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Mechanical model and numerical analysis of a method for local rock reinforcing to control the floor heave of mining-affected roadway in a coal mine

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Abstract. A floor heave controlling method has been substantiated, based on the creation of locally reinforced zones of a special shape in roadway floor, which allows saving stability even with a low rocks friction ratio. The method is based on a mechanical model of the formation of an increasing strength spacer system in roadway floor. The numerical analysis of rock massif stress-strain state carried out by the finite element method, has made it possible to determine the mechanism of floor heave during rock reinforcing. The performed analysis of the simulation results has made it possible to determine the influence of the quality of rock reinforcing and the rock friction ratio value on the amount of heave in the mining-affected roadway. The effectiveness of the proposed method has been proven as a result of a comparative analysis.

1. Introduction

Trends in the change of key focus areas of the world energy are constantly reflected in the vector of the energy policy of different countries. The course towards decarbonization and renewable energy led to the adjustment of the development strategy of the coal industry in Ukraine. So, in 2020, the National Program for the Transformation of the Coal Regions of Ukraine until 2027 has been launched. Its purpose is to consolidate new priority areas for the development of the industry. Review of the materials from the meeting of the Coordination Center for the Transformation of Ukraine's Coal Regions held on 08.10.2020 [1] shows that in the coming years, gradual restructuring and liquidation of investment-unattractive mines are expected, that is, first of all public sector enterprises that are not subject to modernization. The total number of mines in Ukraine is 69, 51 of which are coal mines. At the same time, the greater part of coal production is provided by 20 non-state-owned enterprises. Most of them are part of large conglomerates: Metinvest Holding LLC, Donbas Fuel and Energy Company (DTEK), Donetsksteel - Metallurgical Plant PrJSC [2]. According to experts, the maximum reduction in coal production, possible with the implementation of the current energy strategy of Ukraine, reaches 25%. At the same time, the predicted decrease in the share of coking coal production is insignificant. That is, it is too early to write off the native coal industry. This generally coincides with the global trends, since at the beginning of 2020 the share of coal in the global energy generation balance was 27%, against for 5% renewable energy sources [3].

Actual problems of modern underground coal mining are determined not so much by the tasks associated with achieving high productivity of mining face, which are easily solved by using high-performance mining complexes. The main task is the timely preparation of reserves for extraction and ensuring the operational state of development roadways. Globalization processes in the field of engineering and technology for the extraction and processing of mineral resources have led to significant progress in mining. In particular, it was reflected in the development of technologies for roadways maintenance and lining. Application of two-level bolting systems, shotcreting, and the improvement of lining structures contributed to significant progress in ensuring the stability of the roof and sides of roadways, including the mining-influenced zones. The floor of these main roadways is still not lined most of the time. Therefore, floor rocks, especially in mining affected roadways, at great depths are destroyed and squeezed into the roadway hollow. This fact is noted in the research of scientists from different countries [4-7].

Most often, the floor rocks heave in mining affected roadways is explained by the following reasons: rock volume increase during water saturation, the squeezing out of rocks as from under a stamp, the transition of rocks to a plastic state, creep, squeezing out of disintegrated rocks, as well as a combination of these factors. Different interpretations of the mechanisms of floor rock heave led to the formation of various methods of counteracting this phenomenon.

The main conceptual directions of floor heave counteraction can be summarized by the following methods:

- the use of closed lining structures;
- rock unloading;
- local floor rock reinforcing.

In practice, combinations of these methods are often used.

The first method found its application earlier than others. For a long time, linings with sill in the floor, with a reverse vault, an annular lining structures seemed to be the simplest and most logical solution. However, with the transition of mining to great depths, the effectiveness of closed lining structures has greatly decreased. In the mining-affected areas, these elements were deformed, destroyed and, together with the floor rocks, were squeezed out into the roadway hollow. Nowadays, the ring-type or reverse arch linings are mainly used in the main roadways [8, 9].

To reduce stresses on the roadway contour, various methods of rock unloading are used. Unloading is provided by creating artificial hollows in the floor and sides of the mine or by detonating camouflage explosive charges. The hollows can be grooves, holes or gaps. Rock unloading groove is constructed in the floor on one side of the roadway or on both sides [10]. Most of the time the drill and blast method is used, to create the depressurization hole. The gap is usually located in the center of the roadway section, and its depth is much greater than that of the grooves and reaches several meters [10]. Holes can be drilled both into the floor and into the sides of the roadway. In native mines floor unloading is practically not used as a method of heave counteracting. This is due to the technical complexity and the time-limited unloading effect.

The most modern method of heave counteracting is floor reinforcing. Strengthening is carried out both with preliminary floor rock dinting and replacement of the excavated rock with an astringent solution, and without floor rock dinting by injecting astringent solution into fractured floor rocks or strengthening them with anchor bolts. After strengthening, an artificial beam [11, 12] or vault [13, 14] is created in the floor. A separate direction of this method is associated with the strengthening of rocks under a protective strip at the border with the mined-out space [15]. Strengthening is the most effective way in roadways which are located in the mining-affected areas. However, the main disadvantages of this method such as the high cost of implementation and high rigidity of the created structures have not been overcome yet. The destruction of the lining structure created in the floor occurs in zones of increased rock pressure due to the low threshold of permissible deformations.

The needed flexibility is provided by the methods of the roadway rock strengthening with rock bolts [16, 17]. However, since the floor rocks in the zones of influence of mining are not monolithic, the effectiveness of their bolting is low. In the zones of longwall influence, the degree of floor rock destruction can be such that individual rock fragments have sizes from several centimeters to tens of centimeters [7]. In addition, the plastic deformations are characteristic of clay rocks and mudstones in the presence of water, which reduce the effect of bolting to a minimum.

Thus, the analysis carried out indicates that the most promising way to control rock heave in mining-affected roadways today is reinforcing. Therefore, improving the methods of floor strengthening of this type of roadways, in order to overcome the disadvantages mentioned, is a relevant scientific task.

The purpose of this study is the development and research of floor heave controlling method in roadways located in the mining-affected zone by means of local rock reinforcing.

2. Methods

The research described in the work was based on the position of a mechanistic approach to the problem of floor heave. The heaving process was considered a result of mechanical interactions and the stress-strain state (SSS) evolution of the massif around mining roadway without physicochemical transformations in the rock structure.

Analysis of the contour displacements of the development roadways serving the longwalls, as well as the roadways falling into the bearing pressure zone, shows that the floor heave at the drivage stage is 2-4 times lower than in an area, affected by mining operations. At the same time, fractional analysis of rocks during the floor dinting in roadways supported in pressure-bearing zone allows us to conclude that the rock is usually represented by a block-discrete medium [7]. It is known that under these conditions, a broken rock zone (BRZ) has already formed around the roadway, and the most probable mechanism of heaving is the squeezing out of broken rocks, which are within the boundaries of the breaking face growing under the influence of the approaching front of the longwall, into the roadway hollow. That is why, in such conditions, methods of heave counteracting based on rock unloading are not effective.

The dynamics of floor rock heaving in the development roadways in the zone of influence of one longwall, and the corresponding size of BRZ increase are shown in figure 1.

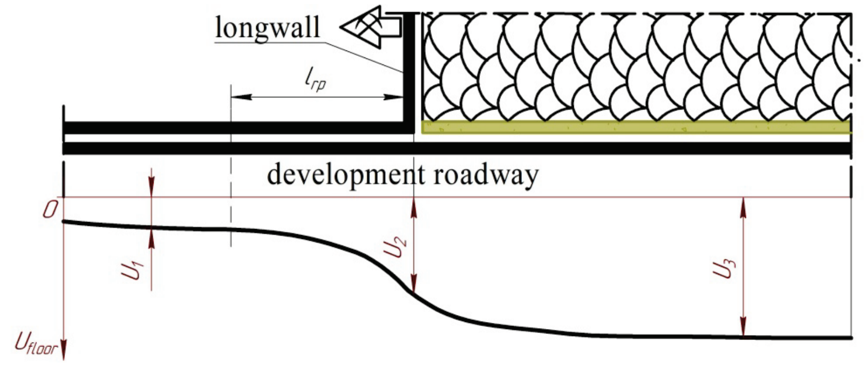


Figure 1. Typical curved graph of floor rock displacement in development roadway [18]: U_{floor} – floor heave, mm; U_1 – maximum floor heave during drivage in an intact massif, mm; U_2 – maximum floor heave in advanced support pressure zone, mm; U_3 – maximum floor heave behind the longwall, mm; l_{rp} – zone of advanced bearing pressure, m.

According to Prof. Cherniak the swelling of the floor, represented by clay and sandy shales, outside the zone of influence of excavation works, occurs as a result of elastic-viscous-plastic deformation and a rock volume increase during destruction. This causes formation in the floor of zones of inelastic deformations and zones of destruction. The sizes of zones increase with time and lead to heaving of floor rocks up to 500 mm or more. The zone of destroyed rocks in the roadway floor can reach 5-6 m, and the rock loosening ratio is 1.06-1.1. In the zone of the face bearing pressure influence, the swelling is intensified. The maximum rates of the roof and floor displacement are observed at a certain (from 5 to 30 m) distance behind the longwall, after which they stabilize. In this zone, floor displacements reach significant values (more than 1000 mm) and floor dinting is required; the underlying rock loosening ratio is 1.1-1.15, and the destroyed rocks zone is 10 m.

Thus, in the area, affected by mining activity, the floor rocks swelling develops under the conditions of inelastic deformations zone and the BRZ already formed around the roadway. This allows, as first approximation, to consider the presence of the indicated zones correct when setting the problem.

This study used mathematical modeling as the main research method, which was implemented in the Ansys Student (Free Student Software) [19] finite element analysis software system. The modeling was carried out in a volume setting on a natural scale. The geometric and physical nonlinearities typical for the problems of mining geomechanics were taken into account. Therefore, the numerical analysis was carried out by the iterative Newton-Raphson method.

The solution used a standard method for simulating the stress-strain state of an array near various mining structures using the principle of forces superposition. The task was solved step by step in a static setting. The analysis of the simulation results was carried out on the basis of processing the stresses obtained in the process of numerical calculation. The first and the energy theory of strength were accepted as working hypotheses.

According to the approach described above, a finite element model was created (figure 2). In the process the development of an arched shape surrounded with a zone of inelastic deformations that was already formed, was simulated. The bearing capacity of the lining arch was assumed to be 600 kN and was simulated by a distributed rebound over the area of the roof and sides, since at this stage it can be assumed that the arch works flexibly in a given resistance mode. As a result of roadway ingress in the mining-affected area, for example, the face bearing pressure zone, the balance in the massif is disrupted due to an increase in the level of stresses. This leads to the destruction of rocks on the zone contour and to an increase in pressure on the front of the zone due to rise the rocks volume during destruction. In the model, this process is simulated by an increase in the external pressure on the air flow control loop. The pressure is assumed to be distributed along the contour evenly. As a result of stresses redistribution within the BRZ, the massif moves towards the roadway contour, which manifests itself in its floor, as heaving.

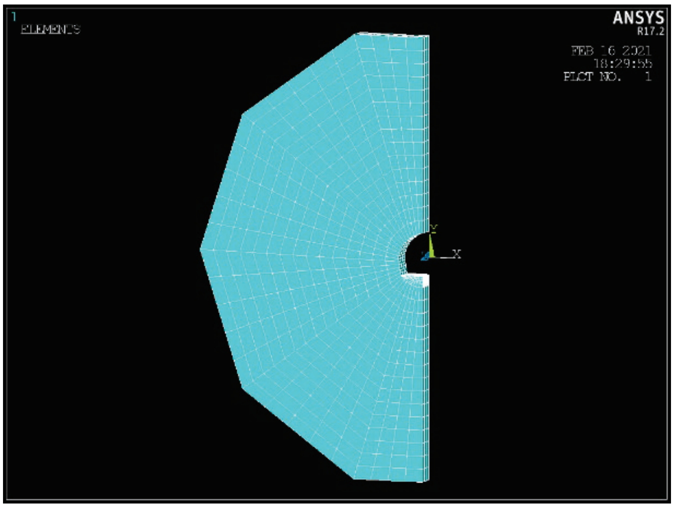


Figure 2. General view of the finite element model.

The problem is assumed to be axisymmetric. An isolated volume of the rock mass was simulated within the BRZ, since within the framework of the problem being solved, the processes at the point of contact between the elastic area and the zone of inelastic deformations can be neglected.

To simulate the behavior of rocks, an elastoplastic deformation model was used, based on the use of the Drucker-Prager equation of state (built on an approximation to the Mohr-Coulomb law in a conical surface form). The adequacy of the deformation model was established by simulation experiments [20]. Taking into account the level of an accuracy admissible for the problem being solved, the adopted deformation model did not require any additional calibration. The properties of rocks within the zone of inelastic deformation are given in table 1.

The solution to the problem assumed the local reinforcing of the massif. The reinforced zone was modeled according to the specified parameters, which are presented below. The modeling also took into consideration the friction between the reinforced zone and the rock massif by changing the friction ratio along the contact planes. The deformation properties of the rock massif in the reinforced zone changed during the simulation: the modulus of elasticity varied between 5 10^8 Pa and 5 10^9 Pa, Poisson's ratio decreased to 0.15 (table 1). The effect of moisture on the rocks mechanical properties was not taken into account in this particular task.

Table 1. Initial data for numerical modeling.

№	Density, kg/m^3	Elastic modulus, MPa	Poisson's ratio	Angle of internal friction, deg	Dilatancy angle, deg	Cohesion value, kPa
			Rocks within BRZ (broken rock zone)			
1	2500	500	0.3	35	33	95
			Rocks within local reinforced area			
2	2500	500-5000	0.15	35	33	95-950

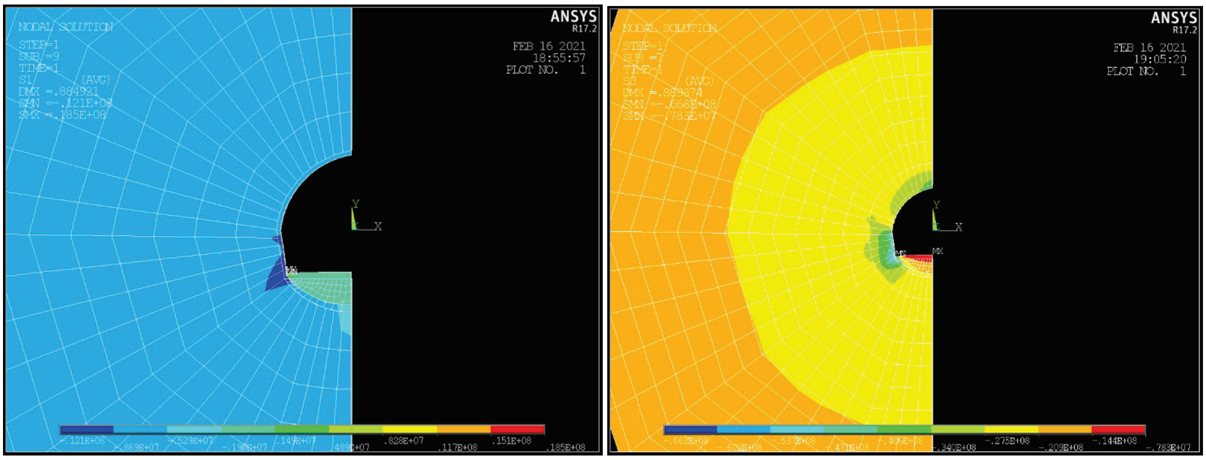
3. Results and discussion

3.1. Numerical analysis of local floor reinforcing

To study the mechanism of heaving development and assess the effectiveness of floor rock reinforcing, simulation modeling of the heaving process was carried out. At the same time, three tasks were successively solved:

- analysis of the massif stress-strain state (SSS) without floor reinforcing;
- analysis of the massif SSS with a reverse vault form floor reinforcing;
- analysis of the massif SSS when the proposed method of floor reinforcing was implemented.

Distributions of the principal stresses around the roadway, when solving the first problem are shown in figure 3.



a b

Figure 3. Distribution patterns of the maximum σ_1 (a) and minimum σ_3 (b) of the principal stresses around the roadway without floor reinforcing.

The analysis of the maximum principal stresses σ_1 distribution (figure 3a) made it possible to conclude that a reduced stresses zone was formed in the roadway floor to a depth exceeding half of the section width. Since the rocks within the BRZ have already lost their continuity and are not being elastically deformed, the presence of a reduced stresses zone indicates the involvement of the rocks part indicated in the process of moving into the roadway hollow. In absolute terms, the roadway floor heave in the center of the span was 15 cm. Analysis of the principal minimum stresses σ_3 distribution pictures (figure 3b) shows that a compression area is formed around the roadway, repeating the shape of the BRZ outline. In this case, the compressive stresses maxima are in the lining leg area, which is explained by the presence of a natural stress concentrator in the corner of roadway contour. Along the roof and sides of roadway contour, increased stresses zones are also observed at a distance of up to half a meter from the roadway lining, which is explained by the resistance of the arch lining. In the roadway floor, a decrease in stresses is observed; the unloading zone is the same in size as in figure 3.a.

Since one of the most promising and widespread methods of heave counteracting is floor rock reinforcing, in the second task, the massif SSS was simulated with strengthening of floor rocks in an inverse arch form, which is one of the best forms of a strengthened zone [13, 14]. Since the study is focused mainly on the floor, the arched shape of the roadway was piecewise linearly approximated in order to increase the speed of calculation and optimize the breakdown of the studied rocks volume into finite elements. At the same time, the deformation properties of the strengthened area and the friction ratio between reinforced and unreinforced rocks changed in the model. The importance of studying the influence of the second of these factors and its presence in the problem being solved is explained by the available experience of rock reinforcing in mine conditions. During the strengthening of rocks with binder mixtures in the Donbas mines conditions, the squeezing out of the strengthened area into the roadway hollow was observed. This indicated a low cohesion between the reinforced and unreinforced areas of the floor rocks.

Similar results were obtained during simulation modeling using the finite element method: at low values of the friction ratio along the contact planes of the reinforced and unreinforced zones, the reinforced area rocks were squeezed out by a common block. Pictures of the principal stresses distribution around the roadway in this case are shown in figure 4 (friction ratio 0.5, reinforced area deformation modulus 1 GPa).

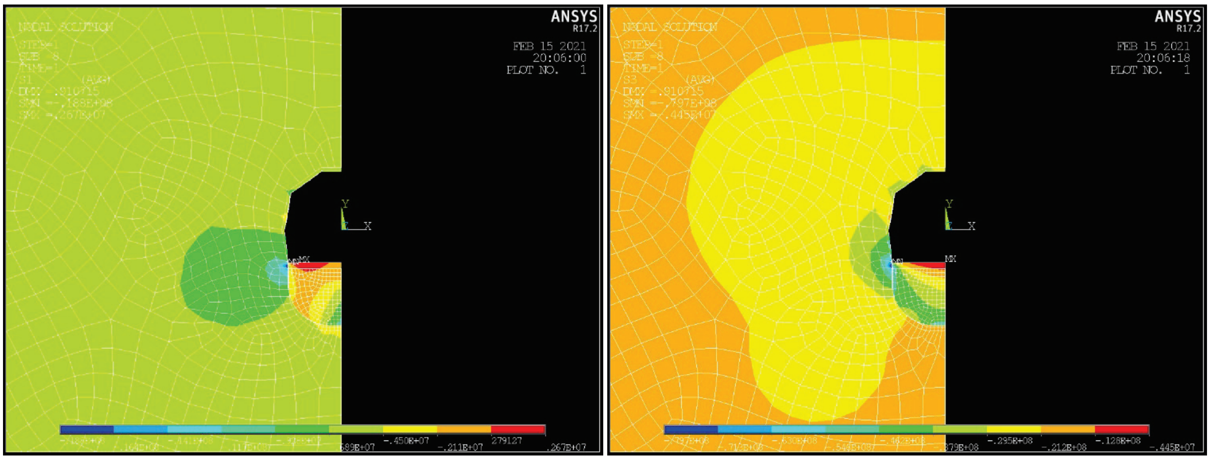


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Figure 4. Pictures of maximum σ_1 (a) and minimum σ_3 (b) of the principal stresses distribution around the roadway with floor strengthening in the form of a reverse arch.

The analysis of the maximum principal stresses σ_1 distribution (figure 4a) made it possible to conclude that a reduced stresses zone has formed in the roadway floor, as in the basic problem, in this case its size and shape coincide with the area strengthened in the reverse arch form. In this case, increased stresses were formed in the lower part of the strengthened zone, caused by compression of the inverse at the contact with the non-strengthened area. This led to the squeezing out of the strengthened zone into the roadway hollow. Reduced stresses were formed in the floor border area.

Analysis of the principal minimum stresses σ_3 distribution pictures (figure 4b) shows that the drift sides and roof SSS is similar to the basic problem. The differences observed in the floor are associated with the movement of the strengthened area toward the roadway.

The rock reinforcing quality influence on the amount of heave is shown on the graphs in figure 5. An indicator characterizing the strengthening quality is the reinforced rocks deformation modulus. In the simulated range, it can be assumed that the smaller the deformations the strengthened mass acquires under loading, i.e. the higher its deformation modulus, the higher is the strengthening quality. According to figure 5, it is obvious that an increase in the strengthened rocks deformation modulus leads to a decrease in floor heaving.

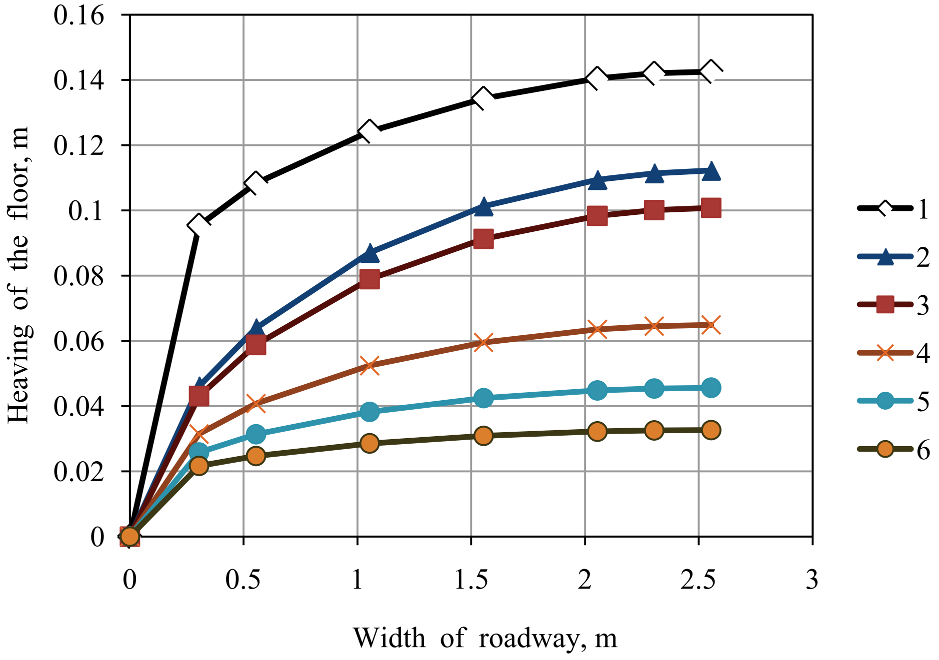

Figure 5. Graphs of the dependence of the roadway floor heaving on the deformation modulus of the reinforced area with a friction ratio of 1: 1 – without reinforcing; 2, 3, 4, 5, 6 – reinforced zone in the form of a reverse arch with a deformation modulus of 0.5, 0.75, 1, 5, 7.5, 10 MPa, respectively.

To estimate the influence of the module of rock deformation (E_{def}) in the reinforced zone on the amount of heaving of the floor (U_{fl}), we introduce a relative indicator - the floor heaving reduction ratio during reinforcing (k_{fl}), which is numerically equal to the floor heaving magnitude ratio after reinforcing to heaving without reinforcing. The graph of this parameter change is shown in figure 6. Based on the results of the mathematical modeling, a curve was constructed that is sufficiently well approximated by the power dependence $k_{fl} = 0.7029E_{def} - 0.487$ with an approximation reliability close to unity. The presented graph analysis allows us to conclude that an increase in the rocks deformation modulus as a result of reinforcing by 20% makes it possible to reduce heave by more than half, after which the efficiency of reinforcing decreases, and a further increase in the deformation modulus by another 80% provides only about 20% reduction in heaving.

The graphs shown in figure 7, reflect the dependence of floor heaving on the friction ratio between the strengthened and non- strengthened areas of the rocks. At the same time, the presented results describe the situation when the strengthened rocks deformation modulus is 1 GPa. A series of experiments have shown that a decrease in the friction ratio equally negatively affects the preservation of floor stability, regardless of the strengthened area deformation parameters.

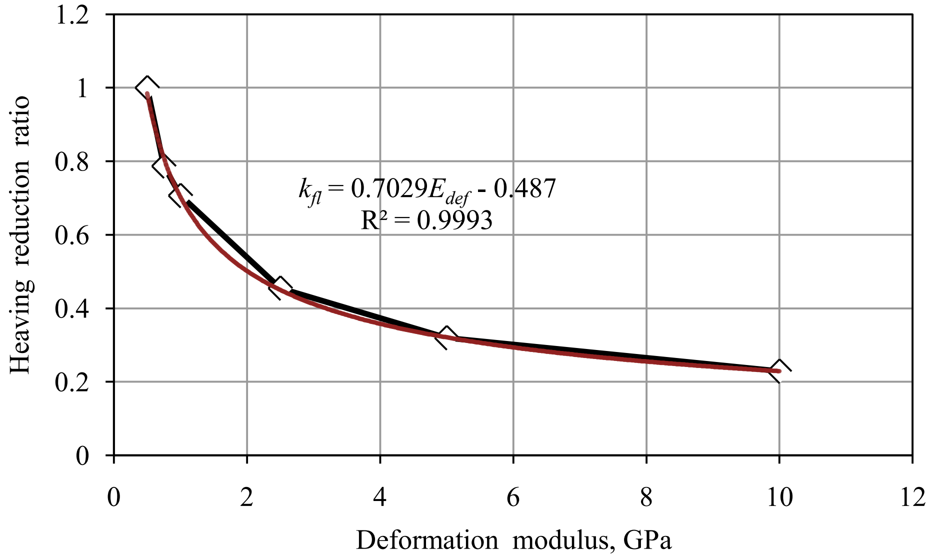

Figure 6. Graph of the dependence of the heaving reduction ratio on the reverse arch form reinforced area deformation modulus.

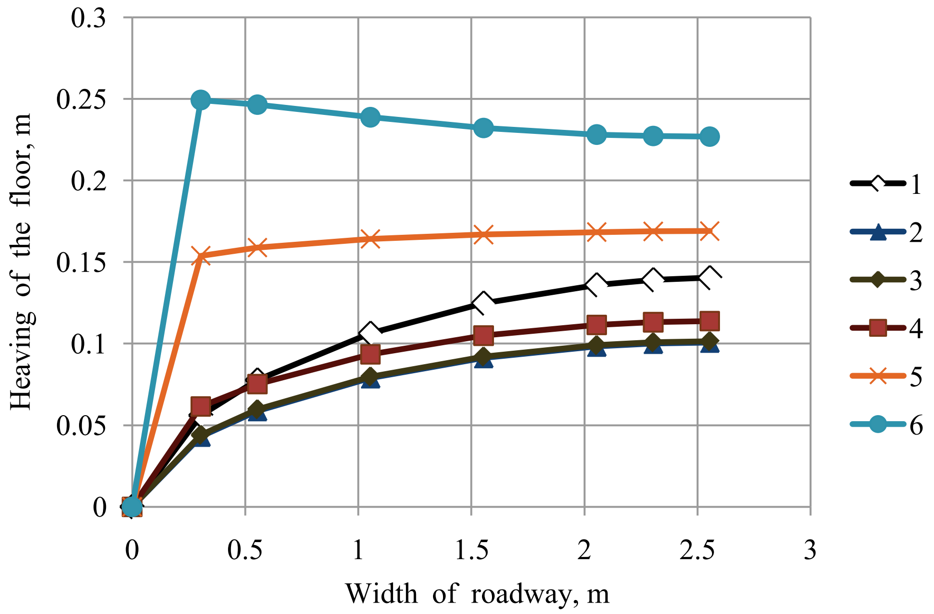

Figure 7. Graphs of the dependence of the roadway floor heaving friction ratio between the reverse arch form strengthened zone and the massif: 1 – without strengthening with a friction ratio of 1; 2, 3, 4, 5, 6 – reverse arch form strengthened zone with a friction ratio of 1, 0.75, 0.5, 0.3, 0.1, respectively.

From the presented graphs (figure 7) it can be seen that a decrease in friction leads to an increase in heaving, which is generally logical. However, the distribution of heaving over the roadway width changes its character from a certain value of the friction ratio. In the experiment carried out, this can be seen from the difference in the types of rock heaving with a friction ratio of 0.3 and 0.5. The difference is noticeable not so much in the floor rise maximum magnitude in the center of the section, but in the distribution over the width. With a friction ratio of 0.3, the floor "slips" by a common block, which is characterized by a jump in the heaving curve in the area between the lining leg (point 0 on the graph) and the distance from the leg 0.25 m. A decrease in the friction ratio to 0.1 leads to a noticeable increase of floor deformation, while heaving develops according to a mechanism similar to that described above.

Furthermore, the phenomenon of reinforced area extrusion by a common block can be observed from the stress distribution isolines. Thus, the effectiveness of floor rock reinforcing during the reverse roof formation is largely determined by the friction between reinforced and non-reinforced rocks.

The simulation results are summarized in the graph in figure 8, which shows the dependence of the heaving change coefficient on the friction ratio between rocks. The heaving change coefficient reflects the ratio of the maximum heaving in the center of the roadway span with floor reinforcing to a similar indicator without reinforcing.

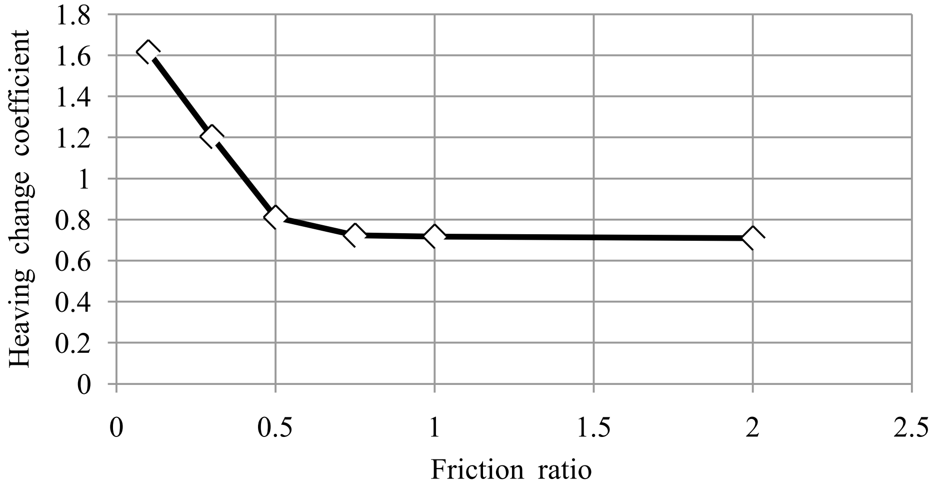

Figure 8. Graph of the dependence of the heaving change coefficient on the friction ratio between the reverse arch form reinforced zone and the massif.

Analysis of the graph indicates that the reinforcing efficiency decreases when the friction ratio decreases below 0.6. Until this moment, the effect of friction between reinforced and non- reinforced rocks on heaving has not been shown, and already with a friction ratio of 0.5, a sharp negative impact begins.

The experiments have shown that the friction ratio of dry siltstone against siltstone is 0.65, argillite against argillite is 0.62, concrete against siltstone is 0.6, and concrete against argillite is 0.55. However, if we take into account the well-known effect of reducing the of friction ratio when wetting the contact surfaces, then the probability of a mechanism for extruding the reinforced area by a common block is obvious.

To ensure the stability of the floor in such difficult conditions, it is necessary to develop a method for heave counteracting, based the creation of locally reinforced zones of a special shape in the floor, which allow maintaining stability even with a low rock friction ratio. The development of such method is based on the idea of forming a spacer system of increasing resistance. A mechanical analogue, allowing to provide the desired effect, is the wedge spacer. On the basis of a well-known principle of operation of the wedge device, the developed method idea dealing with heaving was developed, in which it was proposed to create a roadway floor reinforced area in the form of a wedge directed with a sharp edge towards the roadway floor.

Prospective modeling showed that high efficiency of heave counteracting by a wedge form reinforced zone is provided only in the case when a wedge created from strengthened rocks "expands" into the sides of the roadway, otherwise it is also squeezed into the hollow, like the reverse vault. In this case, the best effect is achieved when two additional local hardened zones are created in the sides of the roadway, acting as a wedge socket.

Pictures of the distribution of the principal stresses around the roadway in this case are shown in figure 9 (coefficient of friction 0.5, reinforced areas deformation modulus of 1 GPa).

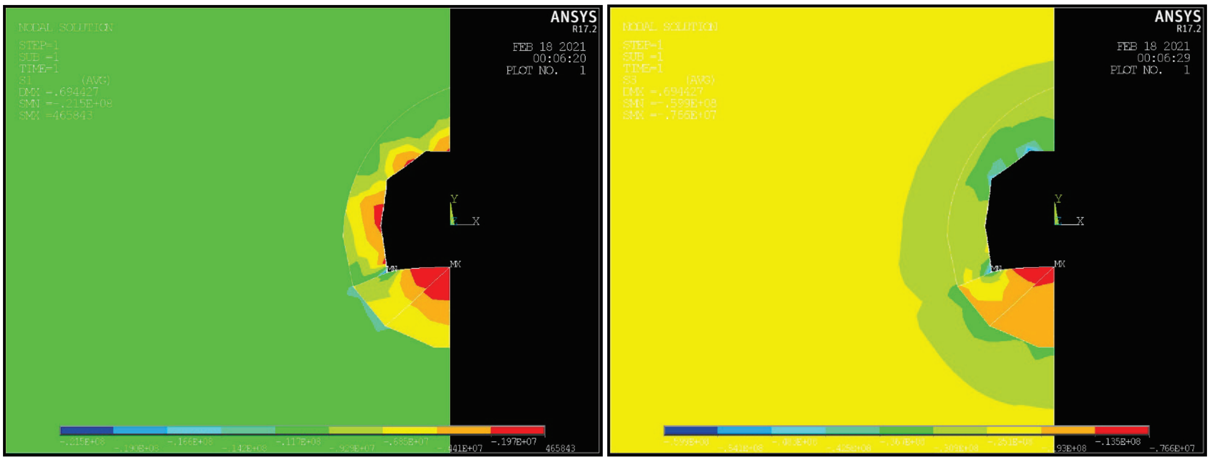

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Figure 9. Pictures of the distribution of the principal stresses maximum σ_1 (a) and minimum σ_3 (b) around the roadway with floor reinforcing according to the proposed method.

Analysis of stress distribution around the roadway shows that in the section floor, when implementing the proposed method, a deformation mechanism develops different from those shown in figures 4 and 5. Although, as in the problem with a reverse vault, in the boundary part of the reinforced area, reduced stresses arise, which is explained by the rocks unloading toward the roadway floor and their corresponding displacement. However, the vertical movement of the central part of the locally rock reinforced area toward the roadway hollow is accompanied by horizontal indentation of the side reinforced zone into the rock massif in the side of the roadway and an increase in the resistance to movement. The expansion causes an increase in stresses between the side of reinforced zone and the massif, which can be seen in figures 9a, b. Thus, the expected effect is achieved.

To assess the effectiveness of the proposed method, it is necessary to proceed to the analysis of quantitative indicators. The effect of the reinforced rock mass deformation modulus on the amount of heaving with sufficient friction cannot differ significantly from the previous problem. Therefore, we will focus on the effect of the friction ratio.

The graphs of the dependence of floor uplift on the rocks friction ratio are shown in figure 10. The first distinctive feature of heaving, when implementing the proposed method, is that the maximum rise is not observed in the center of the span. This is due to the fact that in the span center there was a wedge angle of the reinforced central zone, which rose less than the rocks of the side reinforced zones. The second important feature is that all the floor uplift graphs are lower than the baseline, which characterizes heaving without rock reinforcing. That is, even with a friction ratio of 0.1, the proposed method provides lower heaving values than in the case without reinforcing. This favorably distinguishes it from reverse vault form reinforcing, where, with a similar friction ratio, heaving is greater than in the baseline version. A safety margin is the fact that a decrease in friction between rock fragments in the base case will also cause an increase in floor heave. However, even without taking this into account, it can be seen that the proposed method provides high efficiency.

Obviously, the modeling performed is idealized and reflects only the mechanistic side of the issue, but the results obtained indicate the correctness of the chosen direction of research. The effectiveness of the proposed method of heave counteracting according to the results of mathematical modeling is obvious. To implement the proposed mechanism for the operation of locally reinforced zones, it is necessary to develop a method for forming a reinforced area with specified parameters in the roadway floor, conduct its full-scale tests and, on the basis of the identified shortcomings, create a technology for strengthening the roadway floor.

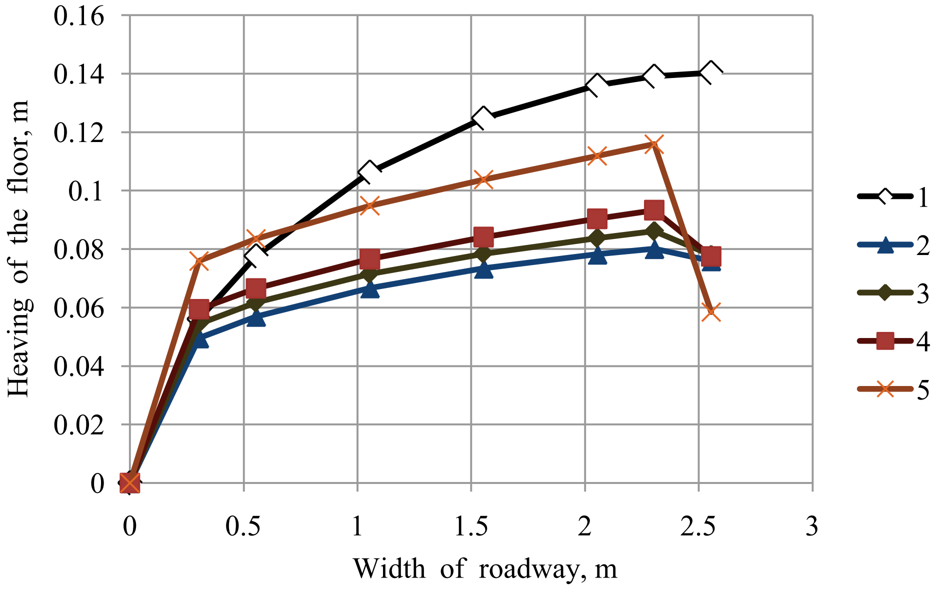

Figure 10. Graphs of the dependence of the floor rocks heaving on the friction ratio between the floor rocks reinforced zones according to the proposed method: 1 – without reinforcing with a friction ratio of 1; 2, 3, 4, 5 – reverse arch form reinforced zone with a friction ratio of 1, 0.5, 0.3, 0.1, respectively.

3.2. The proposed method for local floor reinforcing Numerical

Taking into account the above ideas about the causes and mechanism of floor heaving in the mining-affected zones, a method of heave counteracting is proposed, based on the creation of locally reinforced zones of a special shape in the floor [21].

The method is based on the idea of achieving the formation of a spacer system of increasing resistance in the base, by creating locally reinforced zones with destroyed rocks. It works with a low floor rock friction ratio, which would ensure the rock stability in a block-discrete massif in intense heaving zones.

In the developed method, the roadway floor is strengthened by bonding solutions injected through wells drilled into the roadway floor. In this case, the wells are drilled in such a way that three locally reinforced zones are formed in the roadway floor after injecting the solution: the central one in the form of a straight prism, at the base of which is an equilateral trapezoid, the height of which approximates the vector of maximum deformations of the floor rocks, and two lateral zones, each of which is in the shape of a straight prism, at the base of which is a rectangular trapezoid, the base of which is parallel to the trapezoid lateral side of the base of the central prism (figure 11). To implement the method, it is advisable to use a bonding solution, which has a mobility of at least 30 cm according to the cone spreading test. It can be a solution based on a mineral binder, resin or polymer composition.

Drilling wells in such a way that three locally reinforced zones are formed in the floor makes it possible to create a spacer saving system. The growth of the zone of inelastic deformations provokes the movement of rocks toward the roadway floor, contributes to the movement of the central reinforced zone relative to the lateral ones, and its expansion between them. The resistance of the existing spacer system to the movement of rocks will rise with increasing pressure on the lower part of the central reinforced zone. Orientation of the reinforced zones in such a way that the height of the trapezoid of the base of the straight prism, which forms the central reinforced zone, approximates the vector of floor rock maximum deformations, provides maximum resistance to the floor rock movement into the roadway hollow. Thus, the roadway floor rock stability in the block-discrete massif in the mining-affected zones is ensured.

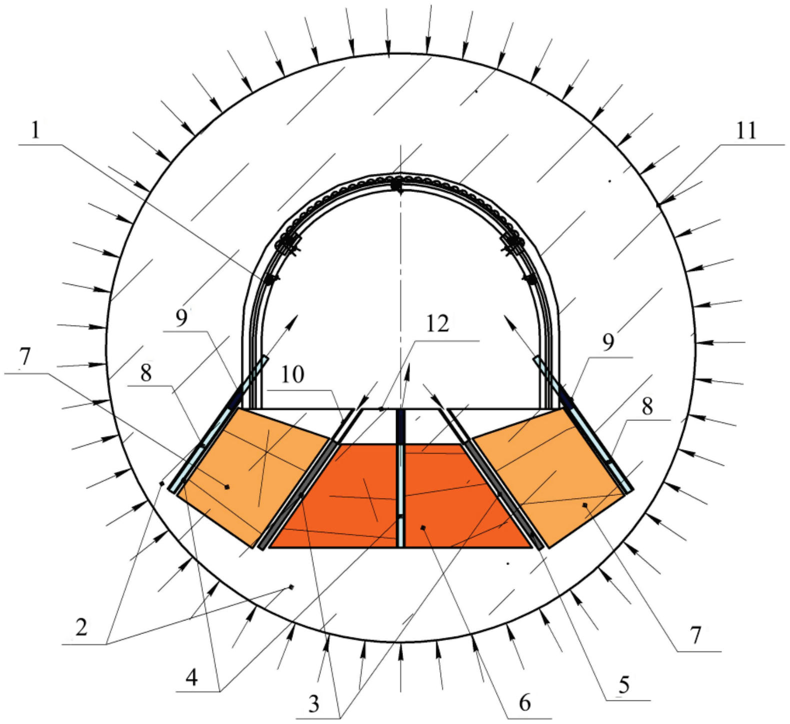

Figure 11. Method of local floor reinforcing [20]: 1 – roadway, 2 – boundary rocks, 3, 4 – wells, 5 – bonding solution, 6 – central locally reinforced zone, 7 – lateral locally reinforced zones, 8 – steel pipes, 9 – packers, 10 – casing pipes, 11 – zone of inelastic deformations, 12 – roadway floor.

4. Conclusions

Despite the noticeable progress in the methods of roadway lining and maintenance over the past half a century, the problem of floor heave remains relevant. Significant success in ensuring the floor rock stability in the roadways located in mining-affected zones at great depths has not been achieved yet. Based on the analysis of the literature, it has been established that rock reinforcing is the most promising way to counteract heaving. The mechanism of the roadway floor heave, which is maintained in the zone of destroyed rocks without floor strengthening and during strengthening, has been established. Based on the performed numerical analysis of the rock mass stress-strain state, the influence of the reinforced rock deformation modulus and the floor rock friction ratio on the amount of heaving in mining-affected roadways is shown. Taking into account the identified disadvantages of floor reverse vault form strengthening, a method of heave counteracting is proposed, based on the creation of floor special shape locally reinforced zones, which allows creating a spacer system of increasing resistance in the massif. The effectiveness of the proposed method and the ability to maintain stability even with a low rock friction ratio have been proven. Such a solution to floor rock heave counteracting is proposed for the first time, which is confirmed by the patent, received for this invention.

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