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NUMERICAL ANALYSIS OF INJECTION ROCKBOLTS PERFORMANCE IN TECTONICALLY DISTURBED ROCK MASS CONDITIONS OF WESTERN DONBAS

Abstract. Maintaining the stability of underground roadways in tectonically disturbed zones is a challenging task due to the reduced strength and highly fractured structure of the surrounding rock mass. Under such conditions, conventional steel arch or combined arch–rockbolt support often fails to prevent the development of extensive inelastic deformation zones. This study investigates the evolution of the stress state around a roadway driven through a tectonic disturbance zone and evaluates the effectiveness of its reinforcement using injection rockbolts. The analysis is based on numerical simulation of the interaction between a fractured rock mass and an injected polymer composition.

The modelling results show that within the tectonically disturbed zone, the use of steel frame support alone leads to rapid deterioration of the stress state, accompanied by a significant expansion of inelastic deformation zones. In particular, the total area of these zones increases by more than seven times compared with undisturbed conditions, while the inelastic deformation zone in the roof increases by more than an order of magnitude. The application of combined frame–rockbolt support partially improves the stress state of the rock mass; however, it does not provide sufficient stabilization of the fractured medium. Reinforcement with injection rockbolts results in the formation of a consolidated rock–polymer arch characterized by increased strength and stiffness and reduced permeability. As a result, the area of triaxially compressed rock increases by 2.4 times, while the extent of inelastic deformation zones in the roof decreases by 4.7 times compared with the roadway without injection reinforcement.

The obtained results demonstrate that the use of injection rockbolts in combination with frame–rockbolt support ensures a transition from the gradual degradation of the stress state, typical of frame or frame–rockbolt systems, to a stabilizing regime. In this regime, the formation of a reinforced rock–polymer zone causes the roof to act as a load-bearing structural element of the surrounding rock mass. The proposed reinforcement scheme is therefore an effective approach to improving the stability of development roadways in tectonically disturbed zones and can be recommended for mining conditions of the Western Donbas coal mines.

Keywords: roadway stability, tectonic fault, injection rockbolts, rock mass reinforcement, stress state evolution, numerical simulation, Western Donbas.

1. Introduction

The mining and geological conditions of Western Donbas are characterized by a combination of specific geological features that significantly complicate the maintenance of roadway stability at depths ranging from 100 to 500 m. The main factors include the heterogeneity of the physical and mechanical properties of rocks, the presence of numerous geological discontinuities, and the increased fracturing of the rock mass [1, 2]. The roofs of underground roadways are composed of weak rocks with low strength, whereas the coal seams themselves exhibit considerably higher strength parameters [3]. This contrast in strength characteristics promotes stress concentration and the development of plastic zones around excavations, making the use of conventional support schemes without additional reinforcement measures ineffective [4].

Tectonic disturbances in the form of faults, thrusts, and crushed zones are also typical of the mine fields of Western Donbas [5, 6]. These structures significantly reduce the strength of the rock mass within disturbed zones, increase fracturing, and

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decrease the load-bearing capacity of the rocks surrounding the excavation contour [7, 8]. Structural discontinuities occurring in many mining areas lead to pronounced non-uniformity of the stress–strain state and may result in local deformations and roof falls [7, 9]. The presence of fault zones combined with the anomalously low stability of rocks significantly complicates the prediction of rock mass behavior and the selection of an optimal support scheme [10]. Under such conditions, support systems must provide not only structural support of the rock strata but also reinforcement of the fractured rock mass surrounding the excavation.

In weak rocks and under conditions of numerous tectonic disturbances typical of Western Donbas, roadway stability is traditionally ensured using frame support, rockbolt support, and combined support systems [11–17]. Steel frames provide rigid confinement of the excavation contour; however, their efficiency in fractured and crushed rocks is limited due to large rock mass displacements and high material consumption [15, 18]. Rockbolt support reinforces the rock mass surrounding the excavation and promotes the formation of a self-supporting reinforced zone, thereby reducing the development of plastic deformation and improving overall roadway stability [11–13, 19]. In complex geological conditions, combined support systems (frame–rockbolt systems) are widely used, allowing load redistribution between rigid and yielding support elements [14, 20]. However, in zones of intense rock fragmentation, conventional support methods do not always ensure the formation of a stable reinforced zone of sufficient size, which necessitates the search for more effective technical solutions [21–23].

One promising approach to improving roadway stability in fault zones is the use of injection rockbolts. These are fully grouted bolting systems that simultaneously reinforce the rock mass and allow strengthening materials to be injected into fractured rocks [24]. Injection reinforcement makes it possible to fill open fractures, increase the shear stiffness of discontinuity surfaces, and form a reinforced zone around the excavation, thereby limiting the development of plastic deformation and reducing contour displacements [25]. Field results obtained during the injection of polymer compositions through IRMA injection rockbolts while crossing the high-amplitude Bohdanivskyi fault at the Samarska mine confirmed reliable stabilization of the rock mass: convergence along the entire roadway did not exceed 0.03 m during the observation period [26]. The combination of rock reinforcement and injection strengthening is particularly effective in highly disturbed rock masses where conventional support systems fail to provide sufficient structural integrity [18, 26, 27]. At the same time, the efficiency of injection rockbolts strongly depends on the degree of rock fracturing, permeability, properties of the injected material, and injection parameters [28]. The lack of quantitative criteria for evaluating their influence on the stress–strain state of the rock mass under specific mining and geological conditions necessitates dedicated studies, including those based on numerical modelling.

Despite the considerable experience in the application of rockbolt and combined support systems, as well as technologies for injection strengthening of rock masses, their effectiveness under conditions of local tectonic disturbances remains insufficiently studied. Most existing recommendations are empirical and do not fully account for the spatial heterogeneity of the physical and mechanical properties of rocks within crushed zones, the complex stress redistribution associated with roadway intersection of tectonic faults, or the temporal evolution of permeability around excavations. This issue is particularly relevant for the mines of Western Donbas, where the combination of weak host rocks and intense tectonic disturbance leads to the formation of extensive plastic zones and significant roadway convergence. In this regard, the aim of the present study is to investigate the stress–strain state of the rock mass surrounding a roadway crossing a tectonic fault and to evaluate the effectiveness of injection rockbolts using the finite element method for the conditions of the Heroes of Space mine, where roadway construction conditions are among the most challenging in the region [29].

2. Methods

2.1 Coupled Fluid-Mechanical Formulation

The rock mass reinforcement process induced by injection rockbolts was described within the framework of a coupled fluid–mechanical model that accounts for the interaction between rock deformation and the flow of liquid polymer in the fractured zone (the complete formulation is presented in [30, 31]).

The mechanical problem was formulated within an elastic–plastic framework using the Mohr–Coulomb failure criterion. The initial stresses corresponded to the in-situ stress state, whereas the boundary conditions included fixed displacements at the external model boundaries and atmospheric pressure applied at the excavation contour. Polymer injection was simulated by prescribing injection pressure in the unsealed section of the borehole during the injection stage.

Polymer expansion during the chemical reaction was introduced through a source term in the filtration equation. As the polymer hardened and filled fractures and voids, the mechanical and hydraulic properties of the reinforced zone gradually changed: compressive strength and elastic modulus increased linearly to values corresponding to hardened polymer, whereas permeability decreased to zero within the filled fracture–pore space. The steel injection tube was assumed to act as a reinforcing rockbolt only after complete hardening of the polymer. The permeability field included both the natural permeability of the rock mass and the excavation-induced technological permeability, which was defined as a function of the stress state.

The stress state was evaluated using the normalized geomechanical parameters

$$Q^* = \frac{\sigma_1 - \sigma_3}{\gamma H} \quad \text{and} \quad P^* = \frac{\sigma_3}{\gamma H},$$

where σ_1, σ_3 are the maximum and minimum principal stresses, Pa; γ is the average unit weight of the overlying rock mass, N/m^3; H is the mining depth, m.

The principal stress anisotropy parameter Q^* characterizes the intensity of shear deformation within the rock mass and can be considered a quantitative indicator of the rock susceptibility to shear failure. The use of the stress difference ($\sigma_1 - \sigma_3$) allows direct evaluation of shear stresses that control brittle rock failure, whereas normalization by γH ensures comparability of results obtained for different depths. The parameter P^* represents the level of confining pressure [32] and physically reflects the degree of loss of triaxial compression (stress relief) within the rock mass in the zone influenced by the excavation.

To quantitatively assess roadway stability, a system of integral indicators was introduced to characterize both the development of potentially hazardous zones and the formation of a favourable stress state.

The first group includes:

- the total area of inelastic deformation zones (inelastic zone, AIZ),
- the area of inelastic zones in the roof (AIZ_{roof}),

which are interpreted as probable failure regions.

The second group includes:

- the area of zones where $Q^* < 0.4$ (triaxial compression area, ATC),
- the area of zones where $P^* > 0.8$ (high confinement area, AHC).

These zones correspond to a triaxially compressed, non-relieved stress state and therefore indicate increased rock stability. The selected criteria make it possible to evaluate not only the limit stability of the excavation but also the quality of stress-state formation around the roadway.

To provide an integrated assessment of the ratio between stabilizing and destabilizing zones in the roadway roof, the following indicator was introduced:

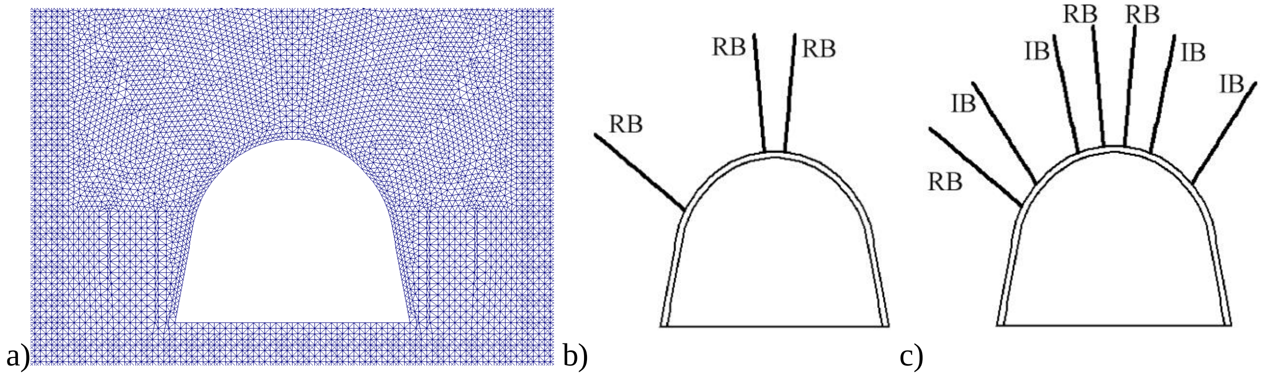
$$K_s = AHC/AIZ_{roof}.$$

Physically, the indicator K_s characterizes the relative proportion of confined, mechanically supported rock compared with the zones that have transitioned into an inelastic state. The larger the value of K_s, the more pronounced the stabilizing effect associated with the formation of triaxial compression zones relative to the development of potentially hazardous areas.

2.2 Finite element model

The finite element model is shown in Fig. 1a and consists of 23,781 nodes and 47,368 elements. Three-node triangular elements were used, whereas rockbolts were simulated using bar finite elements. The arched roadway cross-section was located at the centre of the analysis domain measuring 64 m × 64 m.

The basic computational time step was Δt = 2.7 h, which ensured sufficient numerical efficiency during the stages of slow evolution of the stress–strain state of the rock mass. Conventional rockbolts were installed at the second time iteration, in accordance with the technological requirements of rockbolt installation. Injection rockbolts were activated at the tenth iteration, approximately one day after excavation, when a zone of increased fracturing and permeability had already formed around the roadway.



a) finite element model (central fragment); b) support Scheme 1; c) support Scheme 2;
RB – rockbolt; IB – injection rockbolt.

Figure 1 – Geometry of the problem

To accurately capture the rapid processes associated with polymer injection and hardening, temporal mesh refinement was applied between iterations 10 and 14. During this stage, the time step was reduced to Δt = 20 min. This approach increased the accuracy of transient filtration modelling, allowed volumetric expansion of the material to be taken into account, captured rapid changes in the properties of disturbed rocks, and prevented numerical instability typical of problems involving intensive mass sources and rapidly changing boundary conditions. After completion of the injection and polymer hardening stage, the time step returned to its base value.

2.3 Parameter setting

As a case study, the conditions of roadway development for the 1176 belt entry and the 1176 return airway at the Heroes of Space mine were considered. These roadways were driven through weak rocks intersected by numerous tectonic faults (Fig. 2).

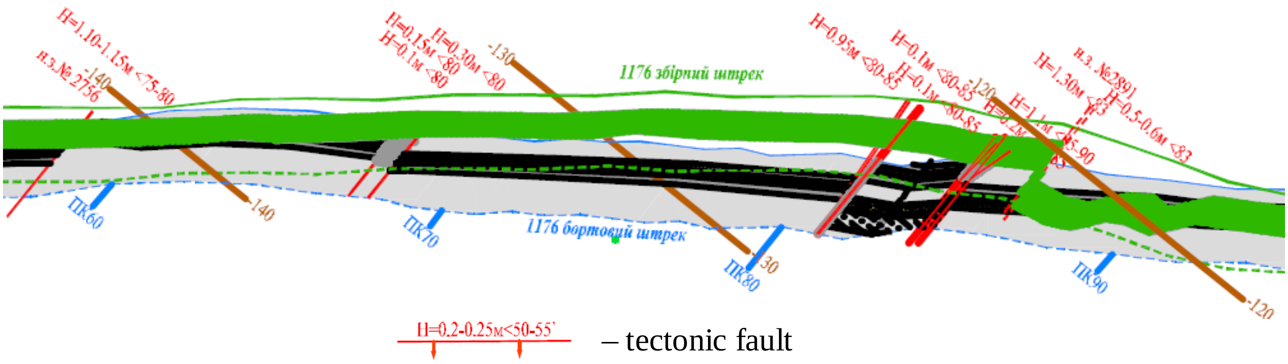


Figure 2 – Combined geological profile of the 1176 belt entry and 1176 return airway

The characteristic lithological composition of the rock mass in this area is presented in Table 1. The main difficulty in roadway development is associated with the risk of roof collapse in tectonically disturbed zones, where the rocks are crushed and highly unstable. The mechanical properties of rocks in both undisturbed and disturbed zones, as well as the properties of hardened polymer, are presented in Table 2.

Table 1 – Lithological composition of the rock mass

Rock	Thickness, m
Unstable siltstone	22
Fractured, loose mudstone; prone to roof falls in tectonically disturbed zones	3
Fractured coal seam C_{11}	1
Loose, unstable mudstone	1.6
Fractured, unstable siltstone	2.2
Sandstone	2
Unstable siltstone	10

Table 2 – Mechanical properties of rocks and hardened polymer

Material	Compressive strength, σ_c, MPa		Elastic modulus, E, GPa		Cohesion, C, MPa	
	Undisturbed zone	Disturbed zone	Undisturbed zone	Disturbed zone	Undisturbed zone	Disturbed zone
Siltstone	22	3.5	34	11	6	1
Mudstone, roof	15	1.0	16	6	4	0.3
Mudstone, floor	10	3.5	16	6	3	1
Coal	26	7.0	3.7	3	7.5	2
Sandstone	30	5.5	40	14	8.5	1.6
Hardened polymer	30		10		10.0	

For the analysis, the stress state of the surrounding rocks was considered both within the tectonic disturbance zone and outside it for the following support systems:

- frame support;
- frame–rockbolt support, Scheme 1 with three steel rockbolts (Fig. 1b);
- frame–rockbolt support reinforced with four injection rockbolts, Scheme 2 (Fig. 1c), used in disturbed zones.

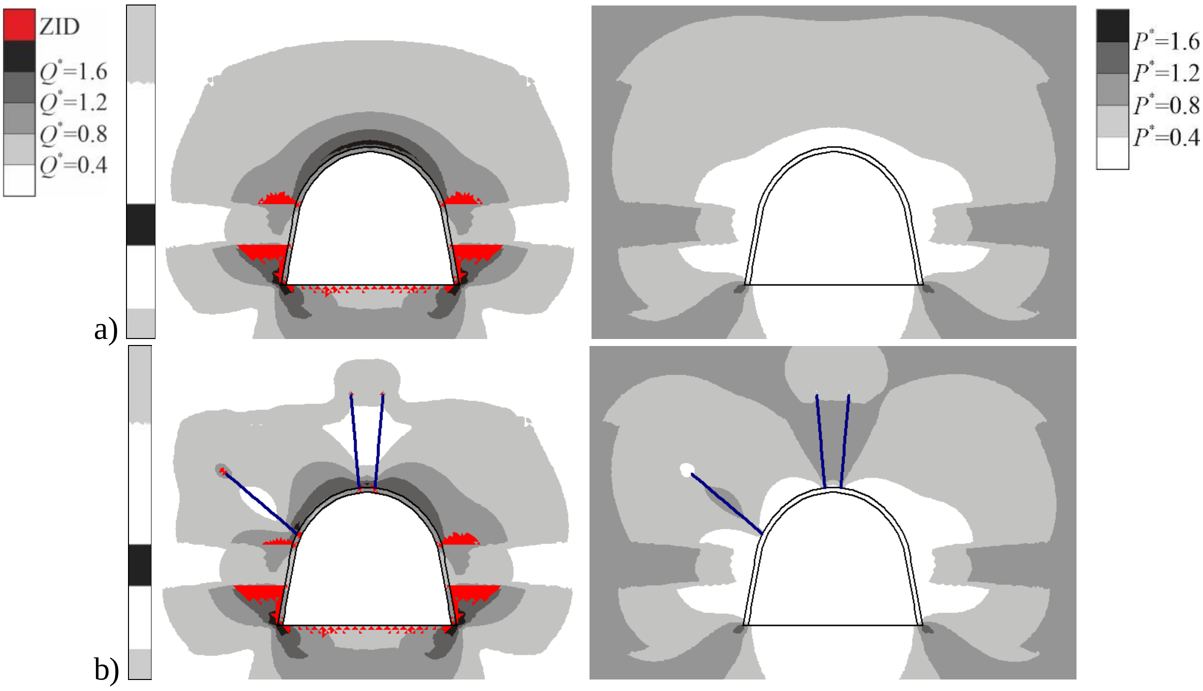
The following parameters were adopted in the simulations: mining depth H = 300 m; unit weight of overlying rocks γ = 25,000 N/m³; lateral stress coefficient λ = 1; roadway width 4.2 m, height 3.3 m; rockbolt length 2.4 m; borehole sealing length 0.7 m; injection pressure p_{inj} = 2 MPa; injection time t_{inj} = 40 min; polymer hardening time t_{hard} = 40 min; viscosity of liquid polymer μ = 0.001 Pa·s. Initial rock permeability was assumed to be: k_0 = 0.001 D outside the tectonic disturbance zone; k_0 = 0.1 D within the disturbed zone; k_0 = 1 D in the immediate argillite roof of the seam within the disturbed zone.

3. Results and discussion

The results are first analysed for a roadway excavated in undisturbed rock mass and within a tectonic fault zone, and are then used to evaluate the influence of reinforcement by injection rockbolts on the stress state, the development of inelastic zones, and the filtration properties of the surrounding rocks.

3.1 Stress evolution and roadway stability outside the fault zone

Figure 3 shows the distributions of the stress anisotropy parameter Q^* and the confining pressure parameter P^* around the roadway supported by frame support and frame–rockbolt support in undisturbed rocks at t = 10 days.



a) frame support; b) frame–rockbolt support

Figure 3 – Distribution of Q^* and inelastic deformation zones (left) and P^* (right) in the undisturbed section of the roadway, 10 days after the face advance

Analysis of the results indicates that under the adopted mining and geological conditions the rock mass remains in a relatively stable state even when only frame support is used. Inelastic deformation zones are mainly localized at the contact between weak mudstone and the stronger coal seam and remain limited in size. Elevated values of the parameter Q^* are observed in the roof and in the lower corners of the roadway (Fig. 3a, left), indicating the development of the deviatoric stress component in these areas. The deformation of the steel frames remains within the elastic range of the material.

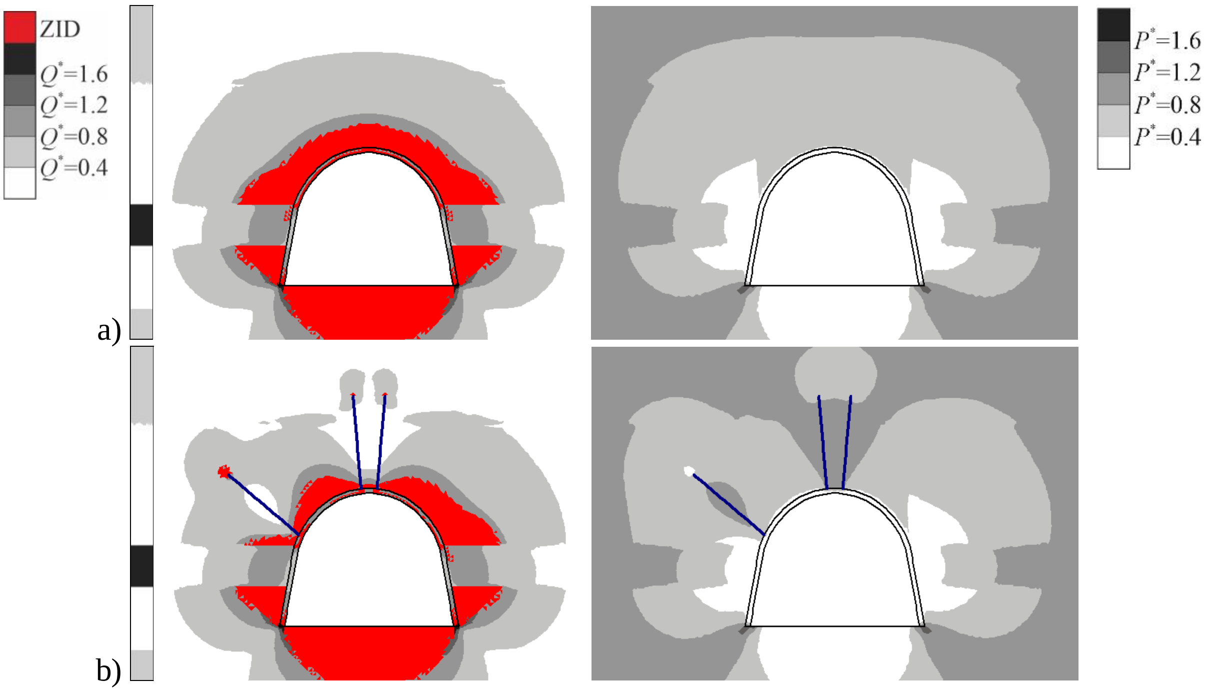
The installation of three rockbolts has little influence on the size of the inelastic zones (Fig. 3b, left) but significantly modifies the stress state in the roof. Areas with reduced stress anisotropy (Q^*< 0.4) appear (Fig. 3b, left), corresponding to a more triaxially compressed stress state, while zones with elevated confining pressure (P^*> 0.8) are also formed (Fig. 3b, right). This indicates an improvement in the stress conditions of the roof rocks and an increase in their local stability.

Thus, in undisturbed rocks the frame support provides sufficient ultimate stability of the roadway, whereas the addition of rockbolts mainly produces a stabilizing effect by promoting the formation of a more favourable spatial stress state.

3.2 Stress evolution and roadway stability within the fault zone

A fundamentally different pattern is observed within the tectonic fault zone, where the reduction in the strength and stiffness of the rocks leads to intensive development of inelastic deformation and a significant deterioration of roadway stability (Fig. 4). When only frame support is applied, the total area of inelastic deformation zones increases 7.3 times compared with the undisturbed section, while in the roof the increase reaches 12.7 times (Fig. 5). This indicates a loss of load-bearing capacity of the weakened rocks and the propagation of the inelastic region deeper into the rock mass.

At the same time, the area of zones with $Q^*< 0.4$ increases approximately fourfold. This effect is not associated with improved stability but rather with a deeper redistribution of stresses in the weak medium: outside the developed inelastic zone an expanded region of increased hydrostatic compression is formed. However, the area of zones with $P^*> 0.8$ remains very small (Fig. 4a, right), indicating insufficient confinement of fractures in the immediate roof.



a) frame support; b) frame–rockbolt support.

Figure 4 – Distribution of Q^* and inelastic deformation zones (left) and P^* (right) within the tectonic fault zone, 10 days after the face advance

The application of frame–rockbolt support reduces the area of inelastic deformation in the roof by 30%, whereas in the floor it remains almost unchanged (Fig. 4b, left; Fig. 5). At the same time, the area of triaxially compressed roof rocks increases 3.2 times, and the area of zones with high confining pressure increases 48 times compared with the case of frame support within the disturbed zone (Fig. 5). This result indicates the formation of a local region of confined rocks around the rockbolts, which limits the development of shear failure mechanisms and stabilizes the roof.

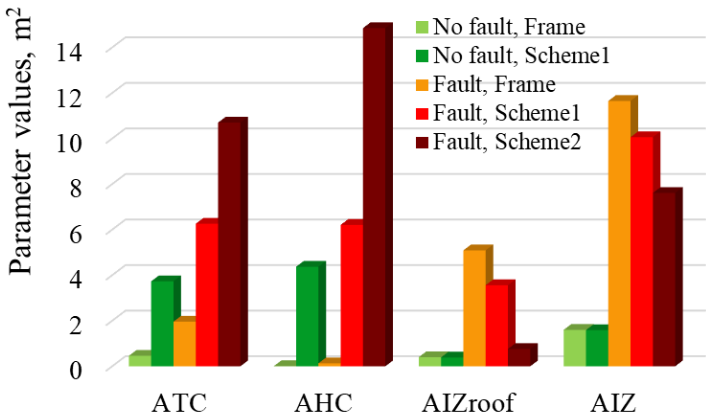


Figure 5 – Variation of the integral indicators describing the development of potentially hazardous zones and favourable stress conditions (t = 10 days)

Within the tectonic disturbance zone, when only frame support is used, $K_s \approx 0.03$, indicating the dominance of stress relief and brittle failure processes. After the installation of rockbolts the indicator increases to $K_s \approx 1.74$, i.e. by almost two orders of magnitude. This confirms that roadway stabilization is achieved not only by reducing the area of inelastic deformation but primarily by the formation of a significant region of confined roof rocks.

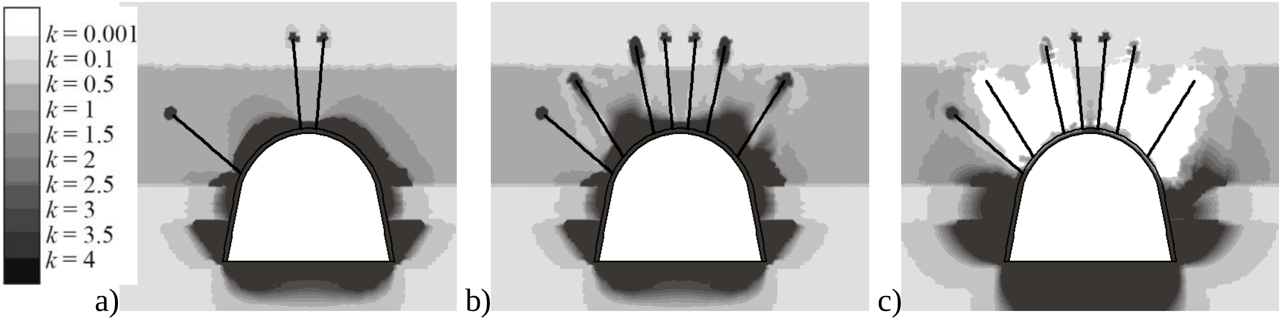
The increase in AHC and the simultaneous decrease in AIZroof exhibit an inverse correlation, reflecting the stabilization mechanism: an increase in confining pressure restricts the development of shear failure mechanisms.

Thus, the integral indicators (Fig. 5) demonstrate that within the tectonic disturbance zone frame support alone is insufficient to ensure roadway stability, whereas the addition of only three rockbolts changes the character of the stress state from stress-relieved to confined, which is accompanied by a reduction of potentially hazardous zones and an expansion of areas of favourable triaxial compression.

3.3 Effect of injection rockbolts on the geomechanical and filtration behavior of the rock mass

Within the tectonic disturbance zone the rocks exhibit increased initial permeability, which further increases during roadway excavation due to the development of fracturing and stratification of the rock mass. As a result, already one day after face advance, before the start of polymer injection, favourable conditions for the propagation of the injected material in the fractured rock develop in the near-contour roof zone (Fig. 6a).

During polymer injection, the pressure of the viscous fluid causes additional opening of existing fractures, which temporarily increases the permeability of the rock mass in the vicinity of the injection rockbolts (Fig. 6b). As a result, the polymer solution actively propagates along the system of fractures and pores in the rock, forming an impregnation zone around the rockbolts (Fig. 7a). After the completion of injection and polymer hardening, this region transforms into a reinforced rock–polymer monolith (Fig. 7b), whose mechanical properties significantly exceed those of the initial rocks. At the same time, permeability sharply decreases, and the formed zone becomes practically impermeable to fluid flow (Fig. 6c).

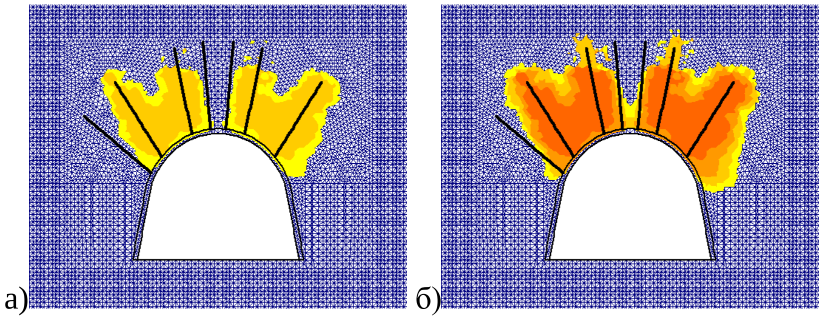


a) t = 10 h; b) t = 10 h 20 min; c) t = 10 days

Figure 6 – Permeability distribution in the tectonic fault zone for support Scheme 2

Thus, the application of injection rockbolts leads to simultaneous modification of two key characteristics of the near-contour rock mass:

1. an increase in its strength and stiffness;
2. a decrease in permeability and isolation of the fractured medium.

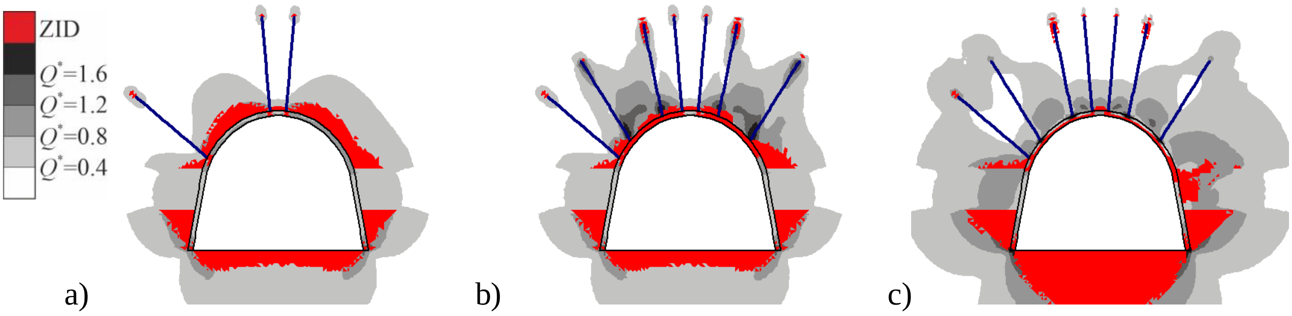


a) t = 10 h 20 min; b) t = 11 h

Figure 7 – Polymer-reinforced zone in the roof rocks within the tectonic disturbance

Further analysis shows how these changes influence the stress state around the roadway. Figures 8 and 9 present the distributions of the stress anisotropy parameter Q^* and the confining pressure parameter P^* at different moments in time: before injection, during injection, and after polymer hardening.

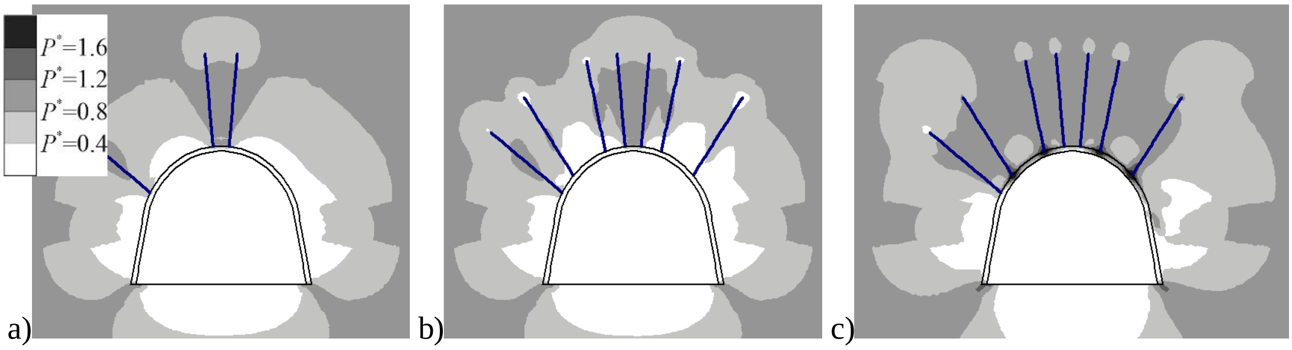
Before the start of injection, after installation of three conventional rockbolts, a zone of increased stress anisotropy (Q^*>0.4) begins to form in the near-contour region. At t = 9 h its depth reaches 1–1.5 m. In the weak roof and floor mudstone, an inelastic deformation zone develops to a depth of about 0.3 m, which increases to 0.7 m at the contact with the stronger coal seam (Fig. 8a). At the same time, the parameter P^* rapidly decreases, reflecting the loss of confining pressure in the near-contour rocks: within a layer up to 2 m thick around the roadway the values P^*< 0.8 are observed (Fig. 9a). Nevertheless, around the steel rockbolts local regions of triaxially compressed rocks remain, where $Q^{*}< 0.4$ and $P^{*}> 0.8$, and deformation occurs within the elastic regime.



a) t = 10 h; b) t = 10 h 20 min; c) t = 10 days

Figure 8 – Distribution of Q^{*} and inelastic deformation zones in the tectonic disturbance zone (support Scheme 2)

During polymer injection a local increase in stress anisotropy is observed around the injection rockbolts (Fig. 8b), which is associated with the pressure of the injected fluid. However, after partial polymer hardening and consolidation of the rocks the inelastic zone decreases, indicating strengthening of the rock mass. At the same time, elevated confining pressure remains in the vicinity of the conventional rockbolts (Fig. 9b).



a) t = 10 h; b) t = 10 h 20 min; c) t = 10 days

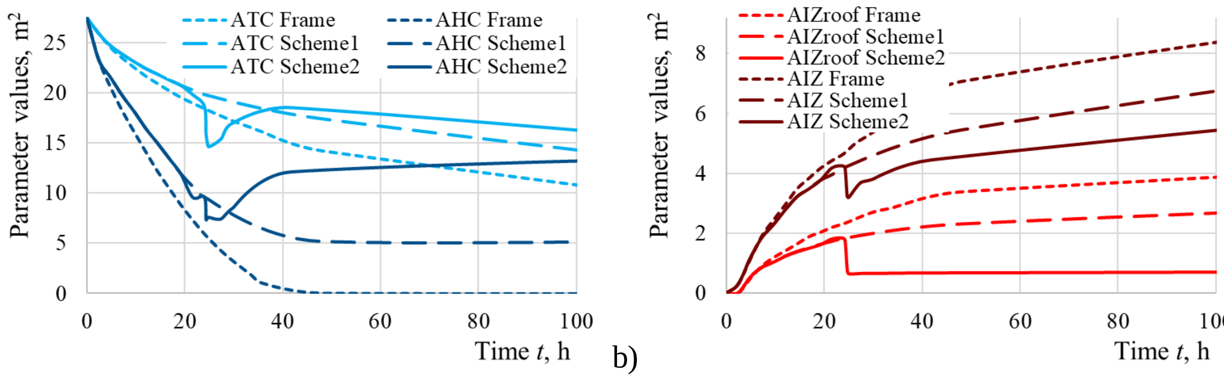
Figure 9 – Distribution of the parameter P^{*} in the tectonic disturbance zone (Scheme 2)

Further polymer hardening leads to gradual expansion of the reinforced roof region where the conditions $Q^{*}< 0.4$ and $P^{*}> 0.8$ are satisfied. Over time this zone covers almost the entire roadway roof, forming a reinforced arch that redistributes loads and ensures stable roadway conditions (Figs. 8c and 9c).

Figure 10 presents the time evolution of the integral indicators characterizing the development of potentially hazardous zones (AIZ and AIZ_{roof}) and favourable stress conditions (ATC, AHC) in the bolted part of the roof for the considered support systems within the disturbed zone.

For the roadway supported only by frame support, a monotonic degradation of the geomechanical state of the rock mass is observed (Fig. 10a). Over 10 days, the area of triaxially compressed rocks ATC gradually decreases from 27.5 to 1.96 m², while the area of high confining pressure AHC practically disappears (Fig. 5). At the same time, the area of inelastic deformation increases significantly: AIZ_{roof} reaches 5 m², while the total AIZ reaches 11.65 m² (Fig. 5).

The installation of three conventional rockbolts (Scheme 1) partially stabilizes the roof (Fig. 10a). However, within the tectonic disturbance zone this proves insufficient, and the inelastic zones continue to expand with time (Fig. 10b).



a) favourable stress state; b) potentially hazardous zones

Figure 10 – Time evolution of stress-state indicators during support installation in the tectonic disturbance zone

A fundamentally different behaviour is observed after the installation of injection rockbolts (Scheme 2). Analysis of the temporal evolution of the integral indicators shows that before injection the development of the stress–strain state follows the same trend as in the case of frame–rockbolt support (Scheme 1): the area of inelastic zones gradually increases, while regions of triaxial compression decrease.

After the start of polymer injection the evolution of the parameters changes abruptly. A short-term restructuring of the stress state occurs, manifested by a temporary decrease in favourable zones (Fig. 10a). However, after polymer hardening a rapid increase in the areas of triaxial compression begins, and already within the first tens of minutes a reduction in the area of roof inelastic zones and stabilization of the stress parameters are observed (Fig. 10). At t = 100 h, the area AHC increases 2.6 times, while the roof inelastic zone AIZ_{roof} decreases almost fourfold compared with the roadway without injection reinforcement. This indicates the formation of a consolidated rock–polymer arch in the near-contour region that effectively redistributes loads and limits the development of failure.

After reinforcement with injection rockbolts the indicator K_s increases from ≈11 for the roadway with frame–rockbolt support to ≈19.5, indicating a fundamental improvement in the geomechanical state of the surrounding rock mass. Thus, injection rockbolts provide not only local reinforcement of fractured rocks but also promote the formation of a stabilizing triaxial compression zone in the roadway roof, which significantly improves its stability within tectonic disturbance zones.

Overall, the obtained results demonstrate that the effectiveness of injection rockbolts in tectonically disturbed zones is associated not only with the additional bolting effect but primarily with the formation of a consolidated rock–polymer zone in the roof. This zone increases the stiffness and strength of the fractured rock mass, reduces its permeability, and promotes the development of a stable three-dimensionally compressed region around the roadway. As a result, the extent of inelastic deformation zones decreases while the area of favourable stress conditions increases significantly. The proposed support scheme therefore enables a transition from the gradual degradation of the stress state typical of frame or frame–rockbolt support to a stabilizing regime in which the reinforced roof acts as a load-bearing structural element.

4. Conclusions

This study used numerical simulation to investigate the evolution of the stress state and stability of a development roadway under conditions of a tectonic fault and to evaluate the effectiveness of reinforcement using injection rockbolts.

1. It is shown that tectonically disturbed zones significantly deteriorate roadway stability conditions. Within a tectonic fault zone, the reduction in strength and deformation properties of the surrounding rocks leads to the intensive development of inelastic deformation zones and a rapid decrease in the confining pressure in the near-contour rock mass.

2. It has been established that within the fault zone, when only steel frame support is used, a sharp increase in the area of inelastic deformation zones occurs: the total failure zone increases by more than seven times, while the roof failure zone increases by more than twelve times compared with the conditions of an undisturbed rock mass.

3. The use of combined frame–rockbolt support improves the stress state of the roof rocks by increasing the area of triaxial compression and partially limiting the development of failure zones. However, under tectonically disturbed conditions this effect remains insufficient due to the weakened structure of the rock mass.

4. Reinforcement with injection rockbolts provides additional strengthening of fractured roof rocks due to the penetration of the polymer composition into the fracture network and the formation of a consolidated rock–polymer arch characterized by increased strength and stiffness as well as reduced permeability. Numerical modeling results show that the use of injection rockbolts within a tectonic fault zone significantly improves the geomechanical state of the near-contour rock mass: the area of triaxially compressed rock increases by 2.4 times, while the development of inelastic deformation zones in the roof decreases by 4.7 times compared with the roadway without injection reinforcement.

The obtained results indicate that the use of injection rockbolts in combination with frame–rockbolt support enables a transition from the gradual degradation of the stress state typical of frame or frame–rockbolt support systems to a stabilizing regime. In this regime, the formation of a reinforced rock–polymer zone causes the roof to act as a load-bearing structural element of the surrounding rock mass. The proposed reinforcement scheme is therefore an effective method for improving the stability of development roadways in tectonically disturbed zones and can be recommended for mining conditions of the Western Donbas coal mines.

Conflict of interest

Authors state no conflict of interest.

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ЧИСЕЛЬНИЙ АНАЛІЗ РОБОТИ ІН'ЄКЦІЙНИХ АНКЕРІВ В УМОВАХ ТЕКТОНІЧНО ПОРУШЕНИХ ПОРІД ЗАХІДНОГО ДОНБАСУ

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Анотація. Підтримання стійкості гірничих виробок у зонах тектонічних порушень є складною задачею через зниження міцності та інтенсивну порушеність вміщуючих порід. За таких умов традиційне рамне або рамно-анкерне кріплення часто не забезпечує запобігання розвитку значних зон непружних деформацій. У роботі досліджено еволюцію напруженого стану навколо виробки, що проводиться через зону тектонічного порушення, та оцінено ефективність її підсилення ін'єкційними анкерами. Аналіз виконано на основі чисельного моделювання взаємодії тріщинуватого масиву порід з ін'єктованим полімерним складом.

Результати моделювання показали, що в межах тектонічного порушення при рамному кріпленні спостерігається швидке погіршення напруженого стану, яке супроводжується значним розширенням зон непружних деформацій. Зокрема, загальна площа таких зон зростає більш ніж у сім разів порівняно з умовами непорушеного масиву, тоді як зона непружних деформацій у покрівлі збільшується більш ніж на порядок. Застосування рамно-анкерного кріплення частково покращує напружений стан порід, однак не забезпечує достатньої стабілізації тріщинуватого масиву. Підсилення виробки ін'єкційними анкерами приводить до формування консолідованого породно-полімерного перекриття з підвищеними міцнісними та деформаційними характеристиками і зниженою проникністю. У результаті : площа зон тривісно стиснутих порід зростає в 2,4 рази, тоді як розвиток зон непружних деформацій у покрівлі зменшується в 4,7 рази порівняно з виробкою без ін'єкційного підсилення.

Отримані результати свідчать, що використання ін'єкційних анкерів у поєднанні з рамно-анкерним кріпленням забезпечує перехід від поступової деградації напруженого стану, характерної для рамного або рамно-анкерного кріплення, до стабілізуючого режиму, в якому внаслідок формування зміцненої породно-полімерної зони покрівля починає виконувати функцію несучого конструктивного елемента приконтурного масиву. Застосування такої схеми підсилення є ефективним способом підвищення стійкості підготовчих виробок у геологічно порушених зонах і може бути рекомендоване для умов шахт Західного Донбасу.

Ключові слова: стійкість виробки, тектонічне порушення, ін'єкційний анкер, зміцнення породного масиву, еволюція напружень, чисельне моделювання, Західний Донбас.