary condition for reliable interpretation.

The inversion of electrical tomography data was carried out using the ZondRes2D software package. At the first stage, the quality of the field data was evaluated using the reciprocity principle, which states that when the positions of the current and potential electrodes are interchanged symmetrically, the measured potential difference should remain unchanged. ZondRes2D provides a built-in mechanism for evaluating measurement quality using colour gradation.

3.3. Electrical resistivity prospecting using the mean gradient installation

Electrical resistivity prospecting with the use of the mean gradient (MG) installation is a surface variant of electrical profiling that allows the investigation of the distribution of specific electrical resistance over an area while keeping the spacing between the current electrodes A and B fixed throughout the entire measurement process.

In resistivity prospecting, the term “installation” refers to the mutual arrangement of the current (A, B) and potential (M, N) electrodes. The choice of installation is a key methodological element that determines the accuracy and depth of the investigation and depends on the geological objectives, technical conditions, equipment characteristics, required depth of penetration and the level of noise. The mean gradient installation provides high productivity and enables simultaneous operation of several measuring systems, but requires more powerful current sources. The depth of investigation in this case depends on the length of the AB line. At the studied sites, the length of the AB line was 100 m, corresponding to an investigation depth of 12-16 m. By changing the AB spacing, the depth of investigation can be adjusted, while the MN spacing controls the measurement resolution.

The study of the sites was performed across the area by sequentially moving the potential electrodes M and N along profiles parallel to the AB line. The spacing between electrodes M and N was 3 m, which ensured the required resolution of the measurements.

For the physical implementation of the method, an alternating current of 4.88 Hz in the form of a square wave was generated using a current source and galvanic electrodes. Such current is considered equivalent to direct current for this method, and the formulas used for DC resistivity interpretation are applied to convert the measurements into apparent resistivities (ρ_k).

The analysis of the MG surveying results was performed using statistical methods. The distribution of anomalous ρ_k values within the investigation contour was examined. To determine the predominant direction of fracturing, distribution maps of ρ_k were constructed with consideration of anisotropy along strike azimuths of 10-15, 60, 90, and 275-320°, selected based on geological data.

The final model was accepted as the one with the smallest interpretation misfit and consistent with the results obtained from other geophysical methods.

3.4. Seismic prospecting using the refraction seismic (RS) method

The execution of seismic surveys (field observations, data processing, and interpretation) is based on the physical understanding of wave processes arising in the geological medium when elastic waves are generated within it. Although the geological environment is generally heterogeneous and anisotropic in its elastic properties, it can, with a certain degree of approximation, be represented by simplified elastic models for which wave propagation is described by fundamental physical laws.

In the refraction seismic method, the most informative waves are the refracted and refracted-diffracted longitudinal waves, while converted and shear waves are used less frequently. This necessitates the directed generation, registration, and processing of only the useful waves, whereas all other seismic responses are treated as noise.

During the fieldwork, a special seismic cable with connected receivers was laid out on the surface. An impulsive seismic source a hammer with a working mass of 6 kg was used to generate the signal. Impacts were applied at several points along the profile (shot points, SP), and the resulting wavefield was recorded by the seismic station.

In this study, layouts consisting of a single spread with 24 seismic receivers (geophones), spaced 2 m apart, were used. Recording of the seismic signals was performed using the digital seismic station “Lakkolit Kh-M3.” The recording parameters were as follows: sampling interval – 2 ms, record length – 256 samples per channel, channel amplification from 0 to 38 dB in 6 dB steps. Vertical geophones GS-20DX were used as receivers.

Processing of the refraction seismic data was carried out using the RadExPro software package. Processing included filtering of the raw data, amplitude correction, and band-pass filtering to suppress noise and enhance useful signals. Subsequent steps involved trace-by-trace picking of first arrivals and constructing first-break travel-time curves, on the basis of which the layered structure of the rock mass was evaluated and the velocities of longitudinal wave propagation (V_p, km/s) were determined.

3.5. Spectral seismic profiling (SSP)

To determine the structural and tectonic framework of the rock mass at the experimental extraction blocks, investigations were conducted using the spectral seismic profiling (SSP) method. The SSP instrumentation and methodological complex makes it possible to identify zones of tectonic disturbances as well as areas of increased fracturing within the rock mass.

The spectral seismic profiling method fundamentally differs from traditional ray-based seismic surveying. In SSP, the geological medium is considered as a set of oscillatory systems rather than as a layered structure. Therefore, the acoustic impulse generated by an impact is transformed into a harmonic (sinusoidal) damped signal directly within the source zone.

Such oscillatory systems can form in virtually any objects that constitute solid geological media. In the case of a plane-parallel geological structure, its natural frequency f_0 depends on the layer thickness *h*. Consequently, by measuring the parameters of the damped sinusoidal signal generated by the impact, the thickness of the investigated structure can be determined.

Each recorded seismic signal is subjected to a Fourier transform, which allows any time-varying process to be represented in the spectral frequency domain. Thus, the processing results take the form of images of seismic spectra that reflect both specific geological objects in the geomechanical sense and indicators of displacements or disturbances within the rock mass.

A characteristic feature of the spectral seismic profiling method is its high mobility and operational efficiency, which enables detailed probing of the rock mass with high spatial resolution.

3.6. Ground-penetrating radar (GPR) surveying

The ground-penetrating radar method makes it possible to investigate the rock mass to depths of up to 20 m, with the ability to differentiate rock blocks according to their electromagnetic properties. High survey resolution is ensured by the continuous nature of measurements along the profiles, which provides high spatial detail.

The operating principle of GPR is based on the emission of ultra-wideband nanosecond electromagnetic pulses, the reception of signals reflected from lithological boundaries or other contrasting objects, subsequent processing of the reflected waves, and measuring the time intervals between them. The probing signals, containing 1.5-2 oscillation periods, are generated by impact excitation of the antennas using a voltage step with a nanosecond rise time.

The essence of the method lies in transmitting electromagnetic pulses and recording signals reflected from boundaries between layers of the investigated medium that differ in their electrophysical properties. The main purpose of applying GPR is to determine the position of these boundaries within the studied object. Such boundaries may include: the contact between material and air; contacts between layers of different composition and physical properties; or zones of local heterogeneities within the rock mass. In this case, the medium is modelled as a layered sequence with constant electrophysical parameters within each layer and the presence of localized objects whose properties differ from those of the host rock.

The most important parameters determining the applicability of the ground-penetrating radar method are the specific attenuation and the propagation velocity of electromagnetic waves in the medium. These parameters depend on the electrical properties of rocks: attenuation controls the depth of penetration, while wave velocity determines the distance to the reflecting boundary.

3.7. Radonometry (emanation surveying)

Radonometric investigations (emanation surveying) were carried out on the ground surface of the near-bench zone, along and parallel to the experimental sites, in order to address the following tasks:

– identification and differentiation of structural weakening zones to confirm the results of other geophysical methods applied directly on the extraction blocks, as well as to increase the informativeness and reliability of the studies;

– assessment of the capabilities of the emanation surveying method under the geological conditions of the Shubarkol coal deposit for the advanced determination of the structural-geodynamic model of the near-bench rock mass and for calculating the geodynamic activity index of the identified deformation zones.

Emanation surveying was performed on near-bench sites No. I, No. II, and No. III, located along and parallel to the experimental extraction blocks. Measurements of radon volume activity (Bq/m^3) in soil air were conducted using RGA-500 radiometers for alpha-active gases along profile lines arranged in boreholes 0.8-1.0 m deep.

To determine the geodynamic component of the radon field, normalization of radon volume activity values in soil air was performed. This procedure allows the elimination of non-tectonic influences (temperature, moisture, and seasonal variations), enhances the geodynamic component of the radon field, and thereby enables the use of emanation survey results for identifying and ranking fractured areas according to the degree of present-day geodynamic activity and deformation intensity of the rock mass.

4. Results and discussions

4.1. Results of electrical resistivity prospecting using the electrical tomography method

Measurements were taken on two parallel profile lines at site No. 1. On profile line 01, the specific electrical resistance (SER) value along the section, according to the inversion results, varies within the range of 300 and 1000 Ohm·m. On profile 02, the specific electrical resistance along the section, according to the inversion results, varies within the range of 200 and 880 Ohm·m.

In general, the results of profile line 01 differ from those of profile line 02 by higher SER values, which is a sign of structurally loosened coal along line 01, located closer to the bench face (Fig. 2).

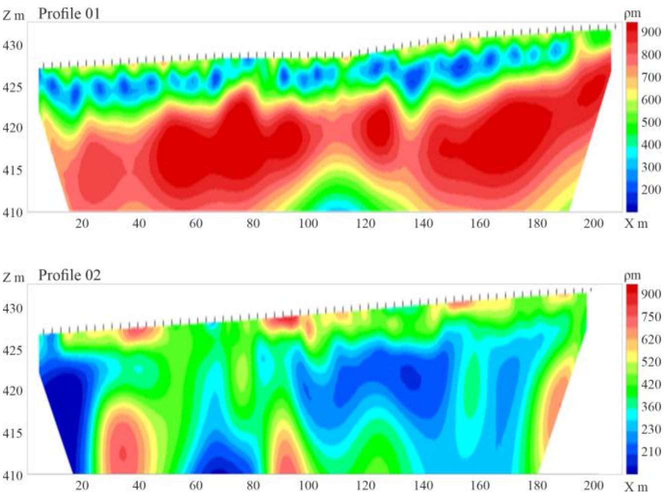

Figure 2. SER sections of site No. 1 based on the electrical tomography results

A horizontal boundary can be clearly observed of SER values changing from 300 to 800 Ohm·m at a depth of 5 to 8 m on profile line 01. On profile line 02, this boundary is less distinct and is located approximately 2 m deeper than on profile line 01. This difference may indicate a certain change in the lithological composition of coals, which, in turn, may affect their strength characteristics.

Measurements were taken on three parallel profile lines at site No. 2. On profile line 04, the specific electrical resistance (SER) value along the section, according to the inversion results, varies within the range of 60 and 1800 Ohm·m. On profile line 05, the SER varies between 35 and 1700 Ohm·m, and on profile line 06, between 45 and 1800 Ohm·m.

Anomalies of low SER values, recorded within 10-20 m on profile line 06, 190-215 m on line 05, and 193-223 m on line 04 are related to the peculiarities of constructing a block model in the 3D inversion program for electrical tomography data (Fig. 3). On all profile lines of this site in the depth range of 3-12 m (depending on profile position), the inversion results show low SER values (35-130 Ohm·m), which is due to the influence of argillite interlayers.

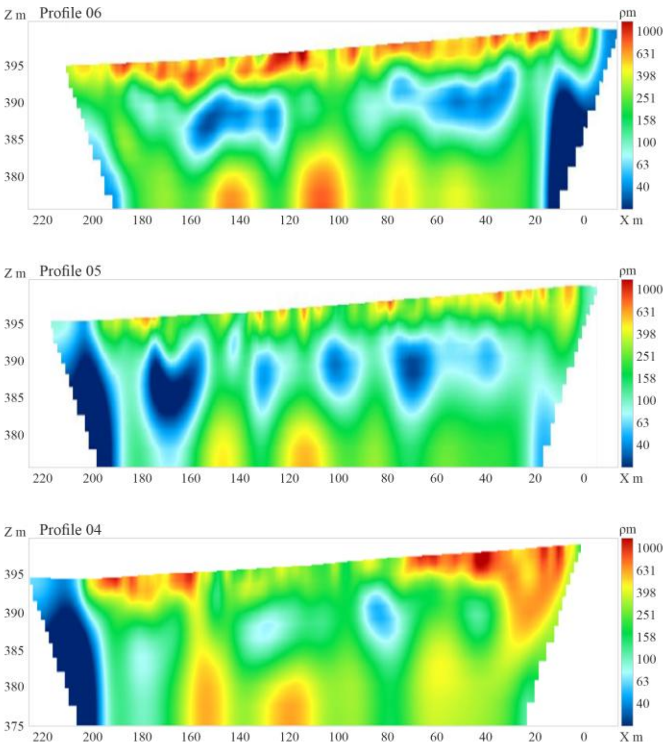

Figure 3. SER sections of site No. 2 based on the electrical tomography results

Given the persistence of these interlayers, an increase in SER values at the same depth interval may indicate the presence of zones of increased fracturing. In addition, in the lower layer, at depths of 14-20 m, in the intervals of 160-135, 138-116 and 98-86 m, three anomalies of elevated SER values (500-1000 Ohm·m) are distinguished, which shift when moving from profile line 04 to profile line 06 in an eastern direction. This indicates the presence of an increased fracturing zone with an azimuth of the strike of 10-15°. In the upper layer, the fracturing of the coals on the extreme profile lines is expressed somewhat more strongly than along the middle line. Accordingly, the identified SER anomalies and their systematic lateral displacement suggest a structurally controlled fracture system that enhances coal permeability and exhibits clear spatial differentiation between the upper and lower layers.

Measurements were taken on three parallel profile lines at site No. 3. On profile line 07, the specific electrical resistance (SER) value along the section, according to the inversion results, changes in the range of 12-500 Ohm·m. A similar range of values was recorded for profiles 08 and 09, namely, 12-500 Ohm-m.

When interpreting the results of electrical tomography in waterlogged areas, it is necessary to take into account that a decrease in the SER values indicates increased rock fracturing. This is because the pore space of the rock, including natural and fractured porosity, is filled with water, and mineralized water conducts an electric current well. On the contrary, an increase in SER values indicates a decrease in fracturing: in less disturbed rocks, fracture porosity decreases, leading to an increase in electrical resistance.

The SER range for this site (15-500 Ohm-m) is significantly lower than the range obtained at the adjacent site (45-1800 Ohm-m), indicating high mineralization of groundwater at this location (Fig. 4).

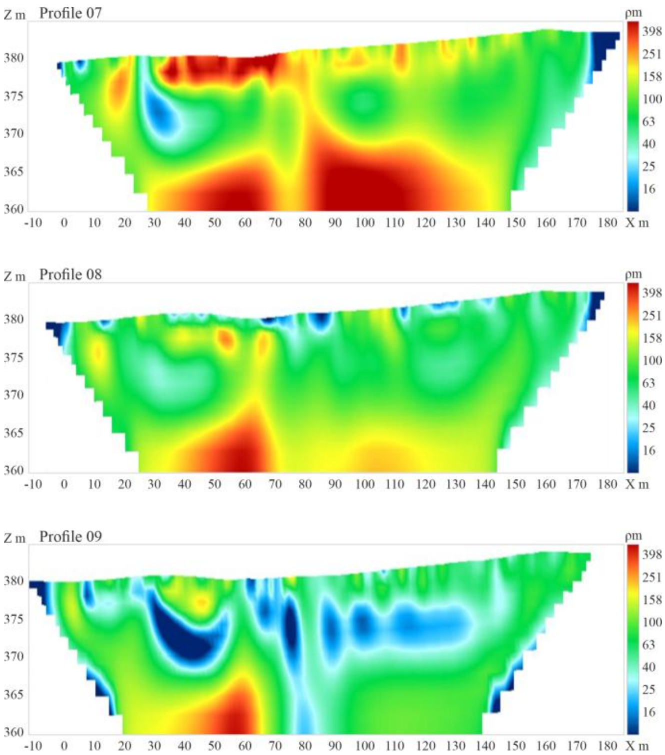

Figure 4. SER sections of site No. 4 based on the electrical tomography results

Part of the site was pre-drilled with boreholes for blasting operations, in which the presence of water is observed. In the southern part of the site, the groundwater level in the wells is practically the same as the daylight surface. On moving towards the northern part, the water level gradually decreases; the maximum depth of the groundwater level is about 3 m. On the northern profile line 07, at a depth of about 3 m from the surface, the boundary of transition of SER values from elevated to reduced is recorded, which correlates well with the groundwater level. The most fractured rocks are localized in the southern part of the site, which is confirmed by the prevalence of reduced SER values.

Measurements were taken on one profile line at site No. 4 due to insufficient platform width to accommodate more than one profile. On profile line 03, the specific electrical resistance (SER) value, based on inversion results, changes within the range of 100-1800 Ohm·m (Fig. 5).

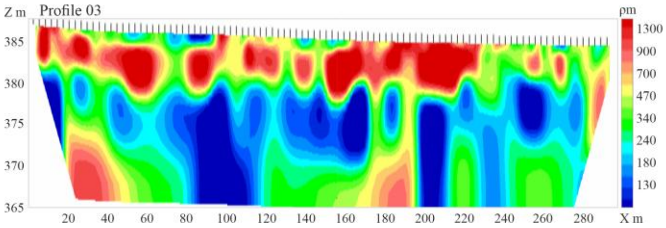

Figure 5. SER sections of site No. 4 on profile 03 of the 2B seam, Pure Berm, based on the electrical tomography results

Up to a depth of about 5 m, there are increased SER values (400-1800 Ohm·m), which can be explained by an increased fracturing of the rock mass resulting from drilling-blasting operations during overburden operations. Beneath, there is a layer of coal with reduced SER values (45-500 Ohm·m), characterized by less fracturing. Due to the vertical variability of the SER values at this site, the zonal propagation of increased fracturing is clearly distinguished.

The results of electrical resistivity surveys using the electrical tomography method at the sections of JSC "Shubarkol Komir" have confirmed the effectiveness of this method for determining the spatial parameters of structural weakening zones and areas of increased coal fracturing. Thus, the electrical tomography method can be recommended for implementation at the enterprise as part of an integrated methodology for studying structural weakening zones of coal benches using geophysical techniques.

The obtained results were used in the integration of geophysical data for the development of a methodology for delineating structural weakening and increased fracturing zones, as well as for training and instruction of the personnel of JSC "Shubarkol Komir".

4.2. Results of electrical prospecting using the resistance method with a mean gradient installation

The results of the survey using the MG installation at site No. 1 (Fig. 6a) show that the apparent resistance ρ_k values vary between 13 and 437 Ohm·m, with an average median value of 100 Ohm·m. According to the distribution pattern ρ_k, the main azimuth of fracture propagation at this site is 60°; the 300° direction is also fixed, but expressed more weakly. The main zone of structural weakening is observed in the southern part of the site.

According to the results of the survey using the MG installation at site No. 2 (Fig. 6b), the ρ_k values vary between 28 and 374 Ohm·m, with a median value of 118 Ohm·m. Based on the distribution of ρ_k, the main azimuth of fracture propagation at this site is 10-15°. The main area of structural weakening is located in the central part of the site.

According to the results of the MG survey at site No. 3 (Fig. 6c), the ρ_k values vary within the range of 10-370 Ohm·m, with a median value of 86 Ohm·m. The main azimuth of fracture propagation coincides with the results for site No. 2 and is 10-15°. The main structural weakening zone is confined to the southern part of the site, which is characterized by increased water content. In boreholes drilled for blasting operations, the groundwater level varies from the surface to a depth of 3 m.

According to the results of the survey using the MG installation at site No. 4 (Fig. 6d), the ρ_k values vary between 15 and 528 Ohm·m, with a median value of 116 Ohm·m.

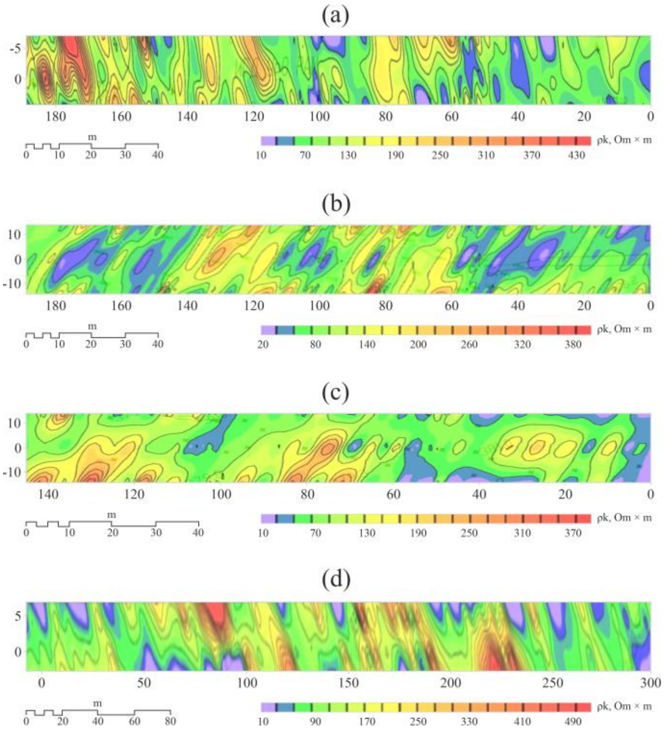

Figure 6. Field of apparent resistances at experimental sites based on the results of electrical prospecting using the MG installation: (a) site No. 1; (b) site No. 2; (c) site No. 3; (d) site No. 4

Analysis of the ρ_k distribution shows that the main azimuth of fracture propagation at this site is 300°. The main structu-ral weakening zones are observed in the intervals of 90-100 and 160-250 m along the profile.

The results of electrical resistivity surveys using the mean gradient installation at the sections of JSC "Shubarkol Komir" have confirmed the capability of this method to determine the predominant azimuth directions of fracturing within the coal mass at the investigated sites, which is of practical value for planning drilling-blasting operations. Therefore, the mean gradient method is recommended for implementation at the enterprise as part of the integrated methodology for studying structural weakening zones of coal benches using geophysical techniques.

4.3. Results of seismic prospecting using refracted waves (RS) method

At site No. 1, seismic surveys were performed on two profiles, with four arrangements on each. As a result of data processing, seismic sections of the distribution of longitudinal wave propagation velocities in the medium were constructed (Fig. 7).

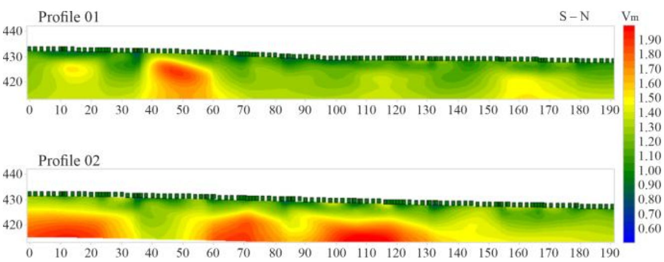

Figure 7. Longitudinal velocity distribution sections at site No. 1

According to the accepted colour scale, the coals in the section vary from intensely disintegrated (blue) to slightly fractured (red). It can be noted that coals on profile 01 are generally more disintegrated than those on profile 02. This is most likely due to the fact that profile 01 passes close to the bench face, as a result of which the rock mass in this zone is more loosened. On profile 01, coals are characterized by a moderate degree of fracturing, with consistent parameter values throughout the entire length of the profile. Zones of weakly fractured coals are observed at depths of 40-60 m and 155-170 m. Profile 02 shows a weakened zone at depths of 30-55 m, which can be observed throughout the entire depth of the survey. In addition, increased fracturing is noted from 130 m to the end of the profile. No significantly loosened coal was found in either section.

Seismic surveys were performed on three profiles at site No. 2, with four arrangements on each. As a result of data processing, seismic sections of the distribution of longitudinal wave velocities in the medium were constructed (Fig. 8).

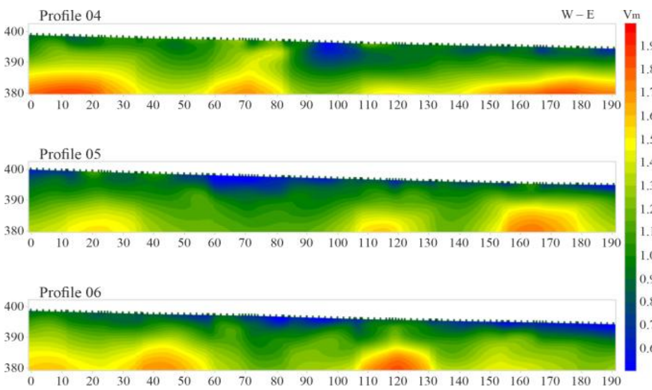

Figure 8. Longitudinal velocity distribution sections at site No. 2

According to the colour scale, the coals in sections vary from disintegrated (blue) to slightly fractured (red). In general, the sections are characterized by coals with a moderate degree of disintegration. Several zones of loosening are observed on profile 04. The predicted decrease in fracturing with depth does not actually occur, being noted only at depths of 10-15 m in the intervals of 0-25, 60-75 and 150-190 m. In the near-surface area, in the range of 85-105 m, there is a local zone of loosening, which gradually fades towards the end of the profile.

On profile 05, coal loosening in the upper part of the section is observed along the entire length of the profile, reaching a depth of up to 4 m in a range of 50-80 m. A similar pattern is observed on profile 06, where increased coal fracturing is recorded in the upper 1-2 m along the entire length of the profile. Zones of weakly fractured coals are local in nature and do not have a significant impact on the overall pattern of velocity distribution.

Site No. 3 is located approximately 25 m below and slightly north of site No. 2. Figure 9 shows that the longitudinal wave velocities at this site are significantly higher than at the others. A distinctive peculiarity of site No. 3 is the increased water content of the rock mass with the formation of puddles on the surface. Water filling pores and fractures increases rock density, which affects the propagation velocity of elastic waves. In addition, there are a significant number of argillite interlayers in the coal, which are also characterized by higher values of seismic wave propagation velocities compared to coal.

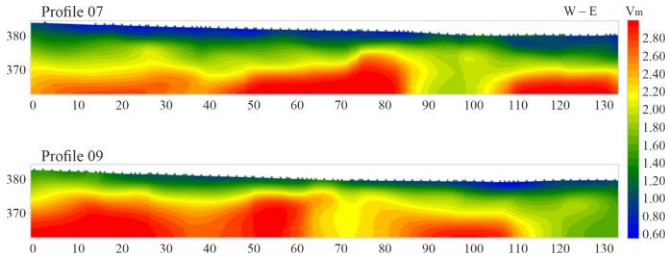

Figure 9. Longitudinal velocity distribution sections at site No. 3

Thus, two factors simultaneously influence the wave velocity in the rock mass: water content and the presence of argillite interlayers, which causes the increased velocity values.

Based on the results of the section interpretation, coal on profile 07 is generally more disintegrated than on profile 09. The upper part of profile 07 (at a depth of 2-3 m) is characterized by increased fracturing compared to profile 09. Throughout the entire interval of survey on profile 07, a zone of disturbed coals is distinguished within the range of 85-105 m. On profile 09, zones of weakened coals are noted in the intervals of 60-80 and 110-135 m. Across the profiles, in the area marked 30-40 m, there is a zone of slight mass weakening.

Section No. 4 is located on the southern flank of the section. Seismic surveys were performed on one profile 03 with six arrangements. The total length of the profile was 286 m. As a result of processing, a seismic sections of the distribution of longitudinal wave propagation velocities in the medium were constructed (Fig. 10).

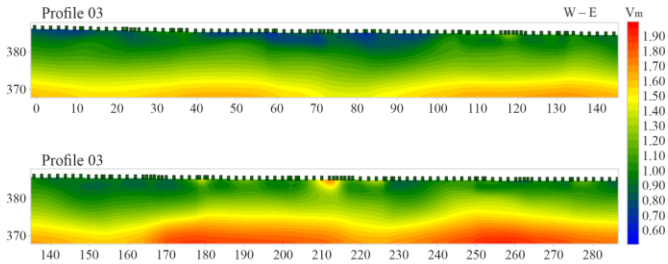

Figure 10. Longitudinal velocity distribution sections at site No. 4

Based on the seismic survey results, this site differs from the others in terms of the subhorizontal persistence of seismic boundaries. On profile, coals with increased fracturing are fixed in the interval 0-100 m at depths of 0-1 m, as well as up to 3 m in the range of 50-90 m. From the mark of 100 m and to the end of profile, the upper part of the section (to a depth of 5 m) is represented mainly by coal with moderate fracturing degree. Less fractured coals can be seen throughout the profile: in the first half, from a depth of about 12 m, and after the 160 m picket, from a depth of about 8 m.

The results of seismic investigations have shown that this method makes it possible to reliably determine seismic wave propagation velocities and, consequently, to assess the geomechanical condition of the coal mass.

4.4. Results of spectral seismic profiling (SSP) survey

At site No. 1, survey was performed using the SSP method on two profiles. As a result of data processing, SSP sections were constructed (Fig. 11a). The measurement results show that the coals in sections vary from intensely disintegrated to slightly fractured. On profile 01, the coals are generally more disintegrated than on profile 02.

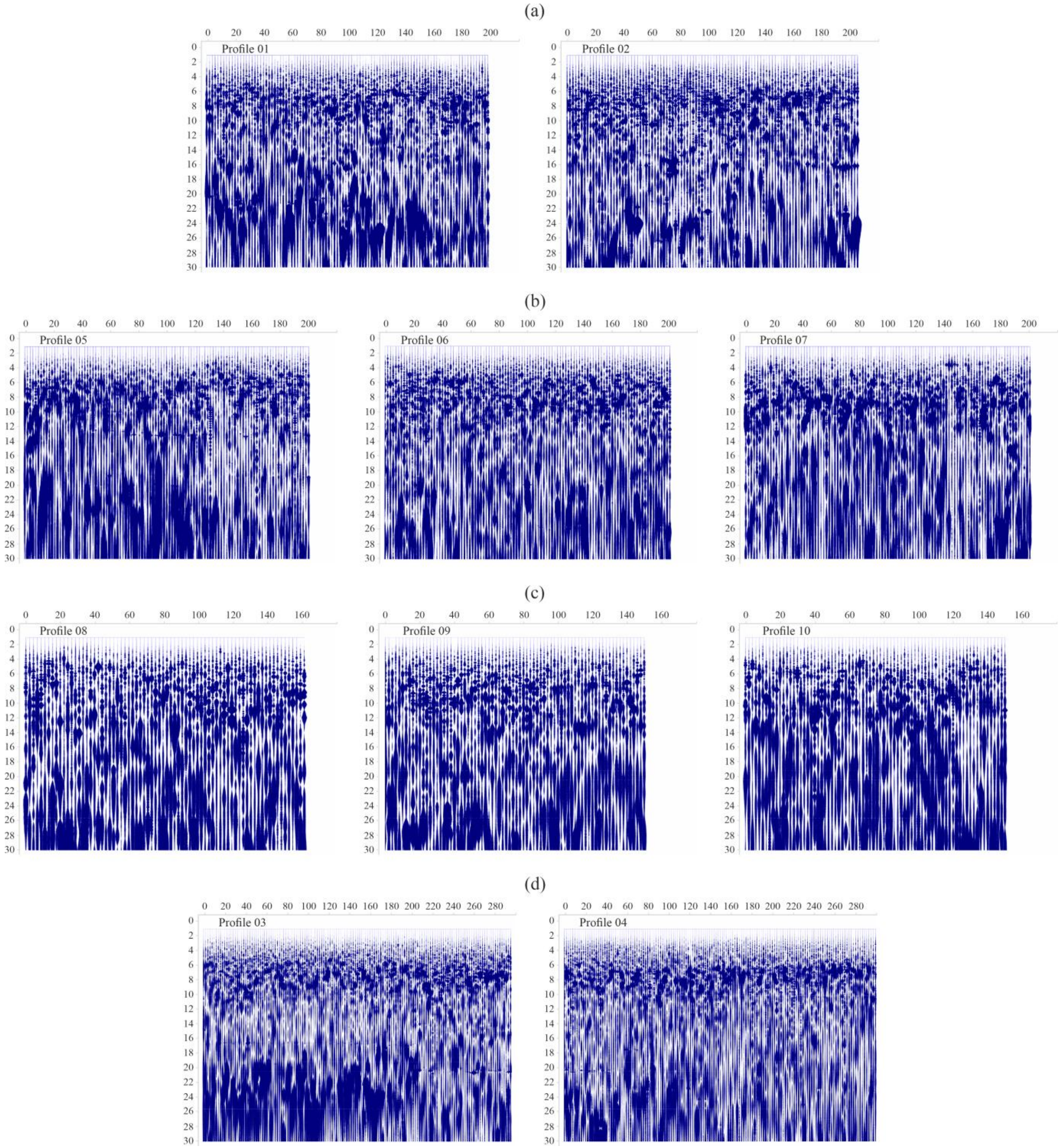

Figure 11. Survey results using the SSP method: (a) site No. 1; (b) site No. 2; (c) site No. 3; (d) site No. 4

This is most likely due to the fact that profile 01 is placed close to the bench face, as a result of which the rock mass in this zone appeared to be more loosened. On profile 01, the coals are characterized by moderate fracturing degree. Zones of weakly fractured coals are noted at elevations of 40-60 and 110-140 m. Profile 02 shows a weakened zone at intervals of 30-60 and 90-120 m, which can be observed throughout the entire depth of the survey.

Based on the results of SSP method surveys at site No. 1, it was not possible to clearly and confidently differentiate coals by degree of fracturing, which is due to the limited resolution of the method in the conditions of studied mass.

At site No. 2, surveys were conducted using the SSP method on three profiles. As a result of processing, SSP sections of signal distribution in the medium were constructed (Fig. 11b). In general, coals of moderate degree of disintegration prevail in the sections.

On profile 05, a zone of intense fracturing is observed at intervals of 130-80 and 20-0 m. The zone is observed from the surface to the entire depth of the survey. On profile 06, coal loosening in the upper part of the section is observed along the entire length of the profile to a depth of approximately 12 m. Profile 07, located closer to the underlying waterlogged bench, is characterized by increased fracturing along its entire length, to a depth of 10-11 m.

The results of site No. 2 surveys show that the upper part of the section is characterized by increased fracturing, which does not allow it to be differentiated by the SSP method into separate zones according to the mass disturbance degree.

Site No. 3 is located approximately 25 m below and slightly north of site No. 2. The results of the SSP method surveys are presented in Figure 11c.

A distinctive peculiarity of site No. 3, which is located approximately 25 m lower and slightly north of site No. 2, is the increased water content of the mass with the formation of puddles on the surface. Water filling pores and fractures increases rock density, which should be taken into account when processing the results. At the same time, water reduces the strength properties of coal, and the presence of numerous argillite layers further influences the wave field structure.

Surveys conducted at site No. 3 revealed the presence of an increased fracturing zone: on profile 08 in the range of 110-70 m, and on profile 10 in the range of 120-90 m. The zone can be observed from the surface to a depth of approximately 11 m and correlates well with a similar zone on profile 05 on the overlying bench. The complex geological structure and high degree of water saturation of the mass did not allow for reliable determination of the presence of other characteristic fractured zones at this site.

Site No. 4 is located on the southern section face. SSP surveys were performed on two profiles, each 300 m long. The measurements show that both profiles (03 and 04) have increased fracturing in the upper part of the section to a depth of 10-12 m (Fig. 11d).

On profile 03, located closer to the bench face, in the interval 170-10 m at depths of more than 20 m, an intensely fractured zone is distinguished, caused by the close location of the double bench. Surveys conducted on profile 04 revealed the presence of a highly fractured tectonic zone in the intervals 60-80 and 110-130 m. The zone can be observed from the surface to the entire depth of the survey; coal within its boundaries is characterized by high fracturing degree.

The results of spectral seismic profiling surveys conducted at the JSC Shubarkol Komir sections confirmed that this method is generally capable of determining the spatial parameters of structural weakening and increased coal fracturing zones. However, the ambiguity of the results obtained, as well as the impossibility of using the method at sub-zero temperatures, do not allow research to be conducted during the long winter period, which excludes its year-round use.

Thus, the spectral seismic profiling method is not recommended for implementation at the enterprise as part of the integrated methodology for studying structural weakening zones of coal benches using geophysical techniques. For this reason, the results obtained by the SSP method were not used in the subsequent integration of geophysical data, and the method itself has been excluded from the list of techniques recommended for industrial application.

4.5. Results of the ground-penetrating radar surveying

At site No. 1, work was performed using ground-penetrating radar surveying on two profiles. As a result of data processing, ground-penetrating radar sections were constructed (Fig. 12a). Based on the measurement results for profiles 01 and 02, two layers can be distinguished. The first layer, at depths of 0-6 m, is characterized by uniform disintegration of the mass, presumably caused by drilling-blasting operations during the removal of overlying overburden rocks. The second layer is an undisturbed coal mass.

The dielectric permeability values vary within insignificant ranges, which does not allow the site to be differentiated into separate blocks. Based on the results of surveys conducted at this site, it was not possible to identify fractured zones and rank them according to the degree of fracturing using the ground-penetrating radar method.

At site No. 2, surveys were conducted using ground-penetrating radar on three profiles. As a result of processing, ground-penetrating radar sections of the dielectric permeability distribution in the medium were constructed (Fig. 12b, profiles 05, 06, 07). In general, coal with a moderate degree of disintegration predominates in the sections.

Based on the measurement results for profiles 05, 06, and 07, two layers can be distinguished. The first layer, at depths of 0-8 m, is characterized by a disturbed mass structure, presumably formed under the influence of drilling-blasting operations. The second layer is an undisturbed coal mass. On profile 05, no differentiation in terms of fracturing degree was identified based on ground-penetrating radar data. On profile 06, coal loosening in the upper part of the section is observed along the entire length of the profile to a depth of 6-8 m. Profile 07, located closer to the bench face, is characterized by moderate fracturing along its entire length, to a depth of 5-7 m.

Based on the results of ground-penetrating radar measurements, it was not possible to differentiate the mass by degree of fracturing, since the dielectric permeability values vary within very small ranges, which does not allow the site to be divided into separate blocks.

The results of ground-penetrating radar surveys at site No. 3 are presented in Figure 12c (profiles 08, 09, 10). A distinctive peculiarity of this site is the increased water content of the rock mass, up to the formation of a puddle on the surface. Water filling pores and fractures reduces the strength properties of coal and changes the nature of the reflected signal. In addition, numerous argillite layers are present in the coal, which also influences the shape and intensity of reflections.

Based on the measurement results for profiles 08, 09, and 10, two layers can be distinguished. The first layer, at depths of 0-5 m, is characterized by a disintegrated rock structure, presumably formed as a result of previous drilling-blasting operations. The second layer is an undisturbed coal mass. Surveys conducted at site No. 3 revealed the presence of a highly fractured waterlogged zone: on profile 08 – in the 80-120 m interval, and on profile 09 – in the 90-130 m interval. The zone can be observed from the surface to a depth of approximately 8 m, and the coal within it is characterized by high fracturing degree.

The complex geological structure and high water content of the mass made it impossible to reliably determine the presence of other characteristic fractured zones at this site.

Ground-penetrating radar surveys were conducted at site No. 4 on two 300-m long profiles. As a result of data processing, sections were constructed (Fig. 12d). The measurements revealed that the upper part of the section is disturbed by mining operations to a depth of 4-5 m. The complex geological mass structure did not allow to reliably determine the presence of characteristic fractured zones at this site.

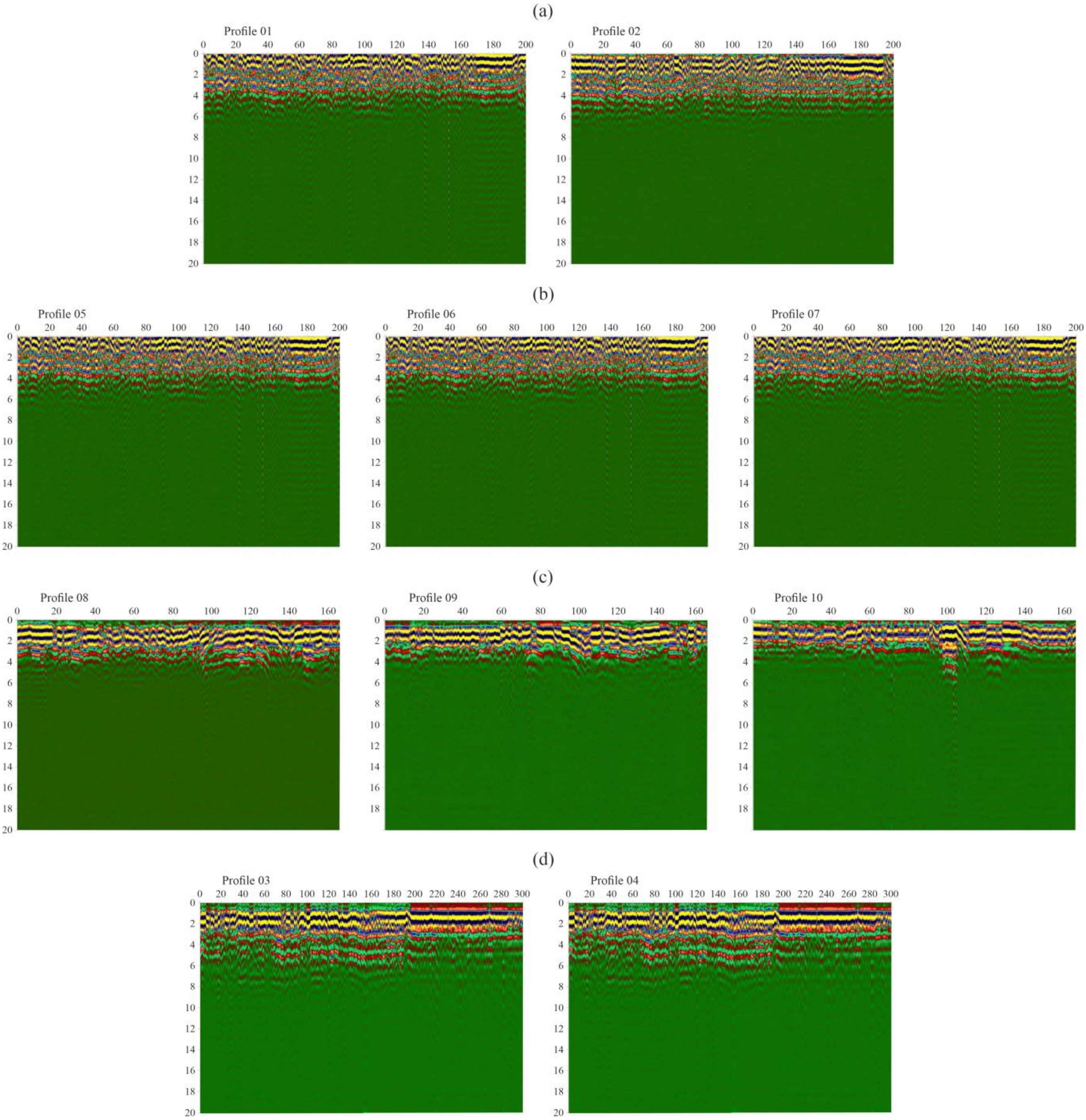

Figure 12. Survey results using the ground-penetrating radar method: (a) site No. 1; (b) site No. 2; (c) site No. 3; (d) site No. 4

The results of ground-penetrating radar surveys conducted at the sections of JSC "Shubarkol Komir" have demonstrated that this method is unsuitable for identifying and determining the spatial parameters of structural weakening zones, as well as for ranking them according to the degree of fracturing within the coal mass. For this reason, the results obtained by the GPR method were not used in the integration of geophysical data for assessing the condition of the experimental sites. Thus, the ground-penetrating radar method is not recommended for application at the enterprise as part of the integrated methodology for studying structural weakening zones of coal benches using geophysical methods.

4.6. Results of radonometry surveys

The field pattern of radon emanations reflects the block structure of the studied rock mass areas, with a clear identification of geodynamically active interblock spaces – discontinuous faults (Fig. 1f). Radonometry results at I, II, and III sites show the mass differentiation in terms of the degree of structural weakening and modern geodynamic activity, as well as determine their spatial parameters.

At site I, measurements of radon volume activity were taken on two profile lines (I and II) oriented in a meridian direction, with a total length of 200 m. The distance between the profile lines was 30 m, and between the measurement points – 10 m.

Based on the measurement results, radon concentration in soil air varies from 363 to 4138 Bq/m^3, while the normalized volume activity values range from 0.3 to 2.1 (Fig. 13a). At site No. II, measurements of radon volume activity were taken on two profile lines (III and IV) oriented in the latitudinal direction, with a total length of 300 m.

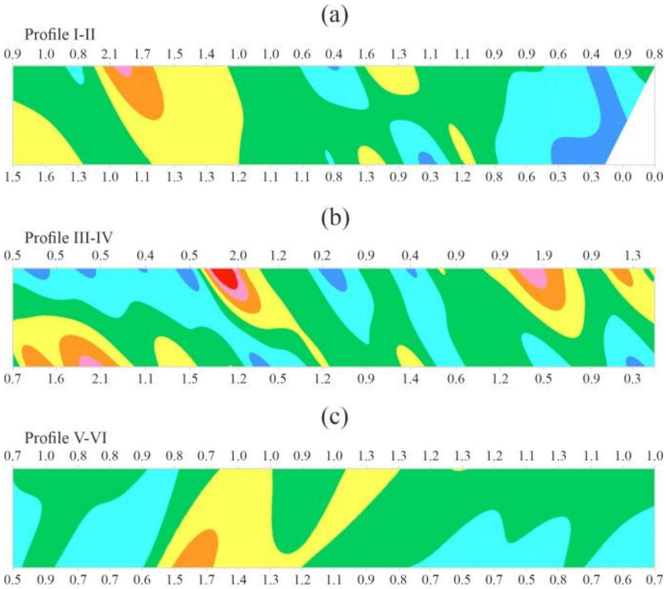

Figure 13. Results of radonometry surveys: (a) site No. I; (b) site No. II; (c) site No. III

The distance between the profile lines was 30 m, and between the measurement points – 10 m. Based on radonometry data, radon concentration in soil air varies from 145 to 1960 Bq/m^3, while the normalized volume activity values range from 0.2 to 2.8. The main discontinuous faults have an azimuth of strike of about 300° (Fig. 13b).

At site No. III, which is located in measuring section and parallel to site No. II, measurements of radon volume activity were made on two profile lines (V and VI) oriented in the latitudinal direction, with a total length of 200 m. The distance between the profile lines was 30 m, and between the measurement points – 10 m.

Radonometry data indicate that radon concentrations in soil air range from 835 to 3703 Bq/m^3, while normalized volume activity values range from 0.5 to 1.7. The main discontinuous faults have an azimuth of strike of about 15° (Fig. 13c).

The use of emanation surveying at the near-bench sites located along the alignment of the experimental extraction blocks was carried out as a verification method for determining the geomechanical condition of the rock mass. The results of the investigations confirmed the spatial parameters of the structural weakening zones previously identified by other geophysical methods applied directly on the extraction blocks.

In addition, considering the efficiency, effectiveness, and high reliability of the method, the radon emanation data obtained for zoning the rock mass according to the degree of structural weakening can be used in determining the optimal parameters of drilling-blasting operations during the removal of overlying semi-rock overburden, as well as in assessing the stability of the pit walls.

4.7. Comprehensive analysis, correlation dependences, and practical interpretation of geophysical data

4.7.1. The influence of fracturing on the technological properties of coal

Figure 14 shows that as the fracturing of the initial rock mass increases, the average size of coal pieces after extraction and drilling-blasting operations decreases regularly, while the proportion of fine particles increases. Thus, operational reports record the share of the 0-6 mm class at the level of 12.6-16%.

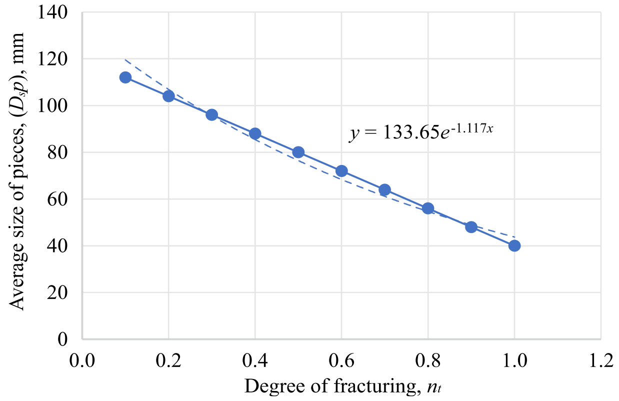

Figure 14. Change in average size of coal pieces depending on rock mass fracturing

Fracturing creates a kind of "pre-cut" in the rock mass: the more natural weakening planes there are, the easier it is to form fine fractions during drilling-blasting preparation and excavation. The noted negative dynamics in fine coal pieces is consistent with deterioration of natural and structural factors influencing the mined coal particle size. This determines the need to develop a system for predicting and managing particle size based on geophysical indicators of fracturing.

4.7.2. Integral correlation of geophysical parameters

Figure 15 presents a combined surface showing how the parameters of different methods – specific electrical resistance (ρ), longitudinal wave velocity (V_p) and radon concentration (C(Rn)) – jointly explain variations in the degree of structural coal mass weakening. Low ρ values and reduced V_p values, all other conditions being equal, correspond to higher fracturing and, as a result, increased radon emanations. The inverse combinations of parameters give lower values of C(Rn). Thus, there is a stable correlation reflecting the physical-geological essence of combining diverse geophysical indicators into a single diagnostic model of weakening zones.

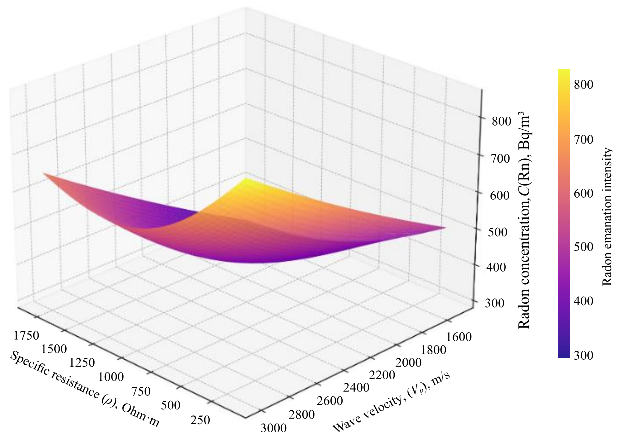

Figure 15. Integral correlation of geophysical parameters (ρ, V_p, C(Rn)) as a criterion for identifying zones of structural weakening: ρ – characterizes the electrical conductivity of the medium, reacting to the presence of a conductive liquid phase and the development of a fracture-pore structure, Ohm·m; V_p – reflects the density, integrity and elastic rock properties, m/s; C(Rn) – records fracture permeability and gas exchange intensity, Bq/m^3

Each of the three parameters is sensitive to different aspects of the same phenomenon – mass defects and saturation. The following patterns are identified in the studied mass:

– different ρ ranges for "dry" and waterlogged areas, confirming the dependence of electrical conductivity on pore space saturation;

– systematic variations in V_p, associated with disintegration and lithology (especially in argillite zones);

– persistent anomalies of C(Rn) along dominant faults, coinciding with decreases in ρ and V_p.

The consistent behaviour of these three parameters indicates the same structural weakening zones, confirming the correctness of the complex interpretation.

The implemented methodology of combined analysis of electro-tomographic, seismic and radonometry data made it possible not only to quantitatively assess the degree of the mass disturbance, but also to reveal the spatial structure of fracture-pore zones that are important for predicting gas yield and filtration properties.

4.7.3. Dependence of specific resistance on fracturing

Figure 16 shows the diagnostic dependence underlying the interpretation of electrical tomography data. As the fracturing of the rock mass increases, the specific electrical resistance (ρ) decreases regularly, which is due to an increase in the fracture-pore conductive structure.

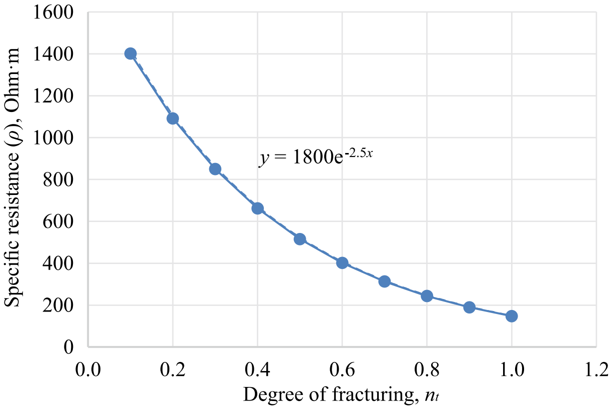

Figure 16. Dependence of specific electrical resistance on the degree of coal mass fracturing

In waterlogged areas, a decrease in ρ indicates a more developed fracture system, as pores and fractures saturated with mineralized water significantly increase electrical conductivity. In contrast, high ρ values are recorded in relatively dense and low-fractured zones.

Water with dissolved salts is an effective conductor, so in areas with developed fracturing, the specific resistance drops to 12-500 Ohm·m, while in "dry" areas, there are ranges of 45-1800 Ohm·m. The differences found directly reflect the degree of water saturation and groundwater mineralization.

It should be noted that in the near-surface zone, loosened by drilling-blasting operations and partially drained, the opposite trend is possible: increase in ρ at high fracturing due to replacement of water by air, which impairs conductivity. Similar effects were observed in the upper 0-5 m of the section (ρ up to 400-1800 Ohm·m), which emphasizes the need to interpret the data taking into account lithological peculiarities and hydrogeological conditions.

4.7.4. Correlation of longitudinal wave velocity and coal strength

Figure 17 shows the positive dependence between the velocity of elastic longitudinal waves V_p and the uniaxial compressive strength σ_c of coal, which is typical for rocks. The higher the elastic wave velocity, the greater, as a rule, the effective stiffness and structural integrity of the mass. For coals of seams 2B and $1B_2$, reference strength levels $\sigma_c \approx$ 17-18.8 MPa are fixed, making it possible to correlate the V_p velocity ranges with actual mechanical characteristics. Thus, sites characterized by low velocities ($V_p <$ 2200-2400 m/s) correspond to disintegration and increased fracturing zones, while values of $V_p >$ 2800-3000 m/s reflect dense and weakly fractured fragments of the mass.

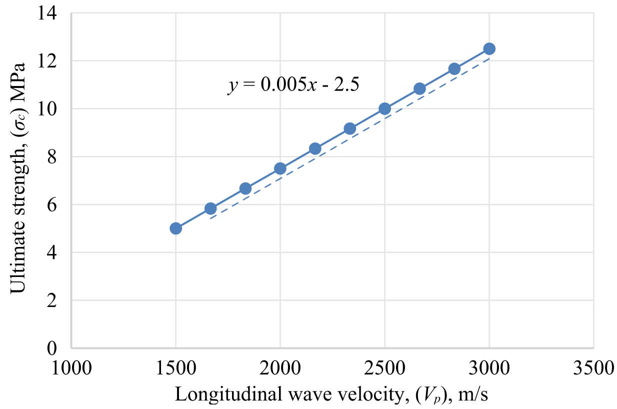

Figure 17. Correlation between longitudinal wave velocity and ultimate strength

The velocity of longitudinal waves is sensitive to fracturing, porosity, and the degree of saturation of rocks. The more solid and dense the medium, the higher the V_p velocity. On seismic sections, high-disintegration zones are visualized as "blue" areas with low velocities, while local "red" areas reflect zones with increased density and strength.

Thus, V_p can be considered as a proxy indicator of the structural mass persistence, correlating with its mechanical strength and serving as an important diagnostic indicator for interpreting the state of coal-bearing strata.

4.7.5. Radonometric indicators of structural mass weakening

Figure 18 shows that radon concentration in soil air increases regularly in zones of structural mass disturbance. Fractures and faults serve as the main migration routes for radon, which is formed during the radioactive decay of uranium and radium in rocks.

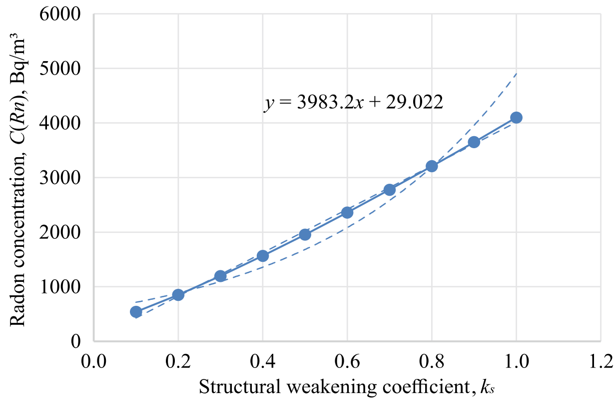

Figure 18. Dependence of radon concentration on the degree of structural rock mass weakening

In the profiles studied, radon concentration C(Rn) varies from ≈145-1960 Bq/m^3 at relatively quiet sites to ≈363-4138 Bq/m^3 in zones of tectonic disturbances. The dominant azimuths of the faults, determined by the structure geometry and seismic data, coincide with the directions of the "beams" of radon anomalies. Thus, elevated C(Rn) values reliably indicate zones of increased fracturing and gas permeability.

Radonometry in this complex serves as a verification method, confirming the results of electrical tomography and seismic prospecting. The coincidence of spatial anomalies in all three independent methods (ρ, V_p, C(Rn)) confirms the high reliability of the identification of mass weakening zones and allows their geometric position to be specified.

4.7.6. Practical interpretation and comparative assessment of methods

A comprehensive comparison of the data obtained shows that the most informative and practically applicable methods for the conditions of the Shubarkol deposit coal seams are electrical tomography (ERT) and mean gradient (MG) methods. These methods ensured high accuracy in locating structural weakening zones, determining the directions of fracture propagation, and quantitatively assessing the degree of rock mass loosening.

Refraction Seismic (RS) and radonometry methods demonstrated good mutual correlation: sites with reduced longitudinal wave velocities coincided with zones of increased radon concentration in soil air, confirming the presence of active tectonic disturbances and making radonometry an effective express-indicator of geodynamic activity.

The spectral seismic profiling (SSP) method confirmed the fundamental possibility of detecting fractured zones, but proved to be of limited applicability in conditions of sub-zero temperatures and high humidity. It is advisable to use it as an auxiliary tool at dry sites.

Ground-penetrating radar (GPR) surveying in highly waterlogged conditions showed low informative value for identifying weakening zones and does not provide the required resolution, as a result of which it was excluded from the set of recommended methods.

Figure 19 shows relative assessments of the informative value, reliability, applicability of six geophysical methods: electrical tomography (ERT), mean gradient (MG) method, refraction seismic (RS) method, spectral seismic profiling (SSP), ground-penetrating radar (GPR) and radonometry.

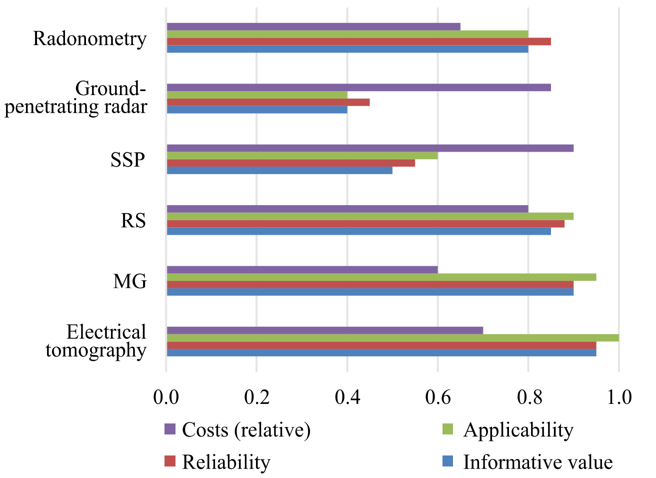

Figure 19. Comparative indicators of informative value, reliability, applicability and cost of geophysical methods

The results of the comparative analysis indicate that electrical tomography and the mean gradient method are the most informative and reliable for diagnosing weakened zones. Their integration provides high-precision spatial distributions of specific resistance and allows identifying the areas of mass loosening. Electrical tomography profiles make it possible to determine the depth and thickness of zones with reduced resistance (fractured and water-saturated rocks), while the mean gradient method specifies horizontal boundaries and directions of the strike.

Comparison of seismic and radiation parameters revealed a stable inverse correlation between ρ, V_p and C(Rn) (Fig. 20). With a decrease in ρ and V_p, an increase in C(Rn) is observed, indicating the development of open fracture systems and an increase in the gas permeability of the rock mass. Thus, radonometric data confirm the interpretation of electrical and seismic anomalies, and the method itself can be used as an express-indicator of geodynamic activity.

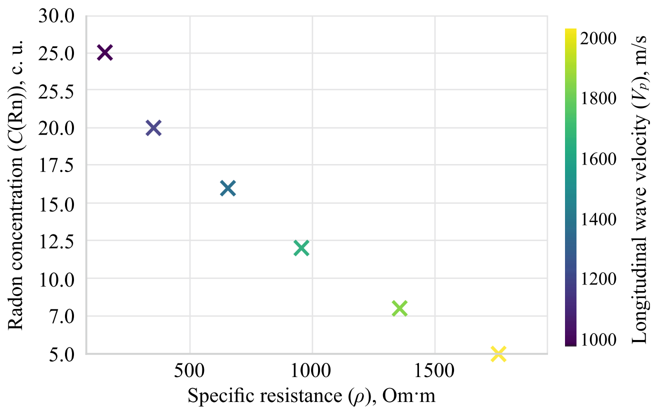

Figure 20. Three-parameter diagram linking the specific resistance (ρ), longitudinal wave velocity (V_p) and radon concentration (C(Rn))

Figure 21 shows the dependence of the proportion of the fine fraction (0-6 mm) on the degree of the rock mass fracturing. The analysis shows that when the fracturing increases from 5 to 50%, the proportion of fines increases from 10 to 16%. This confirms the direct influence of structural disturbance on coal fractional composition and stresses the importance of geophysical mapping for managing particle size during drilling-blasting operations.

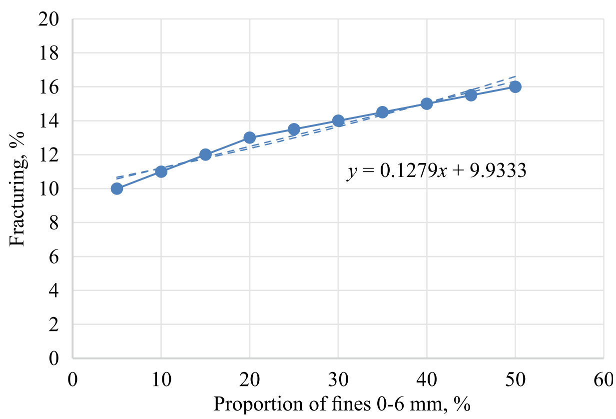

Figure 21. Influence of fracturing on the proportion of fine fraction (0-6 mm)

Thus, the combined results show that electrical tomography and the mean gradient method form the basis of the complex methodology of diagnosing structural weakening zones. Electrical tomography provides detailed determination of vertical and horizontal boundaries of weakened zones, MG method increases sensitivity to local heterogeneities and specifies the rock mass structure, while radonometry performs the function of express control of active tectonic zones.

Under conditions of high water saturation and heterogeneity of the coal mass, the use of seismic methods alone (RS, SSP) does not provide sufficient spatial resolution, which is confirmed by their weak correlation with the electrical and radiation measurement data.

Further improvement of the methodology should be directed toward the integration of electrical and radiation methods, the implementation of automated interpretation algorithms, and the construction of three-dimensional models of structural weakening zones for real-time monitoring of geodynamic activity.

5. Conclusions

Comprehensive geophysical surveys conducted at the Shubarkol coal deposit have made it possible to scientifically substantiate a system for diagnosing and managing coarse-grained coal, and have also confirmed the patterns of formation of structural weakening and fracturing zones in coal seams. The results obtained provide a quantitative basis for predicting the fractional composition of the coal mined and optimizing the parameters of drilling-blasting operations.

Based on a combined analysis of electrical tomography data, the mean gradient method, seismic prospecting using refracted waves (RS), and radonometry, quantitative criteria for assessing the geomechanical state of a coal mass have been determined. It has been shown that the combination of low specific electrical resistance values (ρ < 60-100 Ohm·m) and longitudinal wave velocities (V_p < 1500-1800 m/s) reliably characterizes zones of increased fracturing, water saturation, and structural weakening.

It has been found that the areas with lower ρ and V_p are accompanied by an increase in the proportion of fine fraction (< 6 mm) in the mined coal to 15-16%, which is confirmed by the operational data of the enterprise. Thus, the rock mass fracturing is a determining factor in the formation of coarse-grained coal during drilling-blasting preparation and excavation operations.

A correlation analysis was conducted between electrical, seismic and radon parameters, revealing stable interrelationships: radon concentration C(Rn) increases by 1.5-2 times in zones with reduced ρ and V_p, which confirms their tectonic activity and increased gas permeability. The three-parameter model ($\rho - V_p - C$(Rn)) has proven the efficacy of radonometry as an express-indicator of geodynamically active zones.

The developed integrated methodology for diagnosing weakening zones provides high accuracy of spatial localization – up to ±5 m in depth and ±10 m along the strike, which makes it possible to use it in practice when planning drilling-blasting operations and geomechanical monitoring.

Optimization of drilling-blasting parameters (DBP) taking into account identified geophysical indicators allows reducing the proportion of fines in the mined coal by 3-5%, increasing the homogeneity of the granulometric composition, as well as improving the stability of benches and the safety of mining operations.

The scientific novelty of the research is in the quantitative combination of electrical, seismic, and radon parameters to construct a unified diagnostic model of the coal mass state, and its practical significance is in the ability to quickly predict coal quality and mass state based on geophysical survey results.

Author contributions

Conceptualization: PM, AK, NZ, DD; Data curation: RM, PM, DA; Formal analysis: NZ; Funding acquisition: RM, PM, AK, DD; Investigation: FM; Methodology: PM, AK, DA, DD; Project administration: RM, AK, DA; Resources: FM, NZ; Software: RM, DA, DD; Supervision: FM, NZ; Validation: DA; Visualization: DA; Writing – original draft: RM; Writing – review & editing: RM, NZ, DD. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

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

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Інтегрована геофізична оцінка зон структурного ослаблення вугільного масиву для оптимізації буровибухових робіт та управління крупністю вугілля

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Мета. Метою дослідження є розроблення науково обгрунтованої системи управління крупнокусковістю рядового вугілля на підприємстві АТ "Шубарколь Комір" на основі комплексної геофізичної діагностики зон структурного ослаблення та тріщинуватості вугільних пластів. Робота спрямована на підвищення ефективності буровибухових робіт, зниження частки дрібної фракції та забезпечення стійкості бортів кар'єра шляхом використання геофізичних індикаторів стану масиву.

Методика. Дослідження виконано із застосуванням комплексу геофізичних методів: електророзвідки методом електротомографії (ЕТ), електророзвідки серединним градієнтом (СГ), сейсморозвідки методом преломлених хвиль (МПХ), спектрального сейсмопрофілювання (ССП), георадарного зондування (ГР) та радонометрії. Комплексна інтерпретація включала тривимірне моделювання розподілів питомого електричного опору (ρ) та швидкостей поздовжніх хвиль (V_p), а також статистичний аналіз кореляцій між параметрами ρ, V_p і C(Rn).

Результати. Встановлено, що зниження питомого опору до значень менше ніж 60-100 Ом·м та зменшення швидкостей поздовжніх хвиль до 1500-1800 м/с достовірно відображають розвиток тріщинуватості та розущільнення масиву. Концентрація радону в цих зонах зростає у 1.5-2 рази, що додатково підтверджує їх тектонічну активність. Методи ЕТ і СГ визначено як основні для виділення ослаблених зон; МПХ використано як калібрувальний; радонометрію як контрольний метод; ССП і ГР мають обмежене застосування через високу обводненість ділянки.

Наукова новизна. Вперше для Шубаркольського родовища розроблено й апробовано комплексну методику поєднаного аналізу електричних, сейсмічних і радіаційних параметрів, яка забезпечує кількісну оцінку геомеханічного стану масиву та прогноз його структурних змін.

Практична значимість. Запровадження запропонованої методики дає змогу з точністю ±5 м за глибиною та ±10 м за простяганням визначати зони ослаблення, коригувати параметри буровибухових робіт, зменшувати частку дрібної фракції (< 6 мм) на 3-5% та підвищувати стійкість бортів кар'єру.

Ключові слова: *тріщинуватість, вугілля, геофізична оцінка, родовище, ослаблення, стійкість*

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