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Study and rationale of tectonic fault crossing technology parameters by the mine face of a preparatory mine excavation

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Abstract
The study aims to develop technological schemes for mining through zones with geological disturbances, using systems for securing and stabilising near-contour unstable rocks to reduce their disintegration along the production workings. The study included stand and mine tests of fast-hardening anchoring systems, assessment of their bearing capacity, and mathematical modelling of the stratification of the massif weakened at the contacts, with the representation of geological disturbance around the rock layers and coal seam interlayers, to determine the stresses on the workings support and assess the condition of unstable supported spans in the disturbance zones. The study has shown the effectiveness of testing the technology of supporting workings, covering different degrees of rock mass disturbance, which allows for the successful passage of workings through disturbed areas using a combined support scheme. The developed technological scheme for mining operations, based on analytical modelling and the use of advanced support technology, addressed the geomechanics of disintegration processes in rocks and the impact of mining operating parameters on the moving front of cleaning operations in underground deposits. This study confirmed a significant reduction in risks when mining through disturbed areas of the rock mass due to the use of the developed technological support scheme. In addition, analytical modelling determined the optimal parameters of underground mining operations to improve the stability of mine workings when sinking through disturbed areas.

Keywords
anchoring technology, stress-strain state, anchorage, rock collapse, deformation, mathematical modelling

Introduction

The study of the technology for crossing tectonic faults with a mine face of preparatory mine workings is necessary to ensure the safety and sustainability of mining operations, as tectonic faults and cracks can significantly reduce the stability of mine workings and lead to cave-ins and accidents. These geological features pose a serious threat not only to equipment and infrastructure but also to the lives of workers. In addition, the correct determination and management of the crossing of such zones can optimise production processes, reduce the cost of emergency rehabilitation and reinforcement, and increase the overall efficiency and profitability of mining operations. Given the importance of sustainable and safe mining operations, this study is of key importance for developing and improving technologies in this industry.

This study was necessary to develop effective and safe methods for crossing tectonic faults in mine workings, which is critical to ensuring the stability and safety of mining operations. Tectonic faults and fractures can significantly worsen the sinking process, increasing the risk of cave-ins and accidents, which not only endangers the lives of workers but also leads to significant economic losses (Artykbaev et al., 2024; Brovko et al., 2024). A thorough analysis of the geological, mechanical and hydrogeological conditions in tectonic fault zones can be used to develop optimal strengthening and monitoring technologies, minimise risks and increase the efficiency of mining operations.

Tectonic faults pose a serious threat to the safety and sustainability of mine workings, which requires the development of effective methods for crossing them (Novakovska et al., 2025). Hasterok et al. (2022) emphasised the importance of geological exploration and mapping of tectonic faults, which provides a more accurate assessment of the geological structure of the area. Cantelon et al. (2022) addressed hydrogeological conditions, pointing out the need to account for water content and direction of groundwater flow to prevent flooding. Cao et al. (2021) conducted laboratory tests of the mechanical properties of rocks, identifying their strength characteristics, which helps in modelling the stress-strain state of the massif. Yang et al. (2021) used numerical methods, such as finite elements, to calculate the stability of workings, and Matayev et al. (2021) proposed optimal parameters for the fastening and strengthening of mine workings, accounting for the data obtained.

He et al. (2021) developed innovative anchoring systems that can significantly improve the stability of rocks. Under the guidance of mining rock mechanics, the "short cantilever beam" model is established, and the "equilibrium mining" theory is proposed. The equilibrium between the mining volume and broken expansion volume of the collapsed roof rock mass is realised, and a solution from the mining damage invariant equation is obtained, laying the theoretical foundation for the new coal mining methods. Goushis & M (2022) addressed the use of injectable materials, such as cement and polymer solutions, to strengthen faults and cracks. Boldy et al. (2021) focused on the phasing of mining operations, proposing methods of gradual strengthening of workings to increase their stability. Lu et al. (2021) emphasised the importance of monitoring the condition of workings, proposing sensor systems for early detection of deformations. Onifade (2021) analysed safety requirements and developed educational programmes for staff training, which effectively prevents accidents in mine workings. Despite significant advances in the study of tectonic faults, gaps remain in understanding the interaction of various factors, such as mechanical and hydrogeological conditions, and new materials and technologies for strengthening workings have not been sufficiently explored. Further research into an integrated approach to crossing tectonic faults, including integrating innovative materials and monitoring systems to improve the safety and efficiency of mining operations, is required.

The study aims to develop technological schemes for mining excavations through zones with geological disturbances using systems of fixing and stabilising near-contour unstable rocks to reduce their disintegration along the front of the production excavation. Research goals:

1. Development of technological schemes for mine workings through areas with geological disturbances using rock support and stabilisation systems.
2. Testing of anchoring systems on quick-setting mixtures to assess their load-bearing capacity in unstable rock conditions.
3. Mathematical modelling of stresses on the support and the state of supported spans when crossing geological faults to optimise the operation parameters of mine workings.

Materials and Methods

The study included pilot tests of rope anchors used to secure the junction of a ventilation drift with an assembly chamber at the Abayskaya mine in the Karaganda coal basin. For these experiments, a hydraulic device was used – a rod puller PK-3, which allowed the anchors to be pulled out with the subsequent recording of the readings on the manometer indicator following the accepted test methodology. The study also used anchors made of reinforcing steel of class A-II and chemical ampoules manufactured by Minova Kazakhstan LLP. The load-bearing capacity of the anchor rods was assessed using a PK3 rod puller. As part of pilot tests of mine workings support, rope anchors AK 19/5 designed by Karaganda Technical University (KartTU) were used. The AK 19/5 rope anchors and AK18N injection anchors were also tested to reinforce the 332K12 conveyor drift. All tests were carried out using the Ansys software package to model and implement the task.

The deformed state of the massif changed its stress state, creating zones of unloading and stress concentration around the workings. In the unloading zones, stresses decreased compared to natural (geostatic) conditions, while in the concentration zones, they increased. Stages of the stress-strain state included elastic work of up to 35%, elastic-plastic work of up to 70% of the maximum load and a fracture stage of up to 5%, characterised by avalanche-like cracks and destruction of the surrounding rock mass when the compressive or tensile strength of the rocks is exceeded.

To analyse geomechanical processes, mathematical modelling was used to solve the problem of determining the stress-strain state of the environment surrounding the mine workings in the case of its passage through a weakened or disturbed rock mass. The modelling process was used to determine normal, longitudinal and tangential stresses, reactions, internal forces and deformations. The following formulas were used in the study (1):

$$\sigma_y(\alpha, h) = k_0(h) \times \alpha^3 + k_1(h) \times \alpha^2 + k_2(h) \times \alpha + k_3(h), \quad (1)$$

where $\sigma_y(\alpha, h) -$ tension σ_y depending on the variables α and h, $k_0(h), k_1(h), k_2(h), k_3(h)$ – the coefficients of the function that determine the contribution of each term $\alpha^3, \alpha^2, \alpha$ and the free term in the total voltage σ_y.

The geomechanical model of the technological process of mining in unstable rocks (Figure 1) includes data on the geometry of the workings, as well as the physical and mechanical properties of the surrounding rock mass (including uniaxial compression strength) and the parameters of the advanced (preventive) anchoring.

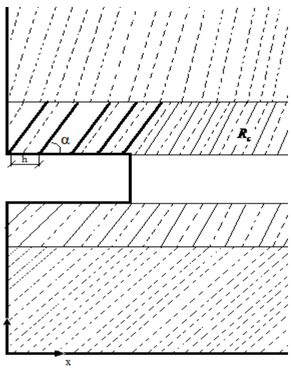
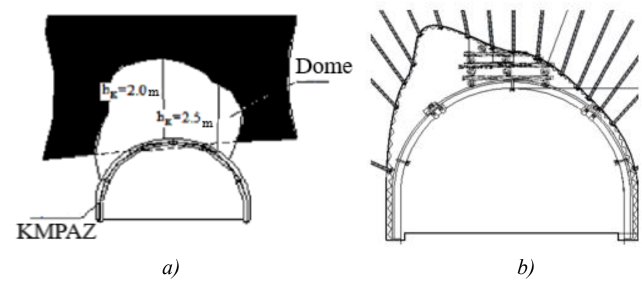


Fig. 1. Geomechanical model of the process of mine shaft sinking in unstable rocks.
Source: compiled by the authors.

The mining pressure was affected by both geological and man-made factors. The geological factors addressed included geological structure, conditions of occurrence, thickness and homogeneity of rock layers, degree of tectonic disturbance, composition and structure of the reservoir and surrounding rocks, hydrogeological conditions, as well as their strength, deformability, density, fracture and other characteristics. Technogenic factors included the depth of the workings, their spatial position concerning the coal seam, the nature and extent of the cleaning and preparation work, the shape and size of the workings, the parameters and methods of work, the speed of work, as well as the features and parameters of the support used, and the procedure for over- and under-mining coal seams.

Figure 2 illustrates the collapse of roof rocks during the excavation process, which forms domes in the centre of the ceiling (Figure 2a). A view of the mine workings with the placement of wooden cages and the installation of additional reinforcing anchors in the domes is also shown (Figure 2b).



a) b)

Fig. 2. Disruption of the contour and collapse of roof and sidewall rocks during the formation of domes when crossing a tectonic fault: a) in the centre of the ceiling, b) in the domes.
Source: compiled by the authors.

During the operation of coal mines, tectonic faults encountered during the development of workings had a significant negative impact. Operations in areas with plicative and disjunctive geological faults were accompanied by frequent disruptions of the rhythm of processes and required the application of special organisational and technical measures and additional time and resources to overcome problem areas. This applied to all aspects of mining operations: treatment, sinking, mine pressure management, mine construction, emission prevention measures, ventilation, etc.

Results

Mining operations disturb the initial stress state of coal and rock masses, leading to unstable zones around the supported mine operations. According to the principles of underground mechanics, the rocks around the excavation move into the cross-sectional area of the mine. These movements increase with decreasing rock strength and increasing degree of rock disturbance. Tensile deformations directed from the centre of the workings to their edges are accompanied by compressive deformations in perpendicular directions, usually coinciding with the outline of the workings. The resulting deformations of the rocks around the workings cause additional stresses that disturb the initial stress state of the massifs.

The operation of mine workings results in a new state of stress and strain around them, which differs significantly from the initial state close to the contour of the workings but remains virtually unchanged at greater distances from it. A characteristic feature of this new state is an increase or concentration of "circumferential" normal stresses and a decrease or dispersion of "radial" normal stresses. Circumferential normal stress, also known as hoop stress, is a type of stress that acts tangentially around the circumference of a cylindrical or spherical object. It is one of the principal stresses in systems with rotational symmetry, such as pressure vessels or pipes. Radial normal stress refers to the stress acting perpendicular to the surface of a cylindrical or spherical object, directed either inward or outward along the radial direction. It is one of the principal stresses in pressure vessels and other structures with rotational symmetry. This concentration of stresses contributes to forming a region of high support pressure, while their dissipation creates zones of relief in the surrounding massif.

When the resulting stress-strain state (SSS) exceeds a certain limit level typical for a given rock mass, the rock mass begins to fracture, accompanied by a further increase in SSS around the workings. The stress concentration or reference pressure moves deeper into the array, relieving the contour area. Rock fracture is a hazard to the operation of mine workings, causing loss of stability and rock fall into the workings (Palka et al., 2022). These are the qualitative regularities of geomechanical processes, regardless of where they occur: around preparatory or treatment workings in underground mining operations in the development of reservoir deposits.

As international (USA, England, Australia, Germany, Russia, Ukraine and other countries) and domestic experience shows, the effectiveness of fixing and supporting operations using primarily anchoring in capital and preparatory workings and junctions up to 8-9 m wide with roofs composed of weak fractured rocks at considerable depths, as well as in the areas affected by cleaning operations, can be reliably ensured by using steel-polymer anchoring supports 2-3 metres long or more. These fasteners, installed along the borehole's length with additional reinforcement with fast-setting resins, can withstand loads of up to 200-250 kN. In particularly difficult conditions, it is possible to further strengthen the anchorage with deep-drilled anchors (Deryaev, 2023; 2024b).

The anchoring system includes the anchors themselves, which are fixed in drilled holes in the roof and sides of the workings, as well as the anchor support elements (plates) and inter-anchor tightening (strips and runs) of the rocks on the contour, which differ from metal-frame and other support systems (Koval et al., 2020). The anchoring starts to bind and strengthen the rock in the roof and sides of the excavation immediately after installation, effectively resisting displacements and fractures. This important advantage saves metal, increases the stability of the roof and ensures reliable support of the mine workings. The use of anchors also has an operational advantage due to the possibility of full mechanisation of the bolting process, which significantly reduces the labour intensity of sinking operations and significantly increases the speed of excavation (Buhaievskyi et al., 2023).

One of the key elements of an anchor support that ensures its load-bearing capacity is the composition of the mixture used to fix the anchor rod using cartridge or injection fast-setting compounds (Prentkovskis et al. 2010; Grigorenko et al. 2019). In the mining industry, mixtures based on organic binders, synthetic resins, and mineral-based mixtures are used to secure anchor rods (Bakiev et al., 2021). Binding compositions for anchors are mainly created based on low-viscosity synthetic thermosetting resins, such as furan, phenol-formaldehyde, urea, epoxy, polyurethane, polyester and others (Schlechte, 2023).

Epoxy resins have high physical and mechanical properties (σ_{comp} = 90-100 MPa; σ_p = 30-50 MPa; σ_{iz} = 80-110 MPa) and good adhesion to metal and rocks. σ_{comp} indicates the compressive strength of the epoxy resin. Compressive strength is the maximum stress that a material can withstand under compression before it fails (Korzhyk et al., 2017b; Peleshenko et al., 2017). σ_p represents the tensile strength of the epoxy resin. Tensile strength is the maximum stress a material can endure while being stretched or pulled before breaking (Korzhyk et al. 2017a; Kukhar & Vasylevskyi, 2014). σ_{iz} denotes the impact strength of the epoxy resin, which measures the material's ability to resist sudden impacts or shocks without fracturing. However, the presence of water in the reaction mixture negatively affects the polymerisation process, which reduces the strength of the resulting polymer. Epoxy binders are not widely used due to their high cost (3-4 times more expensive than other resins), shortage, high initial viscosity, brittleness and toxicity. One of the main disadvantages of epoxy resins is also the long curing time at low positive and negative temperatures.

Despite their high strength for fixing reinforcing bars, polyurethane compositions are also expensive and scarce. Low-cost and easily accessible alternatives to steel polymer anchors have been developed using furan and phenol-formaldehyde resins. When fully cured, these compositions achieve sufficient strength (σ = 50-70 MPa, σ = 4.8-6.5 MPa), density and durability. They can adhere to both steel and rocks in the range of 4-5 MPa. However, their use is limited by disadvantages, such as the use of acidic hardeners and increased toxicity due to the presence of free formaldehyde and phenol. Another notable limitation of these formulations is their reduced effectiveness in wet conditions.

Compositions based on carbomide resins, although the lowest cost among other types of synthetic resins, are characterised by low strength and short life. Polyester compounds demonstrate significant strength when fixing reinforcing bars but poor stability in water-saturated rock formations, showing a gradual decrease in anchor strength of 20% over time and increased toxicity. During the curing process of polyester, significant shrinkage of up to 16% is observed, which must be addressed when setting the parameters of anchorages. The main factors that can limit the use of polyester resins are their high cost, limited availability and toxic properties (Kurta et al., 2004).

The rate of curing of a chemical within a well depends on a variety of factors, including the specific type of chemical used, the concentration of hardener, and the number and size of ampoules. Parameters such as the number, size and technical characteristics of ampoules in the well are selected based on the fastener data sheet. The type of chemical used is perhaps the most fundamental factor, as different resin formulations (such as epoxy, polyester, or vinylester) have inherent curing characteristics. Epoxies typically cure more slowly but provide superior strength and chemical resistance, while polyesters cure rapidly but may offer less long-term durability in challenging environments. Higher hardener concentrations accelerate the polymerisation process, leading to faster curing but potentially generating more heat during exothermic reactions. Multiple smaller ampoules typically ensure a more uniform distribution of the resin mixture compared to fewer larger ones, promoting consistent curing throughout the bond line. Environmental conditions, particularly temperature, significantly impact curing rates. Lower temperatures slow molecular movement and reaction rates, extending curing times significantly. Certain chemical systems are moisture-sensitive and may cure improperly in wet conditions, while others are formulated to tolerate or even utilise moisture in their curing mechanism. Table 1 shows a comparison of the main characteristics of the fixing ampoules.

Tab. 1. Characteristics of ampoules in comparison.

No.	Name of the indicator	Value of the indicator		
		polymer ampoule	cement ampoule	silicate ampoule
1	Ampoule diameter, measured in millimetres	25	25	25
2	Ampoule length, expressed in millimetres	300-350	300-350	300-350
3	Composition of the components contained in the ampoule	Resins based on two polyester components	A mono-component mix containing cement	A mixture of two components to form an inorganic composition
4	Time required to inject the ampoule into the bore, measured in seconds	15	15-25	15
5	Duration of the mixing process, measured in seconds	25	25	10-15
6	The moment of mixing force of the composition, measured in newton metres	160	160	160
7	The time period required for solidification, measured in seconds	60-75	180-300	60
8	Anchor holding force in the borehole in dry rock, measured in kilonewtons	>100	>100	>100
9	Weight measured in kilograms	0.26	0.3	0.3
10	Shelf life in months	6	6	36
11	Storage conditions, °C	up to +18	up to +50	up to +50
12	Toxicity	high	non-toxic	non-toxic
13	Fire hazard	high	low	low
14	Moisture in the borehole	Reduces the anchoring force in the borehole to less than 100 kilotons	The anchors are delivered and compacted one after the other by tamping	Does not affect the fastening force
15	Temperature range for the application, °C	+10÷25	0÷50	-10÷25
16	Permitted clearance between the diameter of the borehole and the diameter of the anchor, expressed in millimetres	8	8	12

Source: compiled by the authors based on Masoule & Ghahremaninezhad (2024).

The current research problem is that the existing methods for calculating the parameters of anchoring and the use of resin products do not consider modern aspects of studying the rock mass's physical and mechanical properties and geomechanics. This includes the design of mining development schemes, including the dynamics of the moving front of the mining operations, the use of layer technology when working with thick seams, and the development of technological schemes for maintaining workings. Particular attention should be devoted to areas of geological disturbance (Prakash & Bharati, 2022).

It is increasingly necessary to develop technologies based on digital modelling of the stress-strain state of the rock massif and strategies for strengthening the contours of mine workings. To reduce costs, reduce complexity and improve the safety of mining operations when crossing geological faults, it is necessary to develop and improve the most efficient technological scheme for securing the workings in the zone of interaction with tectonic faults (Deryaev, 2024a). This scheme involves the use of preventive measures to strengthen the unstable rock mass ahead of the mine face of the workings to stabilise it completely (Figure 3).

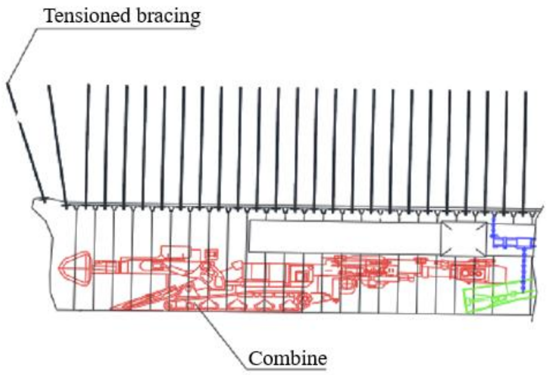


Fig. 3. Technology for preventive advance support of unstable rocks ahead of the mine face of the excavation.
Source: compiled by the authors.

Figure 3 illustrates a preventive technology designed to support unstable rocks ahead of the mine face during excavation. The diagram presents an underground mining setup where a combine (marked in red) is actively engaged in the excavation process. The tensioned bracing system (depicted in the upper part of the figure) is employed to reinforce the unstable rock formations in front of the mining face, ensuring stability and minimising the risk of collapse. The combine is a mechanised mining machine responsible for cutting and extracting material, moving forward as excavation progresses. Meanwhile, the tensioned bracing provides structural reinforcement, likely consisting of pre-tensioned support elements that counteract the pressure the surrounding rock layers exert. This technology is crucial for maintaining operational safety and efficiency, as it helps prevent sudden rockfalls and enhances the overall stability of the excavation site. Experiments with rope anchors on industrial benches and their use in real production conditions made it possible to establish the validity of several design parameters of anchor fasteners.

A set of experimental studies was carried out in laboratory conditions to assess the bearing capacity of steel-polymer anchorage with various shapes of steel anchor ends. These tests were carried out on a concrete block with a height and width of 0.2 m and a length of 0.6 m, with a uniaxial compression strength of 37 MPa, which corresponds to the strength of the argillite rock. During the experiments, a hydraulic device (rod puller PK-3) was used to pull out the anchors, with the subsequent fixation of indicators on the gauge indicator following the adopted test methodology.

For the research, anchors made of reinforcing steel of class A-II with a tensile strength of 143 kN, 0.4 m long and 0.022 m in diameter, as well as chemical ampoules manufactured by Minova Kazakhstan LLP, were used. The anchor to be tested was inserted into the borehole and placed above the chemical ampoule. One end of the anchor rod had an M22 thread and a length of 0.1 m, while the other end was cut at a 60º angle in the shape of a chisel. When quick-setting compounds were used to fix the anchor in a borehole where the length of the fill was 0.3 m and the borehole was 0.4 m long and 0.28 m in diameter, the anchor was 0.22 m long. The strength of the anchor with a chisel-shaped end was 15 tonnes, which is different from the anchor with a 45° cut-off end and a load of 13 tonnes. The load-bearing capacity of the steel-polymer anchor was increased by 1.1-1.15 times due to more uniform mixing of the fixing compound in the borehole.

Practical tests of rope anchors were carried out to secure ventilation drift with an assembly chamber in the Abayskaya mine in the Karaganda coal basin (Nurgaliev et al., 2013). Anchor pull-out tests were carried out on a short section of the set-up to evaluate the performance of the anchor-resin-array system in the mine and to test the load-bearing capacity of the system. The experiments were organised with sufficient precision to reproduce the processes used to install these types of fasteners, including operations, materials and equipment.

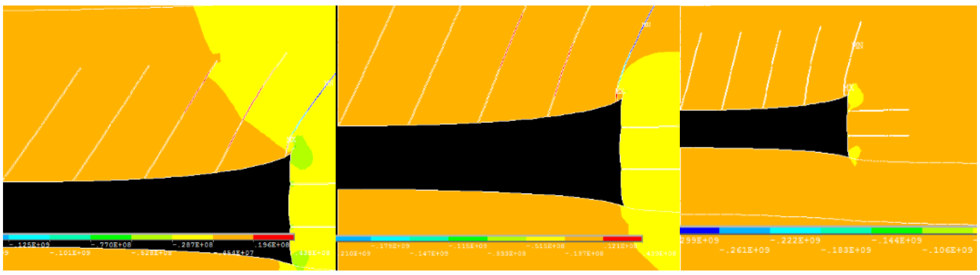
The load-bearing capacity of the used anchor rods was assessed during the excavation process using a PK3 rod puller. The bearing capacity of anchors in active mine workings was tested by loading up to 0.6 of the estimated bearing capacity of the anchor in kilonewtons (Peter et al., 2021). Two rope anchors were installed to test the strength of the anchors in the borehole in these geological conditions. They were subjected to strength tests using the PK-3 rod puller until the maximum design load per anchor was reached, with subsequent recording of its pliability or sliding. If the load was less than 186 kN, the tests were repeated on 2-3 control anchors. If the actual anchoring strength of the rod in the borehole during repeated tests was lower than the calculated one and the deviation did not exceed 10%, adjustments were made to the anchor installation density following the anchorage data sheet.

A load of 26 tonnes (60 bar) was applied to the rope anchor during the withstand test using the PK-3. However, there was no pulling or displacement of the rope anchor. During the pilot tests, the mine used the AK 19/5 type rope anchors developed by Abylkas Saginov Karaganda Technical University. In this case, anchorages were used as reinforcement for dismantling a mechanised cleaning complex on the stopping line of the 332K12 longwall at the 332K12 conveyor drift of the Abayskaya mine in the Karaganda coal basin (Giresini et al., 2020).

Pilot tests of rope anchors AK 19/5, which are characterised by a rope diameter of 19 mm and a length of 5 m, together with a guide tube 1.5 m long and an outer diameter of 22 mm, as well as injection anchors AK18N, were carried out to strengthen the 332K12 conveyor drift, which has a width of 4.5 to 5.2 m and a height of 3.0 to 3.2 m. This drift was supported by a combined support consisting of SVP 27 metal arch support with arches every 0.75 m and 9 steel-polymer anchors. The experiment was conducted on the section from picket PK17+3.5 to PK18+4 m. The boreholes were drilled with an SBR drilling rig at an angle of 10-15 degrees to the vertical plane at intervals of 1.5 m towards the ventilation shaft.

The proposed technology for securing the mine face includes the following steps. The AK 19/5 rope anchor, which is fixed by the ampoule method, consists of a reinforcing rope, a guide tube, a support coupling, a spiral, a wedge and a nut. The chemical ampoules (2-3 pcs, each 600 mm long) are fed into the borehole sequentially through the top-up tubes equipped with fallout prevention devices (e.g. parachute) and delivered to the bottom of the borehole employing a top-up tube. To reinforce the sidewalls and roof of the working mine face (or chamber), 1.5 to 3.0 m long holes are drilled (the width of the crack formation zone), into which AK18N injection anchors with a sealing system are installed. A bonding solution is pumped through these anchors under a 7-8 MPa pressure. The injection process continues until the mud appears in the cracks adjacent to the borehole, and the pressure in the pumping system increases sharply. If the pressure drops, the solution injection resumes.

To improve the technology for determining the parameters of the advance support, geomechanical studies were carried out to find out how the angle of the anchor support affects the weakening conditions of the disturbed rock mass. The problem was solved using modelling and the Ansys software package. Variations in pitch angle, anchor pier spacing, and the condition of the disturbed roof rocks (within the geological fault) were varied to find out the relationships for different levels of roof rock strength. Figures 4 and 5 show the results obtained for rocks with a uniaxial compression strength of R_c = 15 MPa.



a) b) c)

Fig. 4. Stress state evolution in the rock formations surrounding the workings with vulnerable roof rocks having compressive strength Rc=15 MPa: a) α=55°, b) α=65°, c) α=75°.
Source: compiled by the authors.

The relations for deformed rocks with uniaxial compression strength (R_c = 15 MPa) are presented in the following expression (1). The coefficients in the expression are defined as follows:

$$k_0(h) = 8.494 \times 10^{-3} \times e^{-2.25 \times h},$$

$$k_1(h) = -1.474 \times e^{-2.158 \times h},$$

$$k_2(h) = 74.784 \times e^{-2.017 \times h},$$

$$k_3(h) = -1.377 \times 10^{-3} \times e^{-2.263 \times h}.$$

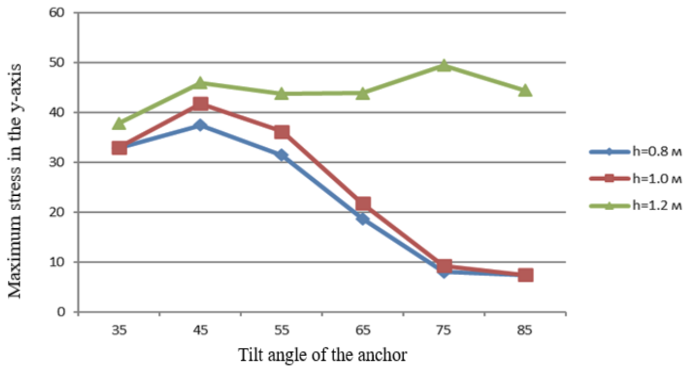
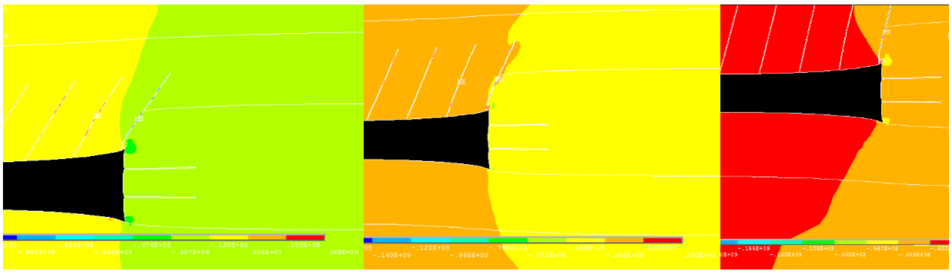


Fig. 5. Stress states of the rocks surrounding the workings with vulnerable roof rocks having a compressive strength of Rc = 15 MPa vary depending on the anchor installation spacing.
Source: compiled by the authors.

Figures 6 and 7 show the results for rocks with R_c = 25 MPa.



a) b) c)
Fig. 6. Change in the stress state of rocks surrounding the excavations with disturbed roof with compressive strength Rc=25 MPa: a) α=55°, b) α=65°, c) α=75°.
Source: compiled by the authors.

Ratios for vulnerable rocks with uniaxial compressive strength R_c = 25 MPa are presented in expression (2). The coefficients:

$$k_0(h) = 2.528 \times 10^{-3} \times h - 1.72 \times 10^{-3},$$

$$k_1(h) = -0.403 \times h0.157,$$

$$k_2(h) = 20.472 \times h - 5.693,$$

$$k_3(h) = -333.322 \times h + 89.935.$$

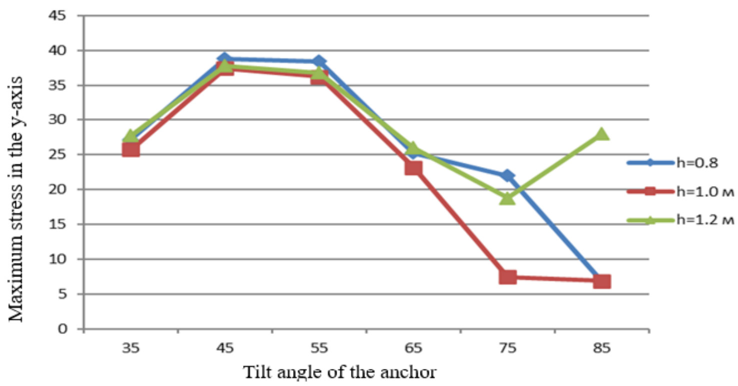
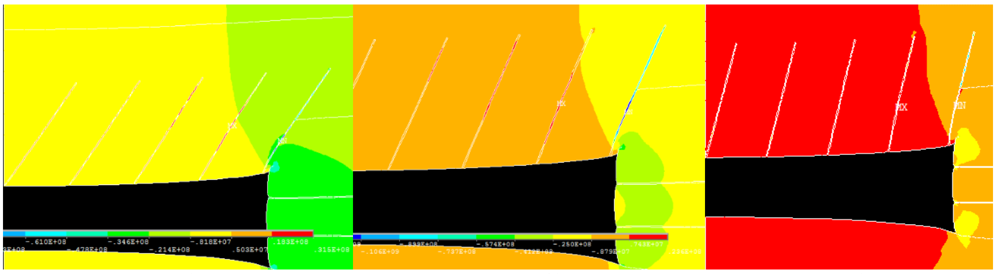


Fig. 7. Changes in stresses in the rocks surrounding the excavations with vulnerable roof rocks characterised by compressive strength Rc=25 MPa, depending on the anchor spacing and installation angle.
Source: compiled by the authors.

Figures 8 and 9 show the results for rocks with R_c = 35 MPa.



a) *b)* *c)*

Fig. 8. Evolution of the stress state in rock formations surrounding excavations with disturbed roof, having compressive strength Rc=37 MPa: a) α=55°, b) α=65°, c) α=75°.
Source: compiled by the authors.

Ratios for roof rocks with disturbed uniaxial compressive strength (R_c = 37 MPa) are presented in expression (3). The coefficients:

$$k_0(h) = 3.864 \times 10^{-3} \times h - 3.426 \times 10^{-3},$$

$$k_1(h) = -0.622 \times h + 0.508,$$

$$k_2(h) = 30.447 \times h - 24.824,$$

$$k_3(h) = -496.795 \times h + 340.248.$$

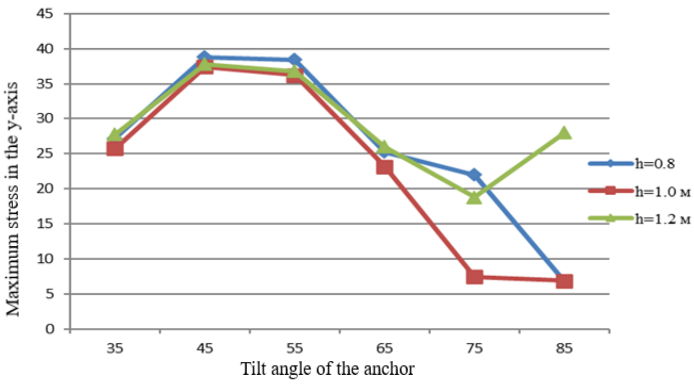


Fig. 9. Diagram illustrating the correlation between the stress state of the rocks surrounding the excavations with vulnerable roof rocks with compressive strength Rc=37 MPa and the angle and spacing of anchor installation.
Source: compiled by the authors.

Within the framework of this project, a set of pilot models of rope anchoring systems designed to secure mine workings was manufactured and tested. In addition, bench tests were carried out on steel anchor end elements. In addition, rope anchors were tested and introduced in industrial conditions to secure the junction of a conveyor drift with a ventilation slope at the K10 seam of the Abayskaya mine in the Karaganda coal basin. Comparative tests of the AMB anchor with various forms of end caps were carried out, and advanced designs of contour support systems for mine workings were created, including a steel-polymer composite anchor with a uniform mixing element, a metal-rope anchor, a steel-polymer composite anchor, a rope anchor with slots and screw holes. A set of pilot equipment was also prepared to strengthen the rocks surrounding artificial underground cavities in the earth's crust. The technical parameters of this equipment have been certified (certificate of compliance with safety requirements) and subsequently implemented in industrial conditions.

The analysis of the results of previous numerical modelling studies has made it possible to establish empirical laws for the fastening of unstable roof rocks. For medium-stable and unstable rocks, a leading anchorage is recommended. The design length of contour anchors within the roof and sides of excavations (L_{ak}), their overlap with neighbouring rows of installed anchors (0.3 L_o), as well as the angle of their inclination relative to the axis of the working plane should be within 10-15 degrees (4):

$$L_{ak} = L_y + L_y/fp\ cos\ \varphi, \text{ m}, \tag{4}$$

where L_y is the potential depth of mine face extraction through the roof (without anchoring), *fp* is the strength factor according to the scale of Prof. Protodyakonova, and φ is the angle of internal friction of rocks. The design length of contour anchors (L_{ak}) ensures that the anchorage extends sufficiently into stable rock layers, reducing the likelihood of displacement or failure in weakened zones. The overlap between neighbouring anchors (0.3 L_o) enhances the overall cohesion of the support system, creating a continuous reinforcement network that prevents localised collapses. The recommended inclination angle of 10-15 degrees is critical because it aligns the anchors with the principal stress direction, maximising their load-bearing efficiency and preventing excessive shear forces that could compromise the anchor's integrity. This inclination also facilitates better interaction between the support elements and the rock mass, improving load transfer and ensuring a more uniform stress distribution across the excavation perimeter.

Based on the research, a fixing scheme was developed using articulated anchors, which increased the bearing capacity of the fixing system. The technology of installing a reinforced system in a well on the production circuit to ensure stability is described in a patent, where a special device is used to prevent the formation of domes. This device for securing mine contours in unstable rock is an anchor consisting of a plastic rod on one side of the borehole and a metal rod on the other, connected by a coupling.

The development of a standardised protocol for the application of preventive anchoring technologies in real-world mining operations is essential to ensure the safety and stability of underground excavations (Florez-Salas et al., 2023). The protocol should include guidelines for assessing the geomechanical conditions of the rock mass, selecting appropriate anchoring systems, and implementing reinforcement strategies ahead of the mine face. Pilot tests, such as those conducted in the Abayskaya mine, provide valuable data on the effectiveness of different anchoring methods under various geological conditions, including rope anchors and steel-polymer systems. Additionally, numerical modelling using Ansys and empirical formulas should be integrated into the protocol to optimise anchor placement, spacing, and inclination angles to minimise stress concentrations and rock fracturing. By formalising these procedures, mining operations can achieve greater efficiency, reduce the risk of collapses, and improve the overall sustainability of resource extraction activities.

Implementation of these advanced anchoring technologies can significantly reduce the surface disruption typically associated with traditional mining methods by allowing for more stable underground excavations. The preventive support techniques described in the research minimise the need for excessive material consumption, particularly metals, which contributes to the conservation of natural resources and reduces the carbon footprint of mining operations. Additionally, the development of non-toxic silicate and cement-based anchoring alternatives, as specified in Table 1, presents environmentally preferable options compared to the highly toxic polymer-based compounds that can potentially contaminate groundwater systems. Proper application of these technologies ultimately leads to more efficient resource extraction with reduced waste production while simultaneously enhancing both operational safety and the long-term environmental sustainability of mining activities.

Discussion

Crossing tectonic faults during preparatory mine workings is a significant engineering challenge that requires in-depth analysis and justification of technological parameters. Tectonic faults, characterised by changes in the structure and mechanical properties of rocks, can significantly affect the stability of workings, increasing the risk of cave-in and collapse. This was also investigated by Xin et al. (2023), where the results confirmed that the analysis and feasibility study of the intersection of tectonic faults in preparatory workings are important aspects of mining design and execution. This requires a proper analysis of rock geology and mechanics, as well as the use of modern analysis and modelling techniques. Tectonic disturbances can create instability and cause changes in rocks, requiring a special approach and the use of specialised equipment. Pan & Wang (2023) also studied that the impact of tectonic faults on the stability of mine workings is a serious problem. Risk assessment involves analysing geological data and identifying faults. Preventive measures are developed, such as strengthening workings and monitoring rock masses. This approach helps ensure the safety and efficiency of mining operations. It is worth noting that it is necessary to develop strategies to overcome these difficulties arising from tectonic disturbances. This includes the use of new technologies, specialised methods, and additional safety measures to minimise risks and ensure successful mining operations in the mine in the face of such disturbances.

One of the key aspects of the study was the mathematical modelling of the SSS of the rock mass at the intersection of tectonic faults. The use of such models determined the stresses, reactions and internal forces in the rocks surrounding the workings, which is critical for selecting the optimal support and stabilisation parameters. Aitkazinova et al. (2022) emphasise that mathematical modelling of the stress-strain state at the intersection of tectonic faults is relevant for studying the impact of tectonic processes on the stability of mine workings. This approach allows scientists to anticipate the risks of cave-ins and develop safety measures, optimising the design and operation of mine workings. Kang et al. concluded (2021) that the optimisation of support parameters when crossing tectonic faults plays a crucial role in ensuring the safety and stability of mine workings. This process involves the analysis of geological data and mathematical modelling results to determine the optimal support parameters, such as the type of anchors, their depth and location, and the characteristics of the materials used. Properly selected support parameters help minimise the risk of cave-ins and increase the efficiency of mining operations. These results confirm the above study because such risk analysis and the development of appropriate preventive measures ensure the safety of workers and the efficiency of mining operations in general. Striving for a deeper understanding of the impact of tectonic faults and using mathematical modelling helps reduce the likelihood of accidents and optimise the processes of preparing and operating mine workings.

Bench and mine tests of anchoring systems using fast-hardening mixtures have demonstrated their effectiveness in conditions of varying degrees of rock disturbance. Tests have shown that using a combined support scheme, including contour steel-polymer anchors, significantly increases rock stability and reduces the risk of disintegration when sinking through geological fault zones. Wang et al. (2023) studied this phenomenon, noting that the effectiveness of anchoring systems based on quick-hardening mixtures is important for ensuring the safety of mine workings. They are designed to hold rocks and prevent cave-ins in areas of rock fractures. The use of fast-setting mixtures allows for reliable anchoring in a short time. Thanks to the fast curing of the mixtures, the installation and fixing of anchors is accelerated, saving time and increasing workers' safety. Zhang et al. (2023) also investigated how the use of combined support schemes can increase the stability of rocks under geological disturbances. These schemes include various types of anchors and fasteners, ensuring an even distribution of loads. The use of quick-hardening mixtures and special geometric shapes of the support elements improves the efficiency of the installation and protection of workings from cave-ins (Babachenko et al. 2022a; 2022b). In general, the research results emphasise the importance of optimising the support parameters when crossing tectonic faults. This allows for an increase in the stability of workings and a reduction in the likelihood of emergencies, ensuring safer working conditions at mining enterprises.

Geomechanical modelling was also used to assess the dynamics of changes in the stress state of the rocks at different anchor angles and spacing. It was found that the optimal combination of these parameters allows the creation of a monolithic slab capable of effectively resisting loads and stabilising the near-contour rocks. Jiang et al. (2024) found that optimised modelling addresses many factors, including the geometry of the workings, rock properties, anchor characteristics and loading conditions. This helps to perform more accurate calculations of the stress-strain state and evaluate the effectiveness of different anchoring schemes. Xu & Huang (2021) also showed that anchor placement parameters, such as inclination angle, pitch and depth of installation, significantly impact rock stability and mine workings reliability. Their optimisation requires consideration of rock characteristics and field conditions to ensure effective anchoring. Comparing the data obtained during the research, it is possible to conclude that the optimal combination of anchor angle and spacing plays a key role in the formation of a stable and durable support system in mine workings. The analysis of the modelling results can be used to identify the optimal parameters of anchor placement that contribute to the formation of a monolithic slab and effective stabilisation of the near-contour rocks.

A study conducted at the Abayskaya mine in the Karaganda coal basin confirmed the practical value of the developed technologies. Tests of rope anchors in industrial conditions have shown that such a support system can be successfully used to ensure the safety and stability of workings when crossing tectonic faults. Wang et al. (2022) also concluded that the practical effectiveness of rope anchors in mine workings is associated with ensuring the safety of the working environment and reducing the risk of rock caving. Economic feasibility also plays an important role, including the cost of installation and maintenance, as well as the cost of subsequent mine repairs. Risk management, including accident probability analysis and rapid response, is also important in assessing practical effectiveness. Moreover, Wang et al. (2024) found that the use of rope anchors plays a key role in ensuring the safety and stability of mine workings. They help to hold rocks and prevent cave-ins, which significantly reduces the risk to workers in the mine. In addition, rope anchors help increase the stability of workings when crossing tectonic faults, an important aspect of underground mining (2023). Their use makes it possible to create a reliable support system capable of withstanding dynamic loads and ensuring the durability of mine workings. When analysing the results of the study, it becomes clear that the developed support technologies using rope anchors have significant potential to ensure the safety and stability of mine workings in conditions of tectonic disturbances. Industrial tests at the Abayskaya mine have confirmed their practical value and efficiency. It is important to note that these technologies can be successfully used not only to prevent emergencies but also to optimise mining processes, increase productivity and reduce operating costs.

Thus, the results of the study contribute to the development and implementation of advanced technological schemes for mining operations that address the specific conditions of geological disturbances. These schemes ensure increased rock stability and safety of mining operations, reducing the risks and costs associated with the collapse and destruction of workings.

Conclusions

An advanced technological scheme has been created to eliminate or reduce negative impacts in mines, including the use of various types of resins (polyurethane, silicate and phenolic) to stabilise and strengthen weakened rock masses, especially in cases of layered mining of thick seams, crossing geological faults and areas of previous mining, as well as when working in areas with geological faults and under the influence of increased bearing pressure from leftover cells in neighbouring seams.

New designs of mine support systems and equipment based on modelling and analysis software help to reduce the time and financial costs of mining companies. This is achieved by improving the reliability and efficiency of mining operations and reducing the likelihood of emergencies.

The proposed method of installing anchors in the overburden creates a structure that imitates a bridge, which contributes to the formation of a single integral block that functions as an integrated rock-bolster system. The main influence on the formation of rock deformation zones is exerted by the strength and thickness of the upper rock layer, as well as the type of support used. The analysis of vertical displacements during the support of the workings at different degrees of rock mass disturbance indicates the need to pass the workings through disturbed areas using reinforced leading support to ensure additional rock stability.

However, it is necessary to note that the limitations of this study are the limited availability of data on the actual conditions of application of new technological solutions in various mining conditions and the limited period to assess their long-term effectiveness. Further research should focus on a more in-depth analysis of the impact of innovative technological solutions on the economic efficiency and safety of mine workings in different geological conditions.

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