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JUSTIFICATION OF THE PARAMETERS OF INJECTION ROCK HARDENING ZONES AROUND MINING WORKINGS AND BURIED STRUCTURES OF CRITICAL INFRASTRUCTURE

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Abstract. The article is devoted to the substantiation of the parameters of hardened zones around mine workings and buried structures of critical infrastructure, taking into account the established patterns of changes in the stress-strain state of rocks. The purpose of the work is to determine the rational shapes and sizes of injection rock hardening zones to increase the stability and operation safety of mine workings and buried structures. Methods: analysis and generalization of data on rock deformation; mine observations; mathematical modeling of geomechanical processes using the finite element method. The features of rock deformation and of underground workings and structures stability loss were analyzed. It was established that rock hardening compensates for the drawbacks of traditional supporting systems without significantly increasing costs. At the same time, the use of various configurations of rock hardening zones allows the supporting system to be adapted to specific conditions, minimize stress concentrations, prevent local collapses, and stabilize the rock mass. The criteria for the effectiveness of injection hardening technology are two main indicators: a reduction of rock volumes that will be deformed with an increase of structural defects, and a decrease in stress concentration. A comparative analysis of hardening zones of various forms showed that the maximum reduction in the volume of inelastic deformation zones up to 85% was obtained when using a smoothed elliptical configuration and up to 71% - when using a scheme with increased coverage of the side parts of the roof. The method of adaptive design of hardening zones was further developed, when shape of hardening zone corresponds to the locality of the forecasted zones of inelastic deformations and has the smoothest boundaries. The adaptive approach assumes that the strengthening zones should not be strictly geometric or unified. On the contrary, they are planned in such a way as to correspond as much as possible to the real conditions of inelastic deformation of the massif with taking into account the variation of the rocks properties, the depth of occurrence, the expected dynamics of stress changes and watering of rocks. This allows locally increasing the strength of rocks, reducing fracturing, preventing the penetration of gases and water into the workings or structure.

Keywords: stability of workings and structures, safety of structures operation, injection hardening of rocks, stress-strain state, geomechanical processes.

1. Introduction

The main difference between mine workings and other types of underground structures is that they are located at great depths from the earth's surface and are mined for the purpose of minerals extraction. Mine workings are completely underground objects and require complex technological solutions to ensure safety and durability due to great depths, high pressure, temperature conditions and ventilation. Buried structures are most often called shallow underground objects, partially or completely located underground and intended for various purposes in urban or industrial infrastructure. This applies, for example, to shallow water pipes and tunnels, underground parking lots and bomb shelters. Buried structures require less complex support systems, since they are located closer to the earth's surface and are less exposed to extreme factors. At the same time, maintaining them in a stable state is no less important.

Underground working and structure stability loss is associated with the mechanical behavior of rocks due to their complex internal structure and the influence of external factors. The nature of deformation depends on the type of rocks (elastic, brittle or plastic), their fracturing, humidity and the presence of cavities. As a result, underground workings and structures are subject to various forms of destruction in the form of collapse of the arch, squeezing out of rocks from the side of the base or walls, as well as water and gas breakthroughs [1–3]. These processes are activated due to changes in stress gradients, exceeding the strength limit of rocks, as well as the presence of tectonic faults or weak zones during flooding. There is a need to urgently monitor the stability and operation safety of the structures [4–7].

It is obvious that one of the controllable factors that significantly influence the increase in the stability of an underground structure of any type is a change in the physical and mechanical properties of rocks, primarily their strength. Increasing the strength of rocks around an underground structure can be achieved in various ways (by constructing anchors, deep injection hardening , freezing, silicification, cementation, tamping of the anchored area, etc.), many of which are currently actively used both independently and in combination with other types of fastening [8, 9], which allows using the bearing capacity of rocks.

Injection hardening of the underground working roof is a progressive method for stabilizing rocks based on changing their physical and mechanical properties through the injection of strengthening compounds [10-13]. The essence of the method is to change the internal structure of rocks and to control redistribution of stresses around the working. Injection materials, penetrating into pores and cracks, bind separate blocks and fragments of rock, increase their adhesion, improve strength properties and reduce fracturing. This allows not only to locally increase stability, but also to stabilize the surrounding massif by reducing the concentration of stresses that can initiate destruction. In addition, fracturing reduce prevents the penetration of gases and water into the working.

In practice, it is necessary to use various configurations of hardening zones, which must be adapted to the specific conditions of the workings location, which allows minimizing stress concentrations and preventing the occurrence of local rock failures. At the same time, the heterogeneity of rocks, the complexity of geological conditions and the nature of loads leads to uncertainty in the stress-strain state of rocks, and, consequently, the parameters for applying injection hardening technology. Therefore, the method for substantiating the parameters of hardened zones requires further improvement in order to ensure maximum efficiency of measures to increase stability, as well as rational distribution of strengthening materials and reduction of resource costs.

The purpose of the work is to determine the rational shapes and sizes of injection rock hardening zones to increase the stability and operation safety of mine workings and buried structures.

2. Methods

Analysis and generalization of data on rock deformation around mine workings and buried structures; mine observations of rock deformation and destruction; mathematical modeling of geomechanical processes using the finite element method to determine rational forms and parameters of injection hardening zones.

3. Results and discussion

First, it should be emphasized that the injection hardening technology, unlike many other methods, allows for the creation of hardening zones of arbitrary configuration. This is done by drilling holes of different lengths in arbitrary directions and then injecting special mixtures under high pressure [14]. At the same time, it is impossible to determine the rational forms and parameters of injection hardening zones without mathematical modeling. The modeling results allow us to determine the stability of rocks and justify the parameters and forms of hardening zones. The modeling determines the zones of destruction of rocks that require hardening, the stages of crack development in them, concentrations and sharp changes in the main stresses. In addition, the tasks of increasing the stability and operation safety of workings and structures are associated primarily with the targeted optimal use of hardening methods to reduce stresses and deformations in the rock massif.

The main parameters of hardening are the physical and mechanical characteristics of rocks after the application of hardening technology (depend on the selected hardening method), as well as the shape, size and locality of the contour of the development of strengthened zones. The key characteristics that determine the effectiveness of strengthening are the achieved strength and increased bearing capacity of rocks. These parameters depend on the mineralogical composition, fracturing, degree of water saturation and plasticity of rocks. When hardening , the emphasis is on increasing the ultimate strength of rocks for compression, tension and displacement, as well as increasing the modulus of elasticity and the angle of internal friction. At the same time, the technological parameters of hardening are the penetration depth of strengthening mixtures (with injection hardening methods), the strength of rocks in the hardening zone, the rate of hardening (ensures the stability of the massif during strength gain). A set of measures allows you to redistribute stresses in the massif, reduce their concentration in the most vulnerable zones.

In general, the sequence of solving the problem consists of: calculating the stresses and deformations of the rock massif around mine workings and structures using the finite element method, identifying zones of inelastic deformations and sharp stress changes, assessing changes in the stress-strain state of the rock massif for various forms of the hardening zone.

To study the effect of hardening zones on the stability of the working, changes in the stress-strain state of the rock massif were determined using the methodology [2, 15-18]. Inelastic states of rocks are calculated using the Mohr-Coulomb criterion:

$$\tau = \sigma_n \cdot tg + \tau_0 , \qquad (1)$$

where τ is shear stress, Pa; σ_n is stress normal to the rock shear site, Pa; φ is internal friction angle, degree; τ_0 is shear strength (cohesion), Pa.

The tensile strength was limited by the criterion $\tau_0/5$. If one of the limiting conditions is fulfilled, then the rock massif stress-strain state and inelastic deformation zones are determined by combination of finite element method and procedure of the initial stress method (a set of calculations are performed with a constant system stiffness matrix). The procedure of the simulation algorithm was implemented in the computer complex “GEO-RS©”. Testing of geomechanical models using examples of comparison of theoretical, laboratory, mine and model experiments was previously carried out many times and is featured in various publications [16, 18, 19]. The deformations difference in the model and laboratory experiments did not exceed 10%. When solving complex mining problems, the error was within the range of 16% to 28%. Therefore, due to sufficient testing of the method and the obviousness of the geomechanical model verification results, these data are not provided.

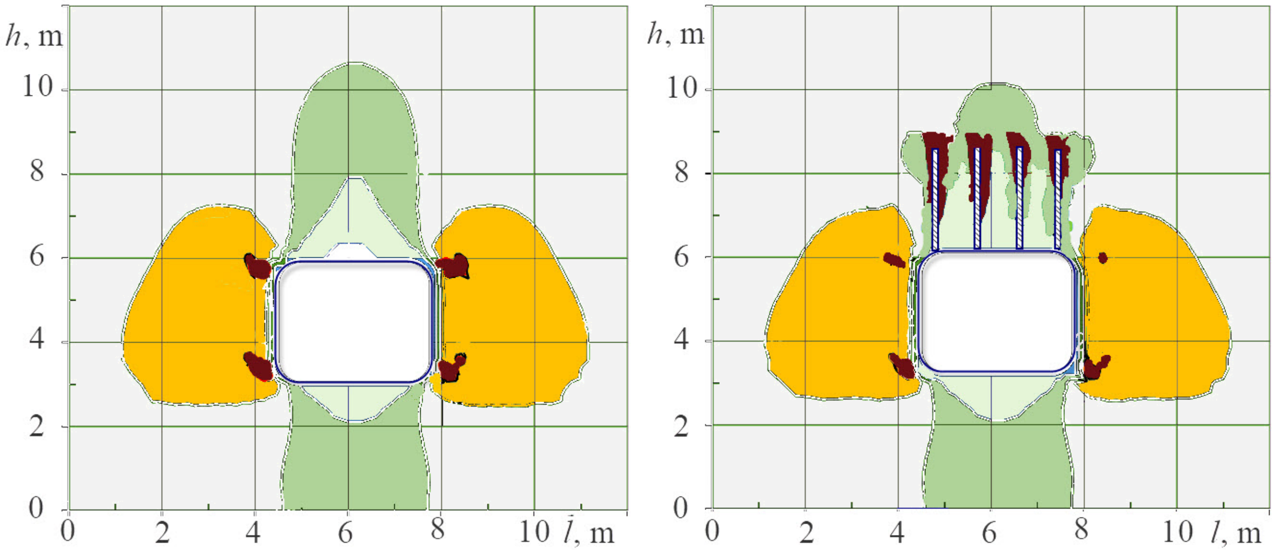
First, calculations of the stress-strain state of rocks were performed without additional hardening, and then by using the roof hardening technology. The first series of calculations was carried out for the worst conditions using the minimum strength properties of rocks. This approach allows us to determine the scenarios for the propagation of crack systems and to identify in advance the location of the most dangerous areas around the working that require additional measures to hardening the roof. Calculations were performed for different stages of the deformation process (a series of quasi-stationary states simulating the deformation process over time). After that, to be able to compare different options, a series of calculations of different shapes, sizes and locality of hardening zones along the contour of the working were performed.

The physical model of the rock massif with dimensions of 25×25 m was digitized in the form of triangular grid with 7200 finite elements and 3721 nodes. Properties of the surrounding rock massif (mudstone) were as follows: elastic modulus $E=3.5\cdot10^4$ MPa, Poisson's ratio $\mu=0.29$, volume weight $\gamma=2.4$ t/m^3, shear strength $\tau_0=6.2$ MPa, internal friction angle $\varphi=35$ deg.; stronger hardening zone – $E=9.5\cdot10^4$ MPa, $\mu=0.3$, $\gamma=2.9$ t/m^3, $\tau_0=50$ MPa, $\varphi=40$ deg.; less strong hardening zone – $E=4.0\cdot10^4$ MPa, $\mu=0.28$, $\gamma=2.6$ t/m^3, $\tau0=8.1$ MPa, $\varphi=37$ deg. The upper sector of the design scheme was set movable in vertical direction, and the lower one was fixed in two directions.

Calculations showed that the maximum principal stresses in the hardening zone (Fig. 1) increase due to the fact that injection materials or hardening compositions change the physical and mechanical properties of rocks, making them more rigid and durable. As a result, this zone takes on most of the load from the rock pressure, playing the role of a redistributing stress barrier. At the same time, a decrease in maximum stresses is observed in the surrounding rocks.

Figure 2 shows the contour lines of the results of comparing the stresses in the rocks of an unsupported working and a working with a hardened roof. This approach allows us to identify zones of sharp changes in the main stresses as a result of the working support. The stresses in the upper part of the hardening zone turned out to be among the highest throughout the working. It is evident from the figure that the roof hardening leads to an increase in stresses at the upper boundary of the hardening zone by 2.0–2.5 times, and the greatest stress differences are formed in the corners of the working roof.

The initial study led to the conclusion that the hardening zone should be created in areas of the greatest stress difference, since these areas are characterized by a high level of stress concentration and the largest areas of inelastic deformation. It is in such zones that stresses often exceed the ultimate strength of rocks, which leads to cracks, local failures and further roof collapse. Given the fact that modern injection hardening technologies allow creating various configurations of hardening zones, this approach opens up wide opportunities for adapting the hardening technology to specific geomechanical conditions. Various configurations of strengthened zones can take the form of local hardening zones, continuous hardening zones or zonal barriers, which allows for the most effective impact on the massif, reducing the risks of failure and ensuring the stability of workings.



without hardening of roof rocks | injection hardening of roof rocks

Ranges of maximum principal stresses in MPa units:

- 0.0…0.4 ; - 0.4…0.8; - 0.8…1.2; - 1.2…1.8; - > 1.8

Figure 1 – Distribution of maximum principal stresses concentration around the workings

The initial study led to the conclusion that the hardening zone should be created in areas of the greatest stress difference, since these areas are characterized by a high level of stress concentration and the largest areas of inelastic deformation. It is in such zones that stresses often exceed the ultimate strength of rocks, which leads to cracks, local failures and further roof collapse. Given the fact that modern injection hardening technologies allow creating various configurations of hardening zones, this approach opens up wide opportunities for adapting the hardening technology to specific geomechanical conditions. Various configurations of strengthened zones can take the form of local hardening zones, continuous hardening zones or zonal barriers, which allows for the most effective impact on the massif, reducing the risks of failure and ensuring the stability of workings.

The criteria for the efficiency of this technology are two main indicators: a decrease in the volume of rocks that have experienced increased fracturing and destruction, and a decrease in the stresses concentration in rocks close to the workings contour. A decrease in the volume of inelastic deformation zones indicates an increase in the strength of rocks and their ability to withstand rock pressure without becoming unstable. This, in turn, prevents formation of cracks, local shifts and collapses. A decrease in stresses concentration indicates a redistribution of rock pressure to stronger and hardened sections of the massif, which reduces the load on weak zones. This helps prevent premature failure of the support, especially in difficult conditions of rock pressure (flooding, dynamic loads) or deep location of workings. Subsequent studies, including numerical modeling and previously conducted full-scale experiments, confirmed that the placement of hardening zones in places of the greatest stress differences significantly reduces the likelihood of rock failure.

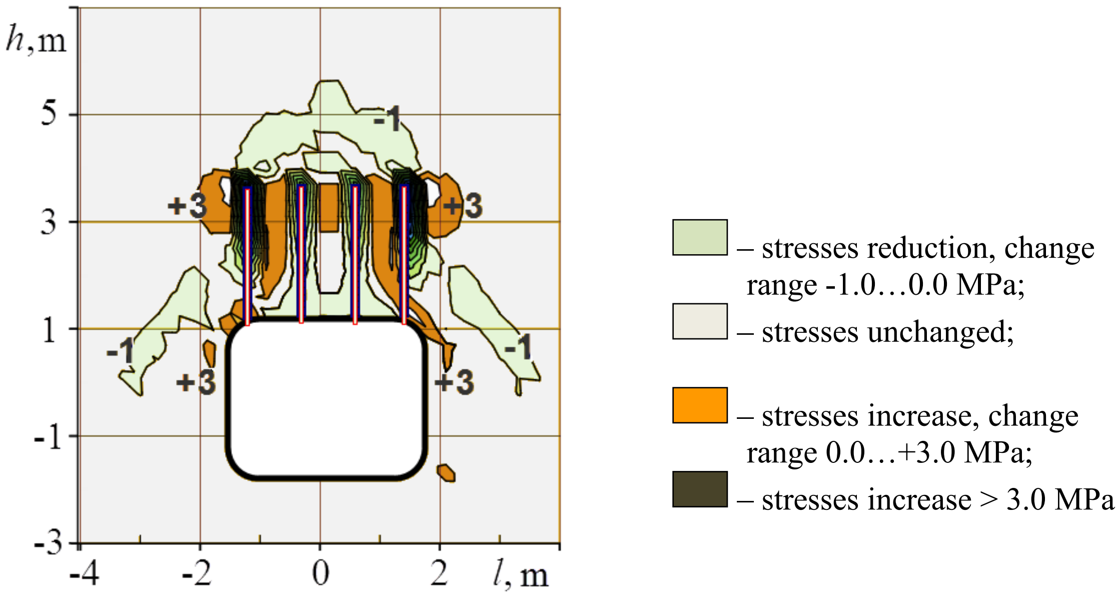


Figure 2 – Resulting diagram of changes in maximum stresses after applying roof hardening technology

At the next stage of mathematical modeling, the shapes and parameters of the hardened zone were determined in the first approximation, i.e., the fundamentally best shapes for a relatively wide range of conditions (averaged data on the physical and mechanical properties of rocks). The calculations were performed for a symmetrical working without the effect of tectonic pressure. For clarity, the calculation was made for conditions when the working was driven without strengthening the roof, which makes it possible to conduct a comparative analysis of the initial state and the state after hardening the roof (Fig. 3).

Let us compare the calculations of an unsupported working and a working supported by a rectangular hardened zone in the roof. In the absence of hardening, ruptures are observed in the central part of the roof, which can lead to the collapse of deformed rocks. In the corner parts of the roof, plastic deformation of rocks occurs, which also affects the sides of the roof to an even greater extent and goes beyond the corner parts of the workings floor. These deformations occur under the influence of unequal-component compression and are manifested through the development of closed cracks and the extrusion of rocks into the working, but usually without their collapse. Closer to the center of the workings floor, as in the central part of the roof, rupture deformations are formed, which can cause cracks and active swelling of the workings floor.

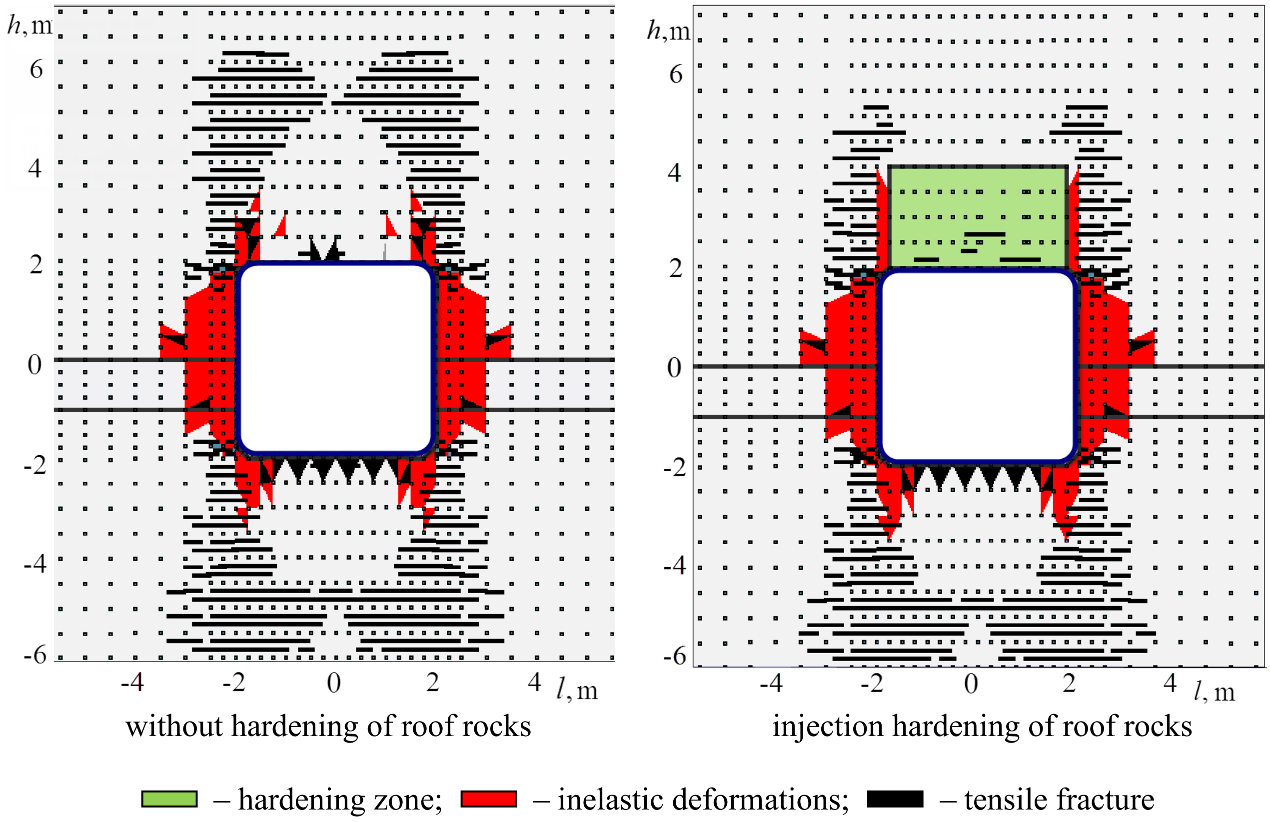
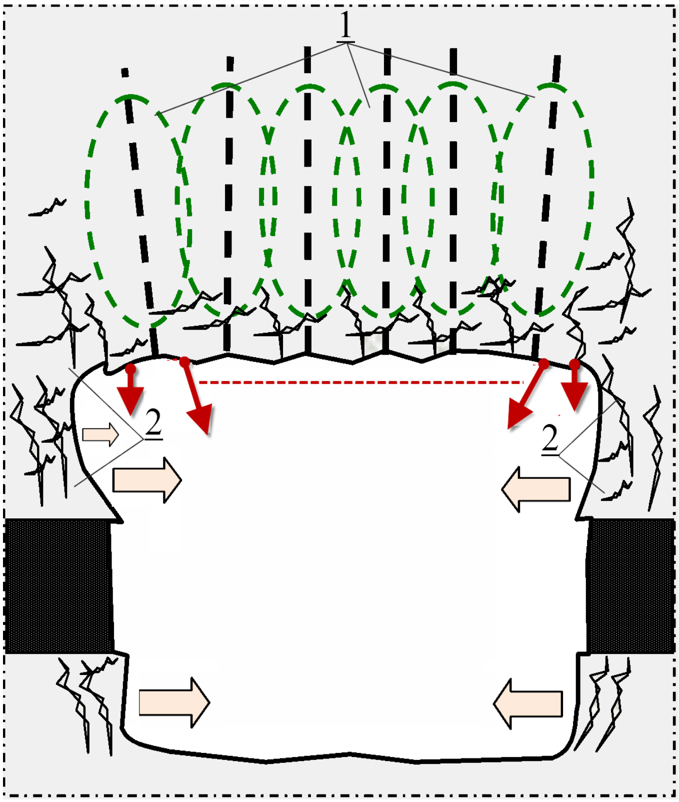


Figure 3 – Study of inelastic deformations and main cracks during the creation of a rectangular-shaped hardened zone in the center of the working roof

The creation of a rectangular hardening zone in the roof of the working significantly reduces the deformation of the hardened roof rocks, but at the same time increases the deformation of the massif in the upper corners. Such hardening of the roof can lead to rock collapse in the upper corners of the working and the emergence of systems of extended main cracks under the influence of rock pressure forces or a decrease in the strength of rocks during flooding. For example, such a process occurs in the Samarska mine (photo in Fig. 4), where anchor support is widely used to strengthen the roof. The nature of the deformation of the roof rocks, obtained from the results of field studies (shown in Fig. 4), confirms the data of mathematical modeling (Fig. 3). Zones of inelastic deformations and main cracks are formed along the boundary of stronger rocks, which in local areas leads to partial collapses of the roof in the upper corners of the working. As can be seen, the hardening zone has not only longitudinal cracks in the upper corners, but also transverse cracks along the entire width of the working (Fig. 4, a, b). This shows that the integrity of the roof is violated and it is divided into blocks that can collapse under dynamic impacts. At the same time, the collapse of the side rocks is mainly scattered in the flooded zones. In the worst case scenario, the collapse of the strengthened rocks along the entire length of the working is possible.

rock falls along the length of the working

rock falls in local areas



lateral squeezing and rock falls in the upper corners of the workings as a result of a decrease in rock strength during flooding (reconstruction of the deformation process)

1 – hardened zone with anchors; 2 – rock falls and collapse in the upper corners of the workings

Figure 4 – Formation of main crack systems along the boundary of the hardened zone in the upper corners of the workings using the example of mine research

In order to exclude a sudden collapse of the entire hardened zone into the working, a hardened zone in the form of a beam (Fig. 5) was investigated, which is deepened into the lateral parts of the working roof. With this approach, we eliminate the problem of rock destruction from compression in the corners of the working roof, but at the same time we get destruction of the hardened zone of the roof from tension in the center. The destruction of the hardened zone from tension in the central part is due to the insufficient thickness of the beam and specific nature of the stress-strain state that occurs with this geometric configuration.

A double increase of the hardened zone thickness leads to a partial decrease in tensile stresses in its central part, but this does not completely eliminate the problem of roof rock collapse in discontinuity zones. Such a modification causes new problems associated with an increase in stress concentration at the corners of the hardened zone. Rock deformations in these areas are caused by the redistribution of loads between the hardened zone and nearby rocks as a result of a change in the geometry of the hardened zone. An increase of the beam thickness increases its tensile resistance in the central part, which is the right solution, but at the same time it increases the rigidity of the system and leads to a concentration of stresses at the boundary of the hardened zone. It is obvious that rock damage in the corners of the hardened zone is caused by a local stress concentration characteristic for the geometry with sharp boundaries. Such stress concentrators provoke rock failure, especially under high loads or in the presence of tectonic stresses. To eliminate this problem, it is necessary to give the hardened zone a shape close to elliptical, which allows for the correct redistribution of stress. The elliptical shape of the reinforced zone ensures a smooth transition of stresses between the hardened zone and the adjacent rocks, as well as the elimination of peak stress values in the corner areas. This reduces the probability of localized destruction in the roof and in the rocks bordering the hardened zone. In addition, a more uniform distribution of stresses increases the overall stability of the workings, reducing the probability of cracks and destruction. Therefore, the hardened zone should be closer to the shape of an ellipse, which completely solves the problem of destruction in the roof.

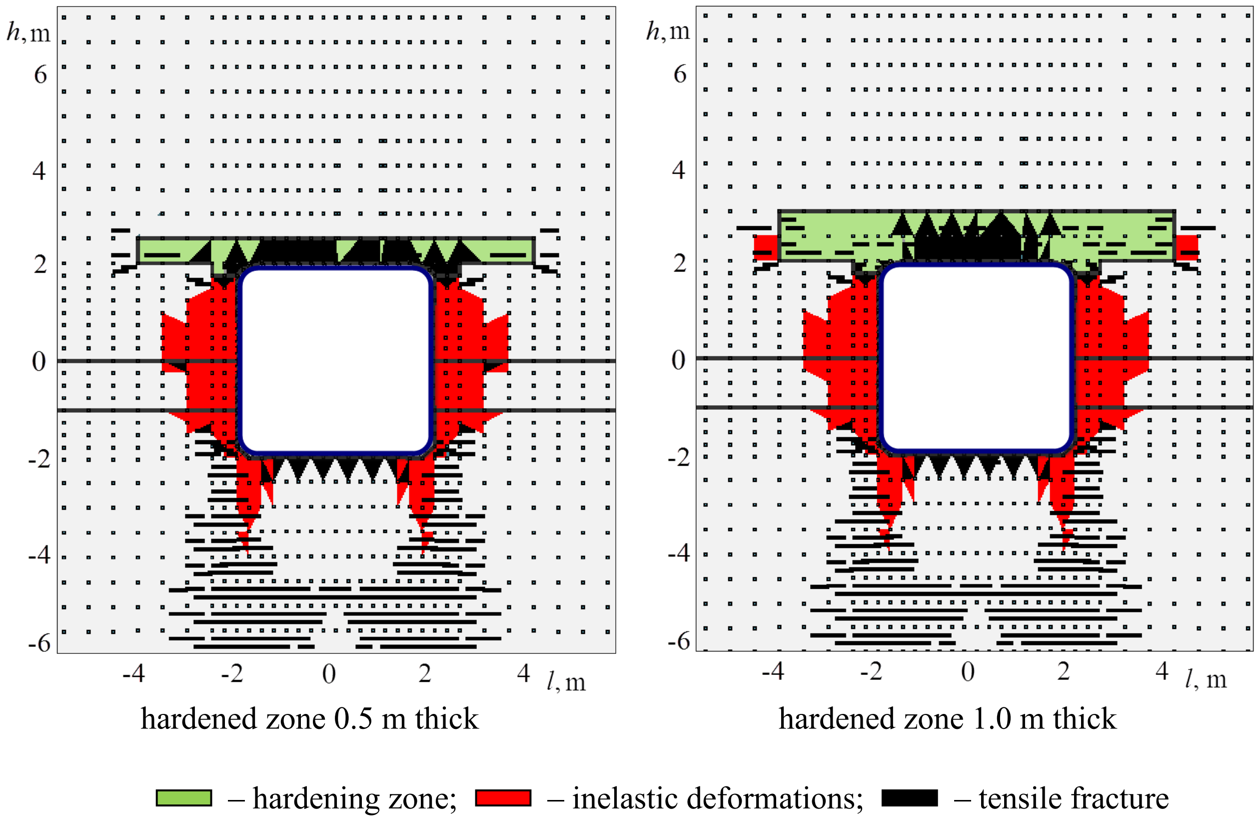


Figure 5 – Study of inelastic deformations and main cracks when creating a hardened zone in the form of a beam of different thickness with coverage in the side parts of the workings roof

A decrease in the strength of the hardened zone, for example, due to the use of low-quality materials, inevitably reduces its overall load-bearing capacity. However, even in conditions where such a zone remains stronger than the surrounding rock but weaker than the normal hardening, its presence still has a significant effect on reducing roof failure (Fig. 6). Even with reduced strength characteristics, the hardened zone reduces the stress concentration in the most vulnerable zones around the working. It results in a decrease in the intensity of roof and corner failures by up to 60% compared to an unhardened rocks (Fig. 3; Fig. 6).

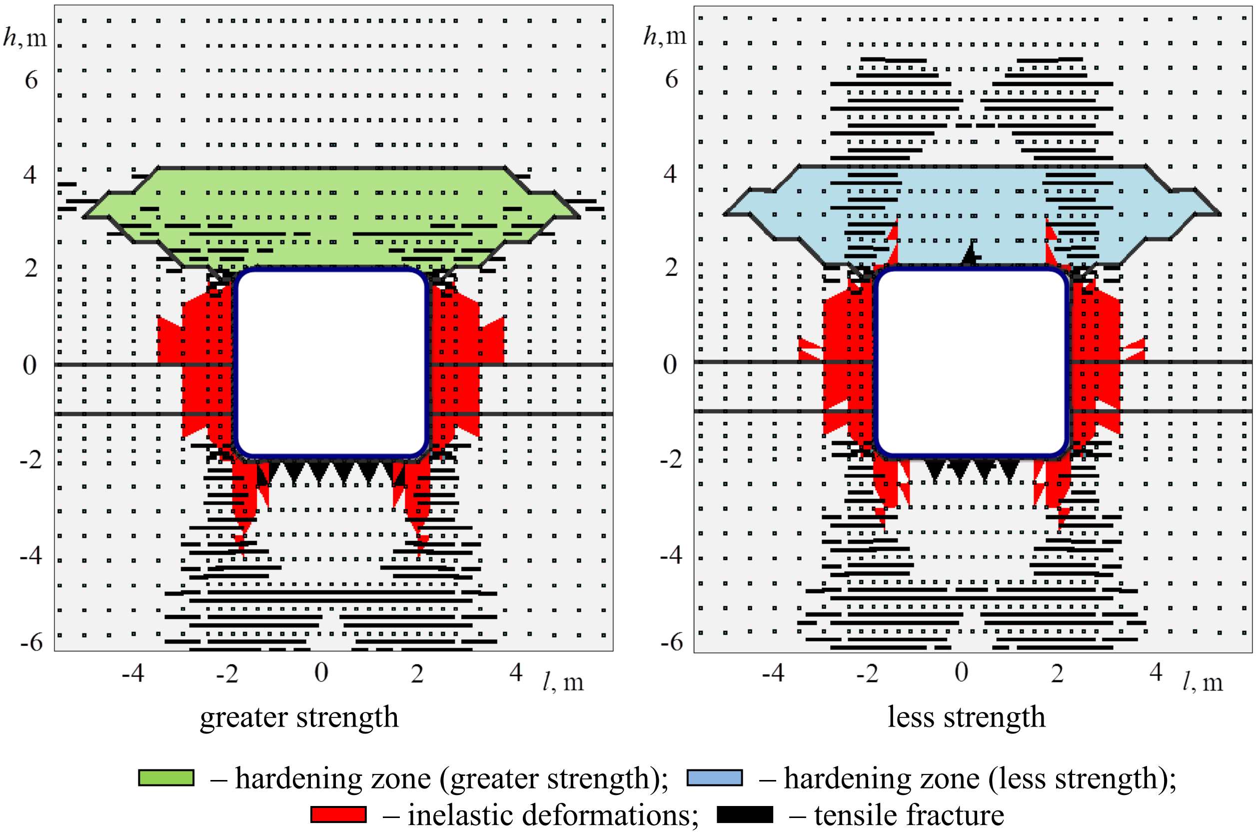


Figure 6 – Study of inelastic deformations and main cracks when creating a hardened zone of elliptical shape of different strength

It is explained by the fact that the hardened zone, even with its relatively low strength, prevents the development of local failure zones, which, if being unhardened, quickly develop into large-scale collapses. To improve efficiency in conditions of limited material quality, it is possible to combine materials with high plasticity or add reinforcing elements, which can partially compensate for the decrease in strength characteristics.

The results of calculating the volumes of inelastic deformation zones for different shapes of hardened zones are summarized in Table 1. The maximum reduction in the volumes of inelastic deformation zones in the roof was obtained when using an elliptical shape of the hardened zone with greater strength (Fig. 6), which demonstrates its high efficiency. A reduction in the volumes of inelastic deformation zones to 85% indicates that this form of force distribution allows for a significant reduction in the influence of loads on the roof, preventing its destruction and improving the overall stability of the workings. However, it is important to consider that such a configuration leads to a decrease in the stability of the sides, although moderately – only by 9%. This is due to the redistribution of stresses, in which the side parts begin to experience a greater load, compensating for the decrease in deformations in the roof.

Table 1 – Comparison of changes in the volumes of inelastic deformation zones for different shapes of hardened zones

Configuration diagram of the hardened zone	Volume of injection hardening per 1 m of working length, m^3/m	Volume of destroyed rocks per meter of working length, m^3			Changes +(-) to input state, %
		Tensile fracture	Inelastic deformations	Total	
Fig. 3, without hardening:					
- entire impact zone	0.00	1.00	9.38	10.38	-
- roof		0.25	1.50	1.75	-
- sides		0.00	6.38	6.38	-
- floor		0.75	1.50	2.25	-
Fig. 3, after hardening:					
- entire impact zone	7.00	0.69	9.75	10.44	0.6
- roof		0.00	1.50	1.50	-14.3
- sides		0.00	6.75	6.75	5.9
- floor		0.69	1.50	2.19	-2.8
Fig. 5, thickness 0.5 m:					
- entire impact zone	4.25	3.44	9.13	12.56	21.1
- roof		2.81	0.00	2.81	60.7
- sides		0.00	7.25	7.25	13.7
- floor		0.63	1.88	2.50	11.1
Fig. 5, thickness 1.0 m:					
- entire impact zone	7.50	3.00	9.69	12.69	22.3
- roof		2.38	0.31	2.69	53.6
- sides		0.00	7.50	7.50	17.6
- floor		0.63	1.88	2.50	11.1
Fig. 6, high strength:					
- entire impact zone	14.50	0.75	8.81	9.56	-7.8
- roof		0.13	0.13	0.25	-85.7
- sides		0.00	7.00	7.00	9.8
- floor		0.63	1.69	2.31	2.8

Taking into account the findings of the studies conducted under difficult conditions of weak and waterlogged rocks, it is proposed to construct adaptive hardening zones taking into account the locality of destroyed rocks (Fig. 7). This solution is based on the adaptive design of hardened zones, when the form of hardening corresponds to the locality of the forecasted zones of inelastic deformations and has the smoothest boundaries to avoid stress concentration (Fig. 8).

Smooth boundaries of hardened zones help reduce stress concentrations in the roof and corners of the working, contribute to a more uniform distribution of stresses at the boundary of the hardened zone and the rock massif, as a result of which deformations will be minimal. This is important for tensile fracture occur conditions, where weak zones of rocks can be the sites of the beginning of large-scale destruction. The use of various forms and technologies of hardening reduce and move away from the contour of stress concentration in the sides of the working. The calculated data will be confirmed in the upcoming study.

The adaptive approach assumes that the hardening zones should not be strictly geometric or unified. On the contrary, they are designed to match as close as possible the real conditions of the massif inelastic deformation, taking into account variations in the properties of rocks, waterlogging, depth of occurrence and expected dynamics of stress changes.

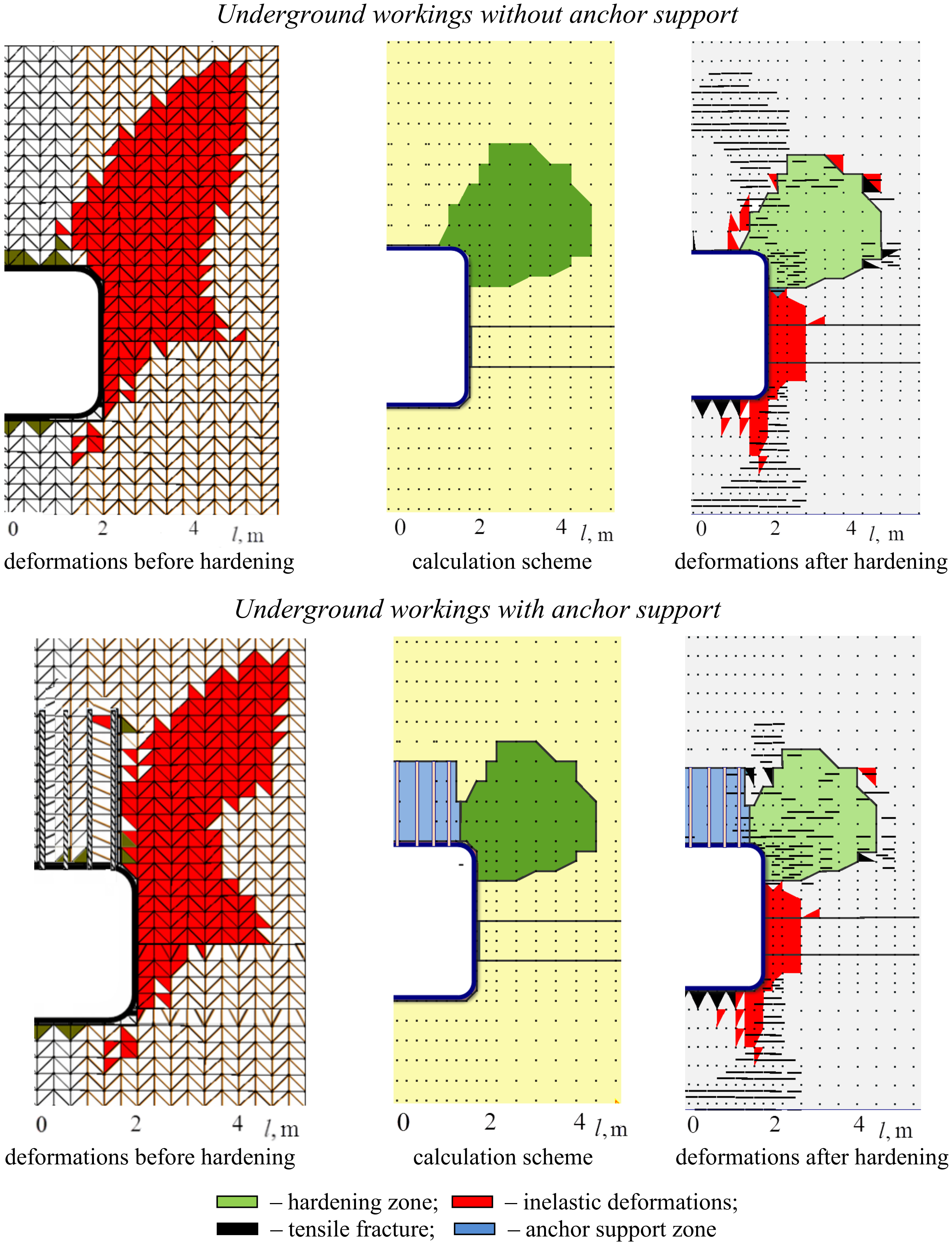
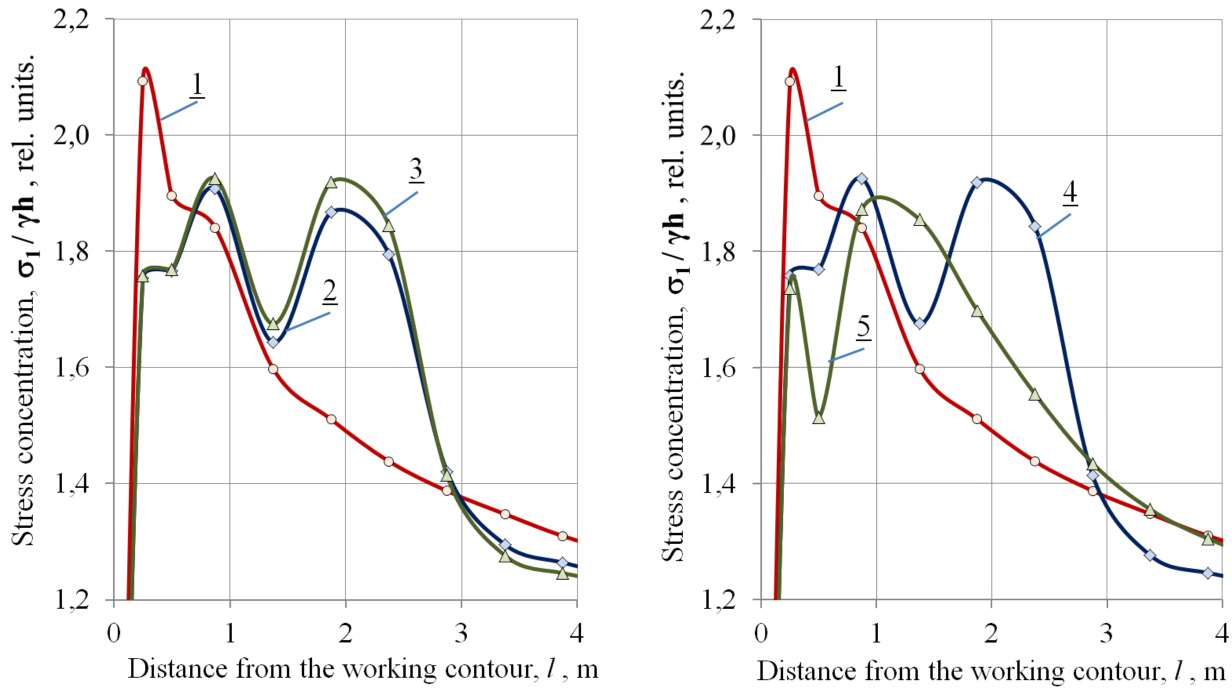


Figure 7 – Study of the adaptive form of the hardening zone



1 – without hardening, Fig. 3; 2 – thickness of the hardened zone 0.5 m, Fig. 5; 3 – thickness of the hardened zone 1.0 m, Fig. 5; 4 – high strength of rocks, Fig. 6; 5 – lower strength of rocks, Fig. 6; σ_1 – maximum principal stress, Pa; γ – volumetric weight of rocks, N/m^3; h – depth, m

Figure 8 – Patterns of change in the concentration of maximum principal stresses in the sides of workings with different shapes of injection hardening zones of the roof

Thus, the shape of the hardened zone, which corresponds as much as possible to the area of non-elastic deformation, represents the most rational approach to ensuring the stability of the workings, reduces the consumption of materials and the consequences of the deformation process. The use of adaptive forms of hardened zones allows for a significant reduction in the zones of inelastic deformations, since the boundaries of the hardened zones are designed in such a way as to be smoothly integrated into the rock massif. Unlike more traditional methods based on unified or less flexible hardening schemes, adaptive forms of hardened zones take into account the specifics of the massif stress-strain state and the dynamics of its change. As a result, this approach makes it possible to effectively adapt the shape and locality of the hardened zones to the characteristics of specific rocks, their heterogeneity and degree of destruction, as well as changes in the technological requirements for the use of underground and buried structures for reuse for further tasks.

4. Conclusions

1. The features of rock deformation and the forms of underground workings and structures stability loss were analyzed. It is established that rock strengthening compensates for the drawbacks of traditional support systems without a significant increase in costs, while the use of various configurations of hardened zones allows adapting support system to specific conditions, minimizing stress concentrations, preventing local collapses and stabilizing the rock mass.

2. Modeling the stress-strain state of rocks using hardened zones of various configurations showed that the hardened zone should be created in areas of the greatest stress difference, since these areas are characterized by a high level of stress concentration and the largest volumes of inelastic deformation. It is those zones where stresses often exceed the ultimate strength of rocks, which leads to the formation of cracks, local destruction and further collapse of the roof. In this case, the criteria for the effectiveness of this technology are two main indicators: a decrease in the volume of inelastically deformed rocks and a decrease in stress concentration near the working contour.

3. A comparative analysis of various forms of hardened zones showed that the maximum reduction in the volume of inelastic deformation zones up to 85% was obtained when using a smoothed elliptical shape and up to 71% - with a scheme with increased coverage of the side parts of the roof. However, it is important to consider that such changes in reinforced zones lead to a decrease in the stability of the sides, although moderately - by 9-23%.

4. Based on the established patterns of change in the concentration of maximum principal stresses in the sides of the workings with different forms of injection roof hardening zones, the method of adaptive design of hardened zones was further developed, when the shape of hardening zone corresponds to the locality of the forecasted zones of inelastic deformations and has the smoothest boundaries. Smooth boundaries of hardened zones reduce stress concentrations and contribute to their uniform distribution. The adaptive approach assumes that the hardening zones should not be strictly geometric or unified. On the contrary, they are designed to correspond as much as possible to the real conditions of inelastic deformation of the massif, taking into account the variation of rock properties, depth of occurrence and expected dynamics of stress changes and rock flooding.

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ОБҐРУНТУВАННЯ ПАРАМЕТРІВ ЗОН ІН'ЄКЦІЙНОГО ЗМІЦНЕННЯ ПОРІД НАВКОЛО ГІРНИЧИХ ВИРОБОК ТА ЗАГЛИБЛЕНИХ СПОРУД КРИТИЧНОЇ ІНФРАСТРУКТУРИ

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Анотація. Стаття присвячена обґрунтуванню параметрів зміцнених зон навколо гірничих виробок та заглиблених споруд критичної інфраструктури з урахуванням встановлених закономірностей зміни напружено-деформованого стану порід. Мета роботи полягає в визначенні раціональних форм і розмірів зон ін'єкційного зміцнення порід. Методи: аналіз та узагальнення даних деформування порід; шахтні спостереження; математичне моделювання геомеханічних процесів методом скінченних елементів. Проаналізовано особливості деформування гірських порід та втрати стійкості підземних виробок і споруд. Встановлено, що зміцнення порід компенсує недоліки роботи традиційних систем кріплення без значного збільшення витрат. При цьому застосування різних конфігурацій зон зміцнення дозволяє адаптуватися до конкретних умов, мінімізувати концентрації напружень, запобігати локальним обваленням і стабілізувати масив порід. Критеріями ефективності технології ін'єкційного зміцнення виступають два основні показники: зниження об'ємів порід у зонах непружних деформацій та зменшення концентрації напружень. Порівняльний аналіз різних форм зміцнених зон показав, що максимальне зниження об'ємів зон непружних деформацій до 85% отримано при використанні згладженої еліпсоподібної конфігурації і до 71% у схемі з збільшеним охопленням бічних частин покрівлі. На основі встановлених закономірностей зміни зон руйнування і концентрації максимальних головних напружень при різних формах зон ін'єкційного зміцнення покрівлі подальший розвиток отримав метод адаптивного проектування зміцнених зон, коли форма закріплення відповідає локалізації прогнозованих зон непружних деформацій і має найбільш плавні границі. Адаптивний підхід передбачає, що зони зміцнення не повинні бути строго геометричними або уніфікованими. Навпаки, вони розробляються так, щоб максимально відповідати реальним умовам непружного деформування масиву з урахуванням варіації властивостей гірських порід, глибини залягання, очікуваної динаміки зміни напружень та обводнення порід. Це дозволяє локально підвищити міцність порід, зменшити тріщинуватість, запобігти проникненню газів та води в виробку або споруду.

Ключові слова: стійкість виробок і споруд, безпека експлуатації споруд, ін'єкційне зміцнення порід, напружено-деформований стан, геомеханічні процеси.