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Stress-strain state of the near-contour rock mass around a gob-side development roadway in underground coal mining

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Abstract

Purpose. To investigate the stress-strain state of the coal-rock mass surrounding a gob-side development roadway and to justify its support parameters under the mining conditions of the Karaganda Coal Basin.

Methods. The study was based on geomechanical modeling of the coal-rock mass surrounding a roadway driven adjacent to the goaf of a previously extracted longwall panel and separated from it by a limited-width coal pillar. The simulations were performed in ANSYS using the finite element method in 2D. The computational model incorporated the goaf, protective coal pillar, stratified structure of the surrounding rocks, mining depth, physical and mechanical rock properties, loading conditions, and roadway support parameters. The stress-strain state and strength factor were additionally assessed in Rocscience RS2 for a ventilation roadway driven along the boundary of the goaf.

Findings. The width and strength of the coal pillar were found to affect stress redistribution around the gob-side roadway significantly. A limited-width pillar shifted the peak maximum stress 5-10 m deeper into the intact coal mass and reduced its magnitude by approximately 1.6 times compared with the pillarless configuration. Stresses directly above the roadway decreased by a factor of 1.2-1.3. Increasing the pillar strength or its width to 20 m reduced the maximum stresses in the rock mass by almost twofold. The RS2 simulations showed that increasing the mining depth from 450 to 700 m increased the maximum principal stresses by a factor of 1.7-1.9 and the roadway contour displacements by a factor of 1.2-1.35.

Originality. Relationships governing stress redistribution and the formation of reduced-stability zones around gob-side development roadways were established as functions of coal pillar parameters, mining depth, and roadway support conditions.

Practical implications. The results provide a geomechanical basis for selecting support schemes for gob-side roadways located within zones of elevated rock pressure.

Keywords: *mine roadway; coal pillar; stress-strain state; rock pressure; finite element method; rock-bolt support; yielding steel arch support; Karaganda Coal Basin*

1. Introduction

A key objective in underground mining is to maintain the stability of development workings at minimum cost by selecting their rational location and appropriate support systems [1], [2]. This requires consideration of the mechanisms of rock pressure manifestation, the stability of the surrounding rock mass, and the potential reduction in coal losses and the overall length of mine workings through the application of pillarless roadway protection methods [3]. Attention should also be given to the use of yielding steel arch supports combined with rock bolts, as well as to stand-alone rock-bolting systems [4].

In the context of Kazakhstan's energy transition and the need to improve the efficiency of mineral resource utilization, technological advancements in the mining industry, including underground coal extraction, have become increasingly important [5], [6]. The justification for such solutions should account for technological, lithological, spatial, and environmental factors, as well as the potential application of digital tools, information technologies, and monitoring systems for the analysis of mining operations and facilities [7]-[9].

Related studies have also addressed improvements in mining systems, construction and support materials, equipment, and engineering infrastructure, highlighting the need for an integrated approach to maintaining the stability and safety of underground workings [10]-[14]. The sustainable development of the mining sector, therefore, requires consideration not only of geomechanical conditions but also of associated environmental, organizational, and anthropogenic factors. In particular, studies of mining-induced impacts on water bodies and groundwater flow demonstrate the importance of assessing the environmental consequences of mineral resource development [15], [16]. Furthermore, improvements in mining safety and operational efficiency depend on the development of engineering expertise, the exchange of professional knowledge, and the adoption of interdisciplinary approaches to technical decision-making [17], [18].

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When assessing the stability of mine workings, it is necessary to consider methods for stabilizing and reinforcing the surrounding rocks to prevent the development of adverse rock pressure manifestations. The intensity of these manifestations depends on the physical and mechanical properties of the rocks surrounding the excavation, its depth, the movement of the overlying strata, and the specific geological and mining conditions [19]. Artificial reinforcement of the rock mass and reduction of the rate of convergence of the surrounding rocks into the excavation make it possible not only to limit displacements and control the deformation process, but also to maintain roadway stability throughout its service life while minimizing the need for repair work.

An increase in underground coal production can only be achieved through highly efficient technologies for driving and maintaining the development workings that delineate longwall panels. This is particularly important when mining thick coal seams, where substantial volumes of the overlying rock strata are involved in the displacement process [20].

As mining depth increases, maintaining the stability of excavation boundaries becomes increasingly challenging due to greater structural disturbance of the coal seams and deterioration in the strength properties of the surrounding coal-bearing rock mass. At mines in the Karaganda Coal Basin, development workings are driven and supported using yielding steel arch supports and rock-bolting systems, including single-level, two-level, and combined support arrangements [21]. The selection of an appropriate support type, the application of rock bolts, and the interaction within the support-rock mass system have been investigated in previous studies [22], [23].

Safe mining operations and efficient coal extraction require consideration of the physical, mechanical, and strength properties of the rocks, their degree of fracturing, and the stress state of the rock mass. These parameters enable characterization of deformation within the near-contour zone and the identification of areas of elevated stress concentration that may threaten roadway stability and personnel safety [24]. Consideration of the technological, lithological, and spatial characteristics of coal deposits is also essential for the reliable assessment of geological and mining conditions and for sound engineering decision-making [25]. Various aspects of geomechanical modeling, rock mass stability assessment, support parameter selection, and the influence of mining factors on the stress-strain state of underground workings have been examined in studies [26]-[30].

An analysis of the current condition of development and extraction workings in coal mines shows that, in several cases, the existing support schemes are insufficient to ensure stable roadway contours and safe operation. Particularly difficult conditions arise during the drivage and maintenance of adjacent roadways located near previously mined longwall panels or separated from the goaf by coal pillars of limited width.

During operation, adjacent roadways supported by steel arch sets are exposed to rock pressure generated by a combination of geological and mining factors. The geological factors include rock mass disturbance, changes in seam hypsometry, weakened zones in the surrounding rocks, and variations in seam occurrence parameters. The mining factors include zones of abutment and elevated rock pressure, the position of the roadway relative to the longwall face, and the action of the principal tectonic stresses. As a result, roadway contours become distorted, and support elements are damaged, including roof sagging, deformation and rupture of the crowns of steel arch supports, failure of continuous lagging elements, displacement of yielding joints, floor heave, and sidewall squeezing.

Typical manifestations of contour deformation in adjacent ventilation roadways during longwall panel extraction are shown in Figure 1. Figure 1a shows damage to the crowns of steel arch supports and reinforcement of the roadway contour by suspending a longitudinal SVP steel section with timber repair props installed beneath it. Figure 1b illustrates roof deformation and flattening of the steel arch crowns, indicating a significant impact of roof pressure on the support system. Figure 1c shows the displacement of the yielding joints of the steel arch supports, expressed in their longitudinal shifting and progressive closure along the roadway. Figure 1d presents an example of sidewall squeezing caused by the action of the natural equilibrium roof and side arches.

To prevent such manifestations of the stress-strain state, various methods of reinforcing yielding steel arch supports are used in roadway maintenance practice. In particular, longitudinal SVP27 steel sections, connected along their length by clamps, may be suspended from the crowns of the arch sets and supported by timber props or repair posts. Under more severe conditions, heavier special sections, such as SVP32, may be used, together with single- or three-element UKR-type reinforcing support systems. In ventilation and ,conveyor roadways driven in thick coal seams, where sidewall deformation and floor heave occur, longitudinal steel sections may also be installed along the travelway side. These sections are supported by additional timber repair props while maintaining the required clearance for personnel movement.

Thus, the examples presented in Figure 1 demonstrate that rock pressure causes deformation not only in the roadway roof but also in its sidewalls and disrupts the proper functioning of steel arch support elements. This confirms the need for further justification of the parameters governing the maintenance of gob-side roadways and for the selection of rational support schemes that account for the stress-strain state of the surrounding rock mass.

Accordingly, the development of advanced support systems and the justification of appropriate methods and parameters for roadway maintenance based on rock mass strength properties and fracturing, as well as the magnitudes and orientations of the principal stresses, remain important challenges in underground coal mining [31]. Addressing these challenges requires a comprehensive assessment of the rock mass's geomechanical state and the selection of support schemes that ensure safe roadway operation while minimizing support material consumption and reducing the labor intensity of subsequent maintenance.

Despite the considerable body of research devoted to the stability of development workings and the application of steel arch, rock-bolt, and combined support systems, the patterns of stress redistribution and the formation of inelastic deformation zones around gob-side roadways driven near previously mined longwall panels remain insufficiently understood. Of particular importance is the justification of the protective coal pillar width and support scheme with due consideration of mining depth, the strength properties of the surrounding rocks, and the influence of the adjacent goaf.

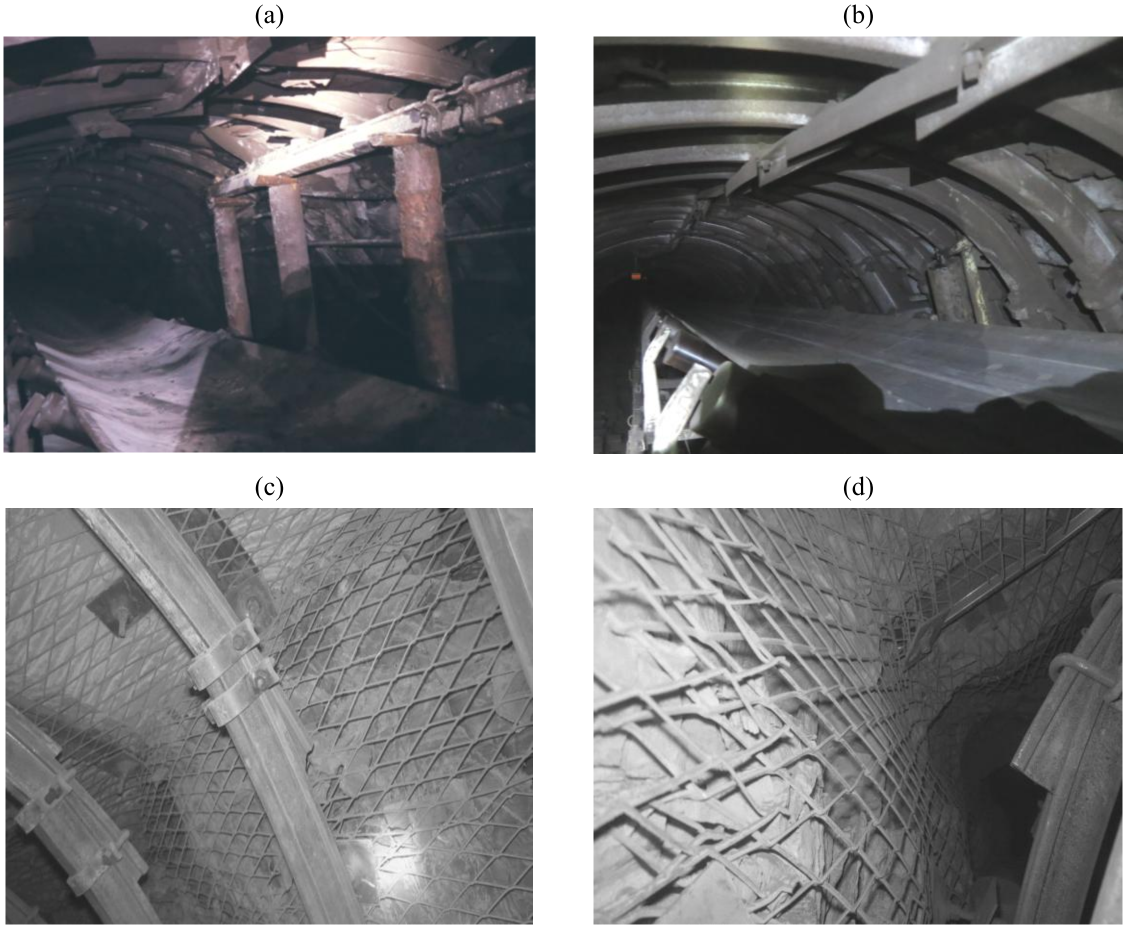


Figure 1. Condition of adjacent ventilation mine workings during longwall panel extraction: (a) deformation of the crowns of steel arch supports, suspension of an SVP steel section, and installation of repair props; (b) roof deformation and flattening of the steel arch crowns; (c) displacement of the yielding joints of the steel arch supports; (d) sidewall squeezing under the action of the natural equilibrium roof and side arches

Against the backdrop of Kazakhstan's expanding mining industry, the improvement and systematization of mining layouts, along with the need to address current energy-related challenges, have heightened the importance of enhancing the safety and operational reliability of underground coal mining [32], [33].

Investigating the stress-strain behavior of the near-contour coal-rock mass surrounding a maintained gob-side roadway, particularly a ventilation roadway, is therefore an important scientific and practical problem for coal mines in the Karaganda Coal Basin.

This study aims to investigate the stress-strain state of the coal-rock mass surrounding a gob-side development roadway and to justify the support parameters for the roadway under the geological and mining conditions of the Karaganda Coal Basin.

To achieve this aim, the following tasks were addressed: to analyse the conditions governing the maintenance of gob-side roadways during longwall panel extraction; to develop a geomechanical model of the rock mass that accounts for the protective coal pillar and adjacent goaf; to determine the distribution of stresses and displacements in the near-contour zone under different geological and mining conditions; to assess the influence of the width and strength properties of the coal pillar on roadway stability; and to justify rational support schemes capable of maintaining the roadway in a serviceable condition throughout its operational life.

2. Materials and methods

The study aimed to identify the patterns governing changes in the stress-strain state of the coal-rock mass surrounding a gob-side development roadway driven adjacent to a previously extracted longwall panel or separated from the goaf by a coal pillar of limited width. The research methodology was based on geomechanical modeling of the rock mass, accounting for geological and mining parameters that influence roadway stability and the intensity of rock pressure manifestations.

The numerical model incorporated the goaf, the protective coal pillar, the stratified structure of the surrounding rocks, mining depth, the physical and mechanical properties of the rock layers, loading conditions, and roadway support parameters. Particular attention was paid to determining the distribution of stresses and displacements within the near-contour zone and to assessing the influence of coal pillar width on the stress-strain state of the surrounding rock mass and the resulting rock pressure acting on the roadway.

The excavation of a mine roadway creates an artificial opening that disturbs the rock mass's initial equilibrium and redistributes stresses within the surrounding rock. Stress concentrations near the roadway boundary are considerably higher than those in the undisturbed rock mass farther from the excavation. These elevated stresses promote the formation of an inelastic deformation zone characterized by fracturing, bedding separation, and local loss of rock mass continuity. The extent and structure of the elastic and inelastic zones depend on mining depth, the physical, mechanical, and technological properties of the rocks, roadway dimensions, the type and mechanical characteristics of the support system, and the dip angle of the coal-bearing strata. Disturbance of rock-mass equilibrium during underground mining may intensify deformation processes and generate geodynamic hazards, thereby requiring comprehensive assessment and continuous monitoring [34]-[36].

The wide range of geological and mining conditions under which gob-side roadways are operated, together with the complex interaction within the support-rock mass system, necessitates the use of geomechanical modeling [37]. Accordingly, numerical models were employed to evaluate the stress-strain state of the rock mass surrounding the roadway. These models enabled accounting for the stratified structure of the rock mass, the location of the goaf, the parameters of the protective coal pillar, the applied loading conditions, and the mechanical response of the support system.

The research methodology comprised several consecutive stages: development of the initial geomechanical model; specification of the relevant geological and mining parameters; preparation of computational schemes for different technological scenarios; numerical simulation of the stress-strain state of the rock mass; visualization of the simulation results; and analysis of the stress and displacement distributions within the near-contour zone of the gob-side roadway.

Advances in the digital modeling, monitoring, and visualization of mining systems provide a basis for more accurate assessment of rock mass behavior, improved development of computational models, and better-informed engineering decisions regarding roadway support parameters [38]-[43].

Geomechanical modeling was performed in ANSYS using the finite element method in a two-dimensional formulation. The finite element approach enabled the coal-rock mass to be represented as a computational domain subdivided into discrete elements. It allowed the redistribution of stresses and deformations around the roadway to be determined while accounting for the effects of the adjacent goaf, the protective coal pillar, and the stratified rock structure. For the problem considered, the following system of algebraic equations was solved:

$$[k]\{U\} = \{f\}, \quad (1)$$

where:

$[k]$ – global stiffness matrix;

$\{U\}$ – vector of nodal displacements;

$\{f\}$ – vector of external nodal forces.

The element stiffness matrix and the corresponding load vector were determined from the mechanical properties of the material, the shape functions, and the applied body and surface loads:

$$[k] = \int_V [B]^T [D][B]\,dV;$$

$$\{f\} = -\int_V [N]^T \begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} dV - \quad (2)$$

$$-\int_V [B]^T [D]\{\varepsilon_0\}\,dV - \int_S [N]^T \begin{Bmatrix} p_x \\ p_y \\ p_z \end{Bmatrix} dS - |P|,$$

where:

$[B]$ – strain-displacement matrix containing the derivatives of the shape function;

$[D]$ – matrix of the elastic properties of the material;

V – element volume.

$[N]$ – shape-function matrix;

$\begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix}$ – body-force vector, whose components are resolved along the coordinate axes according to the dimensionality of the problem;

P_x, P_x, P_z – surface-traction vector;

$\{\varepsilon_0\}$ – initial strain vector;

$\{P\}$ – element nodal-force vector.

A generalized flowchart of the automated system for analyzing gob-side roadway support parameters is presented in Figure 2.

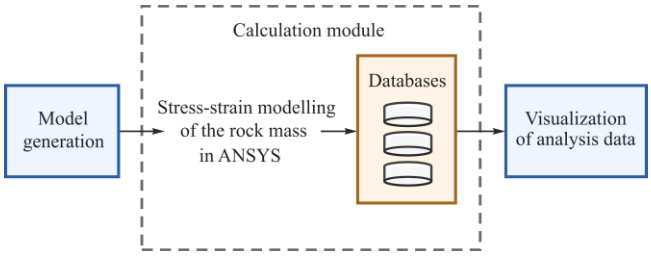


Figure 2. Flowchart of the automated system for analyzing gob-side roadway support parameters

The flowchart comprises three principal stages: model development, simulation of the rock mass's stress-strain state, and visualization and analysis of the numerical results. During the model-development stage, the initial geological and mining data were entered, processed, and converted into a computational scheme suitable for subsequent analysis in ANSYS. A dedicated data-entry software module was used to automate the preparation of the computational models. The interface of this module is shown in Figure 3.

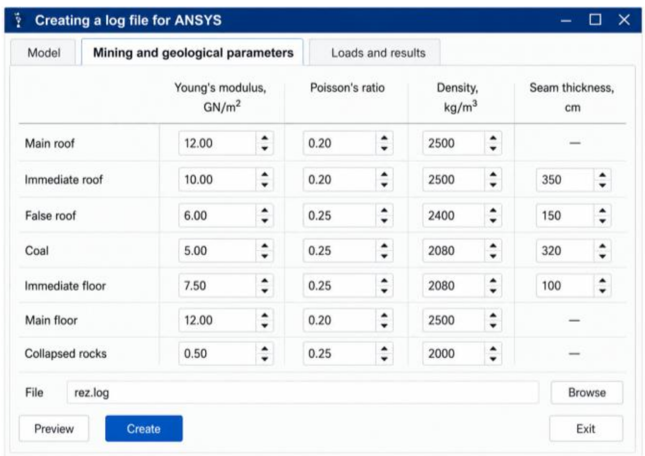


Figure 3. Interface of the data-entry software module

The software module enabled input of the initial parameters required to construct the numerical model, including the roadway depth, the geometry of the computational domain, the location of the goaf, the coal pillar width, the properties of the individual rock layers, loading parameters, and boundary conditions. Based on these input data, an ANSYS command log file containing the computational model definition was generated for subsequent numerical analysis.

The study focused on evaluating the parameters of protective coal pillars and determining their influence on the stress-strain state of the rock mass and the magnitude of rock pressure acting on the underground roadway. For this purpose, several technological scenarios with different coal pillar widths were analyzed under constant geological conditions [44].

The software module allowed multiple command log files to be generated for subsequent processing in ANSYS. Each file contained the input data required to construct a specific computational model, including the geological parameters of the coal seam occurrence; the sequence of rock layers, each defined by its location, dimensions, and physical and mechanical properties; the loads and forces applied to the upper boundary of the computational domain; the support reactions acting along the roadway contour; the model boundary conditions; and additional ANSYS solution parameters specified automatically by the software.

The load applied to the upper boundary of the computational domain was determined from the roadway depth and the average density of the overlying rock strata [45]. A general view of the geomechanical model incorporating the relevant geological and mining conditions is presented in Figure 4.

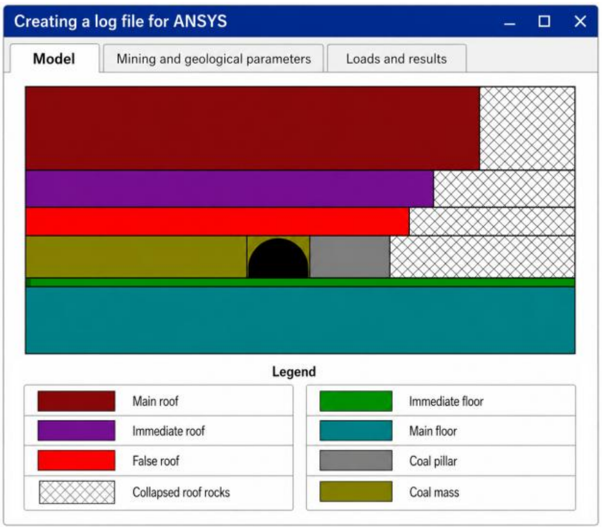


Figure 4. General view of the computational model incorporating the geological and mining conditions

The computational model incorporated the principal lithological components of the coal-rock mass, including the main roof, immediate roof, false roof, coal seam, protective coal pillar, goaf, immediate floor, and main floor. This representation enabled assessment of how the position of the gob-side roadway relative to the goaf and the intact coal mass affected stress redistribution within the near-contour zone.

Following the ANSYS simulations, parameter values were extracted for finite elements located along the plane intersecting the roadway roof. These data were used to establish the variation in stress as a function of the linear coordinate measured relative to the roadway boundary, the edge of the main roof block, and the position of the coal pillar. This approach enabled identification of stress concentration zones, tracing their migration into the intact coal mass, and determining the influence of coal pillar parameters on gob-side roadway stability.

The stress-strain state of the rock mass was additionally evaluated using Rocscience RS2. The simulations were performed for a ventilation roadway driven adjacent to the goaf of a previously extracted longwall panel and supported by a rock-bolting system. Mining depths of 450 and 700 m were considered to assess the influence of depth on the maximum and minimum principal stresses, contour displacements, and strength factor.

The RS2 geomechanical model incorporated the stratified structure of the coal-rock mass, the contour of the gob-side roadway, the adjacent goaf, the protective coal pillar, and the finite element mesh, as shown in Figure 5. This formulation enabled the distributions of principal stresses, displacements, and strength factor within the near-contour zone to be evaluated while accounting for the roadway position relative to the previously extracted longwall panel.

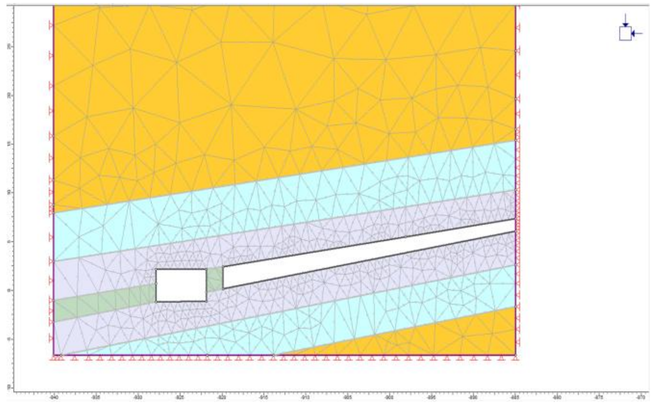


Figure 5. Geomechanical model of the gob-side ventilation roadway developed in Rocscience RS2

The principal output parameters were the distributions of the maximum principal stress σ_1 and the minimum principal stress σ_3; rock displacements along the roadway contour; the locations of stress concentration zones; the extent of inelastic deformation zones; and the strength factor of the rock mass within the near-contour region. These parameters were analyzed to provide a geomechanical basis for selecting rational gob-side roadway maintenance parameters and support schemes that can preserve the roadway in a stable, serviceable condition within zones affected by longwall operations and elevated rock pressure. The developed computational models were subsequently used to determine the stress and displacement fields and identify stress concentration zones around the gob-side roadway. The simulation results and their interpretation are presented in the following section.

3. Results and discussion

3.1. Stress redistribution around the gob-side roadway at different coal pillar widths

The geomechanical simulations provided a load-deformation pattern characterizing rock pressure manifestations along the boundary of the goaf, as manifested in a development roadway. The computational scheme represents the interaction between the stratified coal-rock mass, the goaf, the protective coal pillar, and the roadway support system during stress redistribution around the excavation, as shown in Figure 6.

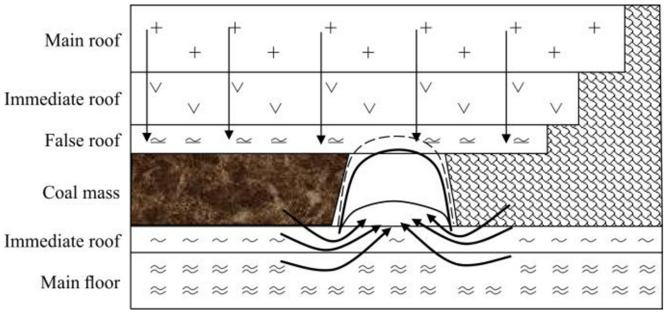


Figure 6. Load-deformation pattern of rock pressure manifestations around the gob-side roadway

As shown in Figure 6, the principal stress redistribution zones develop in the roadway roof and sidewalls, as well as near the interface with the goaf. The presence of the protective coal pillar and the roadway's location along the goaf boundary result in a non-uniform distribution of rock pressure around the roadway contour. The roof and sidewalls are the most vulnerable areas, where inelastic deformation, bedding separation, and local loss of contour stability may occur.

The ANSYS simulations provided the required parameters for the finite elements comprising the computational model. For further analysis, data were extracted from elements located along a horizontal line passing through the roadway roof. These data were used to establish the relationship between stress and the linear coordinate for different coal pillar widths, as presented in Figure 7.

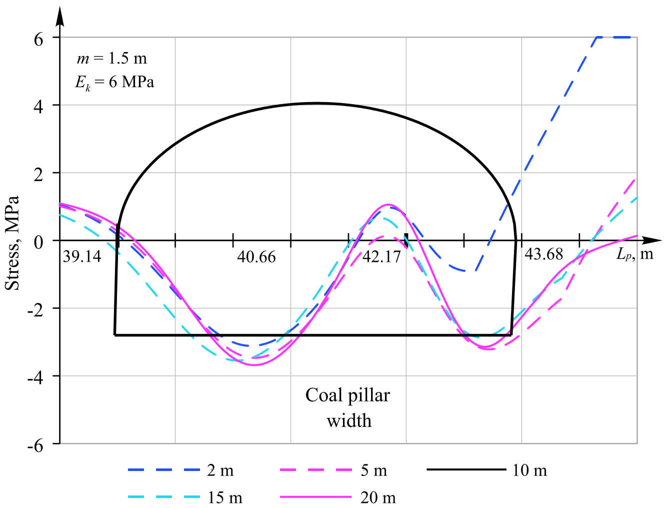


Figure 7. Stress distribution within the near-contour zone of the roadway at different coal pillar widths

Analysis of the obtained relationships shows that the coal pillar width has a pronounced effect on stress redistribution within the near-contour zone of the roadway. As the pillar width changes, the stress concentration zone shifts relative to both the roadway contour and the edge of the main roof block. A coal pillar of limited width shifts the peak stress concentration 5-10 m deeper into the intact coal mass and reduces its magnitude by approximately 1.6 times compared with the pillarless case. At the same time, the stresses directly above the roadway decrease by a factor of 1.2-1.3.

It was established that increasing the strength of the coal pillar, either through its natural properties or additional reinforcement, together with increasing the pillar width to 20 m, reduces the maximum stresses in the rock mass by almost twofold, following an exponential relationship. This indicates that a narrow coal pillar has a beneficial effect on gob-side roadway stability and reduces the intensity of rock pressure manifestations in the near-contour zone.

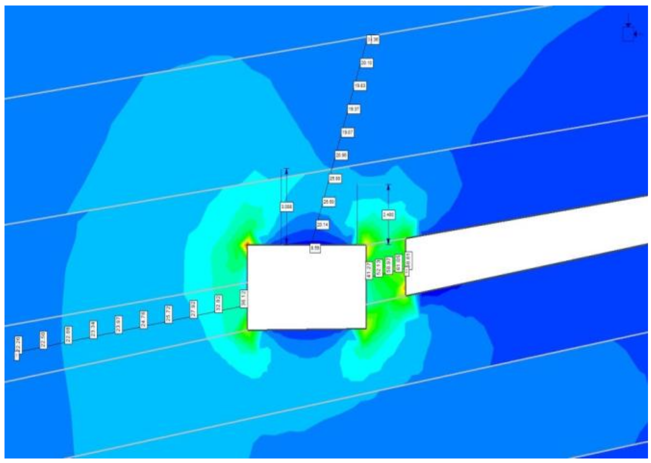
However, increasing the pillar's stiffness and width shifts the stress concentration associated with the edge of the main roof block farther into the caved rock mass while simultaneously increasing its absolute magnitude. Therefore, the selection of coal pillar width should be based not only on reducing stresses directly above the roadway, but also on assessing stress redistribution within the adjacent rock mass and along the interface with the goaf.

3.2. Assessment of the stress-strain state and rock mass strength factor

To further assess the stability of the gob-side ventilation roadway, the stress-strain state of the surrounding rock mass was analyzed using Rocscience RS2. The simulations represented a ventilation roadway driven adjacent to the goaf of a previously extracted longwall panel. The model incorporated a rock-bolt support system and the previously adopted physical and mechanical properties of the surrounding rocks.

Figure 8 presents the distributions of the maximum principal stress (σ_1) and the minimum principal stress (σ_3) at a mining depth of 450 m.

(a)



(b)

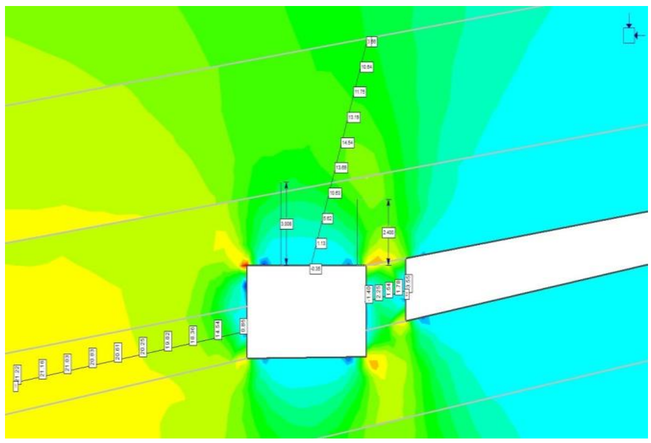


Figure 8. Distribution of principal stresses at a mining depth of 450 m along profiles extending into the roadway sidewalls and roof: (a) maximum principal stress (σ_1); (b) minimum principal stress (σ_3)

Stress variations were analyzed along representative profiles extending from the roadway contour into the roof and sidewalls. This approach enabled the identification of the principal stress concentration zones and the evaluation of how stresses varied with distance from the roadway within the near-contour rock mass.

The simulation results show that the stress field within the zone influenced by the gob-side roadway is highly nonuniform due to the roadway's position relative to the goaf and the intact coal mass. The most pronounced changes in the stress state occur in the roof and sidewalls, where the load is redistributed among the near-contour zone, the protective coal pillar, and the adjacent rock layers. Stresses increase on the side of the intact coal mass, whereas a destressed zone accompanied by local changes in the stress field develops towards the goaf.

As the mining depth increases from 450 to 700 m, the maximum principal stress (σ_1) increases by a factor of 1.7-1.9, while roadway contour displacements increase by a factor of 1.2-1.35. These results demonstrate the substantial influence of mining depth on gob-side roadway stability and confirm that the depth factor must be considered when selecting support parameters.

Analysis of stress distributions along profiles extending from the roadway contour shows that the maximum principal stress (σ_1) varies nonuniformly within the roof and side rocks. Stress increases in the roof and in the intact coal mass on the longwall panel side, indicating the formation of stress concentration zones. By contrast, stresses decrease on the side of the previously extracted panel because of the unloading effect of the goaf and the resulting redistribution of loads within the adjacent rock mass.

Figure 9 presents the strength factor distribution obtained from the RS2 simulation. This parameter was used to assess the stability of the near-contour rock mass and to identify areas susceptible to inelastic deformation and local instability.

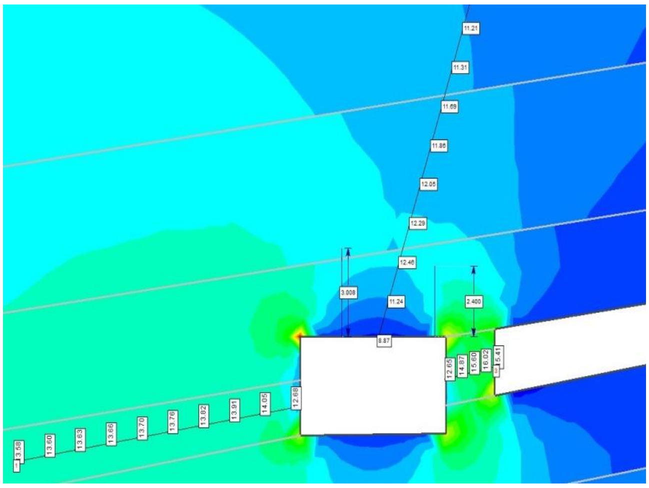


Figure 9. Strength factor distribution within the near-contour zone of the gob-side roadway at a mining depth of 450 m

The results show that when low-strength rocks, particularly argillite, occur in the immediate roof, zones with reduced strength factors develop around the roadway. These zones represent potentially unstable areas of the rock mass in which fracturing, bedding separation, and local roof falls may occur. The most critical areas are the roof and the roof-to-sidewall junctions, where elevated stresses and displacements coincide with reduced strength factors.

At a mining depth of 450 m, the variations in stress and rock displacement can be approximated by the following relationships:

$$\sigma(h) = 13.033 + e^{-0.268h+2.175};\qquad(3)$$

$$u(h) = -1.4 \cdot h + 9.75,\qquad(4)$$

where:

$\sigma(h)$ – stress, MPa;

$u(h)$ – rock displacement, mm;

h – partial coordinate defining the position of the analyzed point within the numerical model or its distance from the roadway contour along the selected profile.

Thus, the RS2 simulation results confirm that the stability of a gob-side roadway is governed not only by the magnitude of the acting stresses but also by the spatial distribution of the strength factor within the near-contour rock mass. As mining depth increases, rock pressure manifestations become more intense, requiring reinforced or combined support schemes that ensure the coordinated interaction of rock bolts, yielding steel arch supports, and the surrounding rock mass.

The identified patterns demonstrate that the maximum and minimum principal stresses, roadway contour displacements, and strength factor should all be considered when selecting gob-side roadway maintenance parameters. This integrated approach provides a more reliable assessment of roadway stability within the zone affected by longwall mining. It enables support parameters to be refined based on the actual stress-strain state of the surrounding rock mass.

3.3. Recommendations for selecting roadway support systems

Based on geomechanical modeling results and analyses of rock pressure manifestations, recommendations were developed for selecting appropriate support systems for gob-side roadways. The support scheme should be selected with consideration of the intensity of rock pressure manifestations, the roadway position relative to the advancing longwall face, mining depth, the strength properties of the roof and floor rocks, and the stability of the near-contour rock mass. This approach enables support parameters to be adapted to specific geomechanical conditions and improves the reliability of roadway stability assessment under varying levels of mining-induced loading.

The roadway maintenance conditions were evaluated using the support difficulty coefficient:

$$K_m = H / R_c,\qquad(5)$$

where:

H – roadway depth, m;

R_c – average design compressive strength of the roof rocks, MPa.

An integrated approach to selecting roadway support technology according to the intensity of rock pressure manifestations is presented in Figure 10. Under pillarless mining conditions and at $K_p < 13$, roadway stability may be maintained using the primary yielding steel arch support with a load-bearing capacity of $N_c = 290$ kN [46], [47]. As the support difficulty coefficient increases and the influence of longwall operations becomes more pronounced, combined support schemes are required.

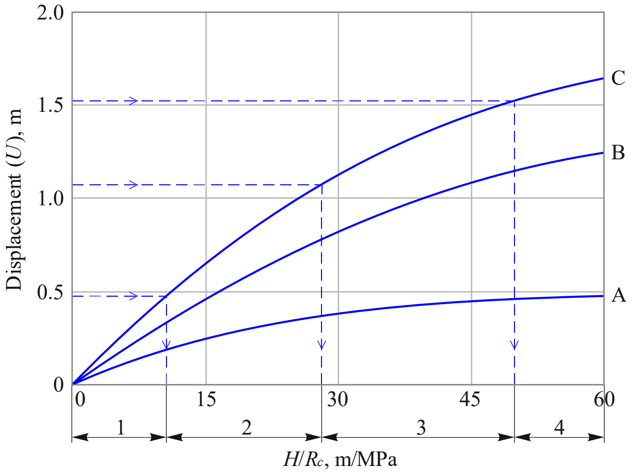


Figure 10. Geomechanical framework for selecting roadway support systems according to the intensity of rock pressure manifestations: A and B – roadway location outside and within the zone affected by longwall operations ahead of the face, respectively; C – influence of longwall operations behind the face; 1 – yielding steel arch support; 2 – combined yielding steel arch and rock-bolt support; 3 – yielding steel arch support, rock-bolt support, and supplementary reinforcement; 4 – yielding steel arch support, supplementary reinforcement, and yielding rock-bolt support

Analysis of Figure 10 shows that a yielding steel arch support is a rational solution under conditions of minor rock pressure. When the roadway enters the zone affected by longwall operations ahead of the face, a combination of yielding steel arch and rock-bolt support should be used. Under elevated rock pressure, particularly when the roadway is located behind the advancing longwall face, reinforced combined support systems are required. Such systems may include yielding steel arch supports, rock bolts, supplementary reinforcement, and yielding support elements.

The support method was also selected using a design chart that accounts for the roadway dimensions, the geometry of its arched roof, and the properties of the surrounding rock mass. The recommended application ranges for different support systems are presented in Figure 11.

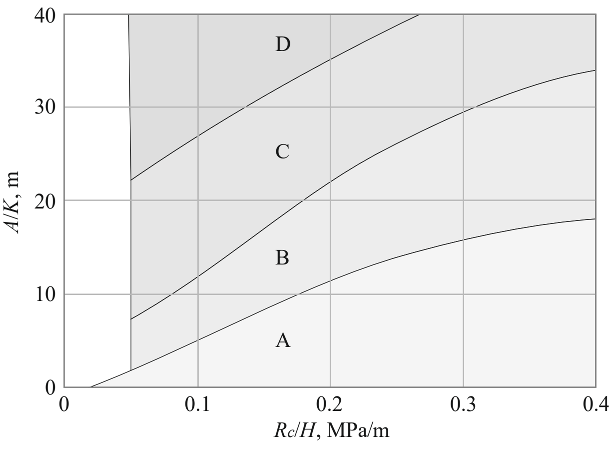


Figure 11. Selection of the roadway support method: A – rock-bolt support; B – two-level rock-bolt support; C – combined rock-bolt and yielding steel arch support; D – rock-bolt and yielding steel arch support supplemented by reinforcing support within the zone affected by longwall operations

The chart is applicable under the following boundary conditions:

$$\begin{cases} 1 \le h/A \le 2.5 \\ 0.5 \le r/A \le 0.75 \end{cases}, \qquad (6)$$

where:

h – rise of the roadway arch, m;

r – radius of the roadway arch, m;

A – roadway height, m.

The design chart accounts for the roadway dimensions, the coefficient (*K*), which depends on the functional purpose of the roadway, the mining depth (*H*), and the design compressive strength of the roof rocks (R_c). A value of ($K = 5.0$) is adopted for extraction workings, ($K = 4.0$) for development workings, and ($K = 1.4$-1.6) for permanent mine workings [48]-[50]. The appropriate application range for single-level rock-bolt, two-level rock-bolt, combined, or reinforced combined support is determined from the corresponding combination of these parameters.

The practical implementation of combined steel arch and rock-bolt support should ensure coordinated interaction between the profiled steel arch sets, resin-grouted steel roof bolts, and sidewall bolts. As the heading advances, the steel arch sets and roof bolts are installed in a staggered sequence. Additional intermediate resin-grouted steel bolts are installed in the sidewalls between adjacent steel arches within the plane of the coal seam. A higher bolt density is recommended on the up-dip side of the seam, with at least three bolts per linear meter, whereas a lower density of at least two bolts per linear meter may be adopted on the down-dip side. This approach was applied and further developed in Patent for Invention of the Republic of Kazakhstan No. 37901 *“Method for Conducting Development Workings in a Highly Gassy Coal Seam”* [51].

Thus, the support system should be selected using a differentiated approach that accounts for the calculated support difficulty coefficient, the roadway position relative to the longwall face, roadway geometry, and the pattern of stress redistribution within the near-contour rock mass. This approach reduces roadway contour deformation, improves roof and sidewall stability, and decreases the amount of repair and rehabilitation work required during the operation of gob-side roadways.

4. Conclusions

Geomechanical modeling was conducted to investigate the stress-strain state of the coal-rock mass surrounding a gob-side development roadway located near a previously extracted longwall panel. The results demonstrated that the roadway position relative to the goaf and the parameters of the protective coal pillar significantly affect stress redistribution, the formation of rock pressure concentration zones, and the stability of the near-contour rock mass.

The ANSYS simulation results revealed the influence of coal pillar width on the stress state of the surrounding rock mass. A limited-width coal pillar was found to shift the peak maximum stress 5-10 m deeper into the intact coal mass and reduce its magnitude by approximately 1.6 times compared with the pillarless configuration. At the same time, the stresses directly above the roadway decreased by a factor of 1.2-1.3.

Increasing the strength of the coal pillar, including through additional reinforcement, and increasing its width to 20 m reduced the maximum stresses in the rock mass by almost twofold. However, increasing pillar stiffness and width also shifted the concentration of edge stresses in the main roof farther into the caved rock mass. This effect should therefore be considered when selecting roadway protection parameters.

Additional modeling in Rocscience RS2 enabled assessment of the stress-strain state of the gob-side ventilation roadway while accounting for the strength of the surrounding rock mass. An increase in mining depth from 450 to 700 m resulted in a 1.7-1.9-fold increase in the maximum principal stress and a 1.2-1.35-fold increase in roadway contour displacements. Zones with reduced strength factors were concentrated mainly in the roof and at the roof-to-sidewall junctions.

The established relationships provide a basis for the differentiated selection of gob-side roadway support systems according to the support difficulty coefficient, coal pillar width and strength, mining depth, roadway position relative to the longwall face, and the pattern of stress redistribution in the surrounding rock mass. To maintain roadways in a stable and serviceable condition, combined support systems incorporating yielding steel arches, rock bolts, and supplementary reinforcement are recommended in zones of elevated rock pressure.

Author contributions

Formal analysis: KA; Investigation: TD, DS; Methodology: EK, GS; Project administration: AZ; Supervision: EK; Validation: EK, AZ; Visualization: TD; Writing – original draft: EK, AZ, TD, DS, GS, KA; Writing – review & editing: EK, AZ. 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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Дослідження напружено-деформованого стану приконтурного масиву навколо присічної підготовчої виробки під час підземної розробки вугільних пластів

Е. Халікова, А. Жумабекова, Т. Дьоміна, Д. Сиздикбаєва, С. Гульміра, К. Айболат

Мета. Встановити закономірності формування напружено-деформованого стану вуглепородного масиву навколо присічної підготовчої виробки та обгрунтувати параметри її кріплення під час відпрацювання вугільних пластів Карагандинського басейну.

Методика. Дослідження виконано шляхом геомеханічного моделювання вуглепородного масиву навколо виробки, проведеної поблизу виробленого простору раніше відпрацьованого виїмкового стовпа та відокремленої від нього вугільним ціликом обмеженої ширини. Моделювання здійснювалося в програмному середовищі ANSYS із застосуванням методу скінченних елементів у двовимірній постановці. Розрахункова модель враховувала вироблений простір, охоронний вугільний цілик, шарувату будову вміщуючих порід, глибину ведення гірничих робіт, фізико-механічні властивості порід, умови навантаження та параметри кріплення виробки. Додаткове оцінювання напружено-деформованого стану та коефіцієнта запасу міцності виконано в програмному комплексі Rocscience RS2 для вентиляційної виробки, проведеної вприсічку до виробленого простору.

Результати. Встановлено, що ширина та міцність вугільного цілика істотно впливають на перерозподіл напружень навколо присічної виробки. Наявність цілика обмеженої ширини зміщує пік максимальних напружень углиб непорушеного вугільного масиву на 5-10 м і зменшує його величину приблизно в 1.6 рази порівняно з безціликовою схемою. Напруження безпосередньо над виробкою знижуються в 1.2-1.3 рази. Підвищення міцності цілика або збільшення його ширини до 20 м забезпечує майже двократне зниження максимальних напружень у масиві. Моделювання в Rocscience RS2 показало, що зі збільшенням глибини розробки від 450 до 700 м максимальні головні напруження зростають у 1.7-1.9 рази, а зміщення контуру виробки – у 1.2-1.35 рази.

Наукова новизна. Встановлено закономірності перерозподілу напружень і формування зон зниженої стійкості навколо присічних підготовчих виробок залежно від ширини та міцності вугільного цілика, глибини ведення гірничих робіт і умов кріплення виробки.

Практична значимість. Отримані результати становлять геомеханічну основу для диференційованого вибору схем кріплення присічних виробок у зонах підвищеного гірського тиску та дають змогу уточнювати параметри комбінованого кріплення з урахуванням фактичного напружено-деформованого стану приконтурного масиву.

Ключові слова: *гірнича виробка; вугільний цілик; напружено-деформований стан; гірський тиск; метод скінченних елементів; анкерне кріплення; металеве аркове кріплення; Карагандинський басейн*

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