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Research paper

The mechanism of roadway deformation in conditions of laminated rocks

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ABSTRACT

The high stress condition of the rock mass requires a change in the approach to the design and usage of roadway support. It is necessary to take into account the mutual deformations of the "support – rock mass" system, as well as the peculiarities of the deformation mechanism of the roadway rock contour. The purpose of this paper is to analyze the mechanism of roadway deformation in conditions of laminated rocks and "deep mine". A simple approach to the analysis of stress distribution around the roadway that includes Kirsch equations is used. It is shown that the strength anisotropy determines the weakest place in the roadway contour, where destruction takes place. The deformation of the rock mass around a single roadway occurs in the form of extrusion wedges of laminated rocks in the roof and floor is also show. The results of in-situ observations over the displacement of the roof and the floor of "deep mine" roadways are analyzed. The linear correlation between roof sag and floor heave is established. It is stressed that roof sag must be prevented in order to effectively counteract the extrusion of the floor rock.

1. Introduction

The roadway drivage inevitably disturbs the steady-state equilibrium of rock massif. This causes a redistribution of stress in the vicinity of the roadway contour and its deformation.

A vertical convergence is the most visible manifestation of strata pressure. It can be considered as the following processes:

1. Roadway roof sag, due to:
   1.1 the yielding of a steel arch support,
   1.2 the plastic deformation of a steel arch support,
   1.3 the steel arch support racks penetrating the floor.
2. Roadway floor heave.

With the increase of mining depth the manner of strata pressure manifestation changes It is manifested predominantly as the deterioration of the conditions of roadway maintenance and the excessive losses of its cross-section. Therefore the concept of a "deep mine" has been developed and includes a ratio of gravitational forces (in-situ stress) with the strength of rock mass (Hucke, Studeny, Ruppel, & Witthaus, 2006; Litvinsky, 2012; Zaslavskij, 1966). It was established that the ratio can be expressed as the following (Zaslavskij, 1966):

$$K_Z = \frac{\gamma H}{R} \tag{1}$$

where:

K_Z – the criterion of roadway stability by Zaslavskij (1966);
γ– the unit weight of overburden, MN/m^3;
H – the depth of roadway, m;
R – the UCS of rock mass, MPa.

The dependence of the relative displacement of a roadway contour (u/a, where u – vertical convergence, a – height of roadway) on the criterion K_Z was established empirically by in-situ measurements and is presented in Fig. 1.

It can be seen (Fig. 1) that the roadway contour is stable when $K_Z < 0.3$ and there is a trend of increased displacement when $K_Z > 0.3$.

According to Litvinsky (2012), the formation of the natural pressure arch in the roof and floor of the roadway is characterized by the destruction of the roadway contour rocks under tensile stresses; this, in turn, indicates "shallow depth" conditions. For these conditions, the value of stability criterion K_Z does not exceed 0.3–0.4. Otherwise, the destruction of the roadway contour rocks under compression stresses is typical for conditions in which $K_Z > 0.4$(Litvinsky, 2012). Consequently, this conditions are of the "great depth" of mining or the "deep mine".

The increase in roadway cross-section losses, when $K_Z > 0.3 - 0.4$, is confirmed by the results of research (Fesenko, 2005), where the state of 699 Donbas mine roadways was statistically analyzed and the dependence of the probability of roadway floor heave occurring with various criteria was established. It has been shown that with the increase of K_Z the probability of floor heave is greater (Fig. 2).

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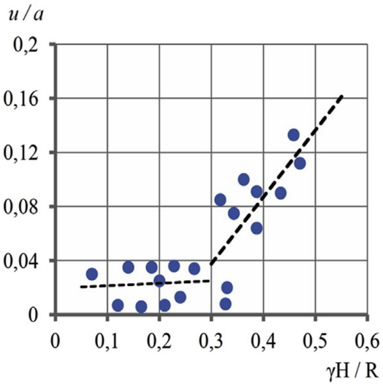


Fig. 1. The dependence of the relative displacement of a roadway contour (u/a) on the criterion $K_Z = \frac{\gamma H}{R}$ (Zaslavskij, 1966).

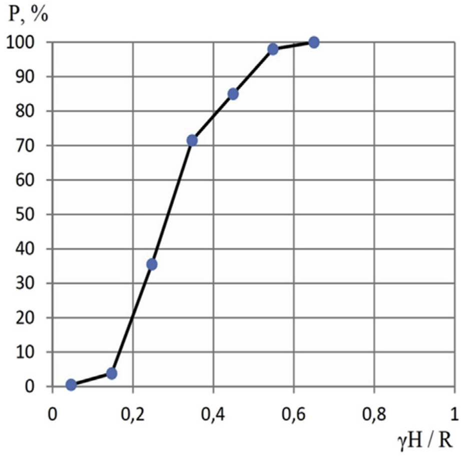


Fig. 2. The dependence of the probability (P) of roadway floor heave on the criterion$K_Z = \frac{\gamma H}{R}$ (Fesenko, 2005).

According to Fig. 2, when $K_Z > 0.4$ the probability of floor heave is greater than 80%.

The roadway effective support under conditions of great mine depth is a current problem for the mines of Western Donbas (Solodyankin, Martovickyi, & Smirnov, 2015a). Up to 25% of all roadways are in a critical state, clayey enclosing rocks make roadway maintenance complicated (Solodyankin, Martovickyi, & Smirnov, 2015b). Roadway drivage at “great depth” requires a change in the approach to the design and usage of the support (Cao, Cao, & Lin, 2016; Chaoke, Jianxi, Bingli, & Yongjun, 2017; Hucke et al., 2006; Litvinsky, 2012; Prusek, 2010). The rock mass permanently deforms and displaces the roadway in an inwards direction. Under such conditions, it is necessary to take into account the mutual deformations of the “support – rock mass” system, as well as the peculiarities of the deformation mechanism of the roadway rock contour. The latter enables the justification of the optimal parameters of the installation of rock bolts and standing support.

The purpose of this paper is to analyze the mechanism of the roadway deformation in the laminated rock and “deep mine” conditions.

2. Materials and methods

2.1. Study area

The study area is the deformation of rock mass around a single roadway driven in laminated rocks. The study consists of two parts: theoretical and in-situ. For the theoretical analysis of the stress distribution around the roadway a simple approach which included the Kirsch equations is applied. In-situ investigations included visual observations and measurements of the roof and floor displacements in the roadways of Western Donbas. Additionally, some visual observations in the roadways of Central Donbas mines were added for comparison with flat dip strata conditions of Western Donbas. A list of the roadways is presented in Table 1.

Measurements of the displacement of the marks in the roof and floor are made with respect to a horizontal line (Fig. 3).

This horizontal line is formed by marks which are embedded in the sides of the roadway and supposed to be immovable. Thus, the displacement of the roof and floor is obtained separately.

2.2. Geological conditions

The rock mass of Western Donbas is composed of thin-laminated sedimentary rocks. Coal seams are thin (their thickness does not exceed 1.2 m) and have a flat dip (0–4°). Rocks are soft clayey siltstones and mudstones with UCS 15–30 MPa. There are no active tectonic processes. The depth of mining is from 150 to 600 m. The typical geological

Table 1
Information about roadways and in-situ investigations.

Roadway	Value of criterion K_z	Strata dip angle, °	Research technique	Remarks
“Im. Geroyev Kosmosa”				Western Donbas mine
1141th	0.5	0–4	Measurements of the roof and floor displacements	
1116th	0.7	0–4	Measurements of the roof and floor displacements	
1019th	0.8	0–4	Measurements of the roof and floor displacements	
“Zapadno-Donbasskaya” mine				
802th	0.8	0–4	Measurements of the roof and floor displacements	
Main Ventilation Crosscut	0.5	0–4	Visual observations	
“Svyato-Andreyevskaya” mine				
13th Eastern Roadway	0.5	0–4	Visual observations	
“Stepova” mine				
163th	0.4	0–4	Visual observations	
“Belozerskaya” mine				Central Donbas mines, added for comparison with the flat dip strata conditions of Western Donbas
Incline #1 of l_8 seam	0.5	10–13	Visual observations	
Northern roadway of l_8 seam	0.5	10–13	Visual observations	
“Sukhodolskaya-Vostochnaya” mine				
Main Crosscut	0.6	10–13	Visual observations	

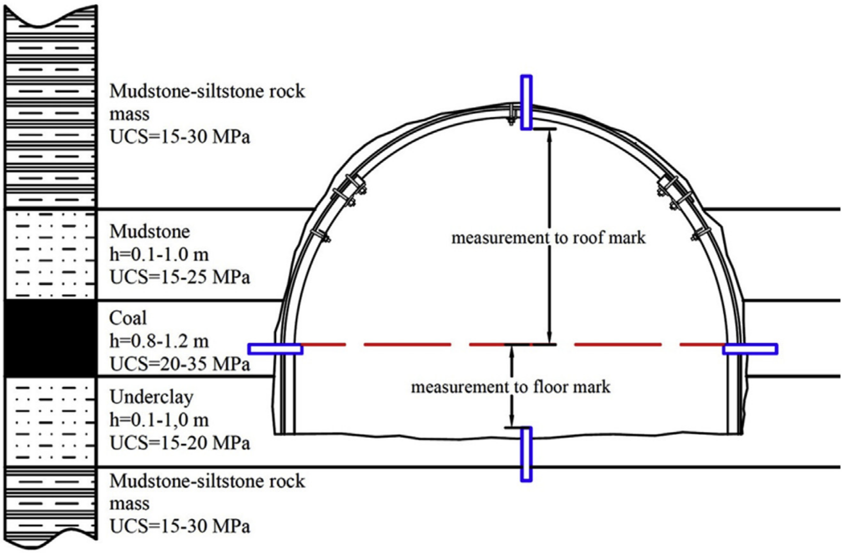


Fig. 3. Typical geological structure and measurement method.

structure is presented in Fig. 3.

3. Results of the research

It is known that the objective laws of the distribution of stress around a circular roadway, located at a depth of more than twice that of its diameter, can be described using the polar coordinate system (Fig. 4) which utilizes the theory of elasticity – Kirsch equations (Brady & Brown, 2004):

$$\sigma_r = \frac{\gamma \mathrm{H}}{2}\left[(1+\lambda)\left(1-\frac{\rho^2}{r^2}\right)+(1-\lambda)\left(1-\frac{4\rho^2}{r^2}+\frac{3\rho^4}{r^4}\right)\cos 2\theta\right] \tag{2}$$

$$\sigma_\theta = \frac{\gamma \mathrm{H}}{2}\left[(1+\lambda)\left(1+\frac{\rho^2}{r^2}\right)-(1-\lambda)\left(1+\frac{3\rho^4}{r^4}\right)\cos 2\theta\right] \tag{3}$$

$$\tau_{r\theta} = -\frac{\gamma \mathrm{H}}{2}(1-\lambda)\left(1+\frac{2\rho^2}{r^2}-\frac{3\rho^4}{r^4}\right)\sin 2\theta \tag{4}$$

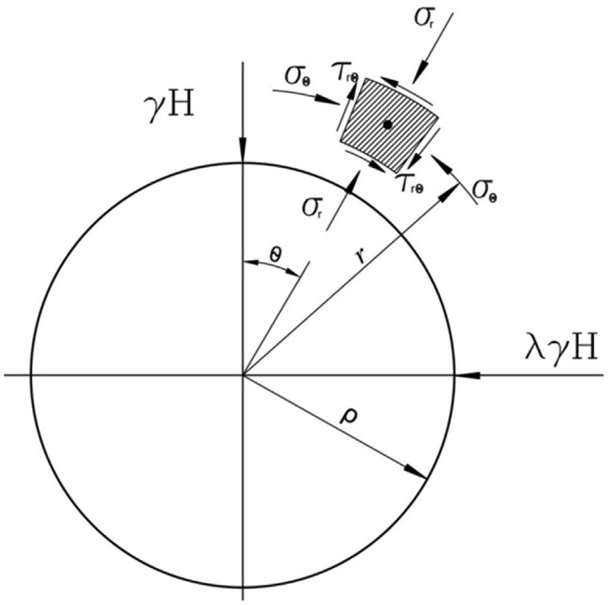


Fig. 4. Determination of the stress distribution around a circular roadway with the polar coordinate system using the theory of elasticity.

where: σ_r, σ_θ, $\tau_{r\theta}$ – radial, circumferential and shear stress respectively, MPa;

λ – the stress ratio;
ρ – the radius of the roadway, m;
r – the distance from the center of the roadway to the point of the stress calculation, m;
θ – the angle in the polar coordinate system, degree.

The determining factor of stress distribution is the stress ratio λ – the ratio of horizontal stress to vertical stress.

Figure five shows the graphs of the dependencies of the relative circumferential stress (σ_θ expressed as a proportion of γH) in the roof and sides of the circular roadway on the stress ratio coefficient λ, which were obtained on the basis of equation (3) (Fig. 5).

When $\lambda < 0.3$, there is tension in the roof and floor. When $0.3 < \lambda < 0.7$ there is compression in the roof and floor and a value of $\sigma_\theta/\gamma H$ approaches 1. When $0.7 < \lambda < 1$ a value of $\sigma_\theta/\gamma H$ approaches 2.

The rocks are able to deform differently in an elastic, plastic and viscous state. On this basis, the stress ratio λ should differ from its definition only by Poisson's ratio (Brady & Brown, 2004), taking into account the duration of the formation of a stressed state from gravitational and tectonic forces.

The equation to determine the stress ratio λ, which takes into account the viscoelastic strains of the rock mass, is derived by Olovjannyj

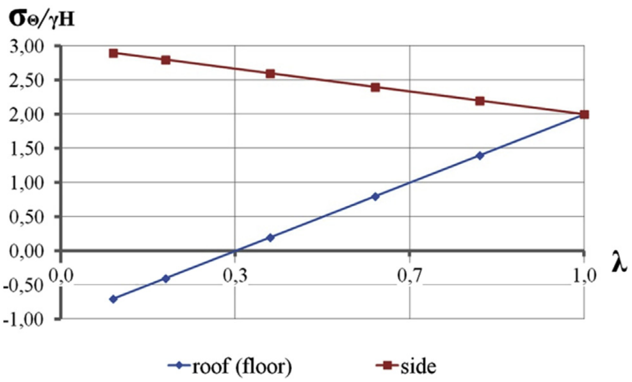


Fig. 5. The dependencies of the relative circumferential stress σ_θ/γH in the roof (floor) and sides of the circular roadway on the stress ratio coefficient λ when $\rho/r = 1$.

Table 2
Results of the stress components' determination.

Method		Vertical component, MPa	Horizontal component, MPa	Minimal principal stress, MPa
Acoustic emissions		10.6	–	–
Overcoring		11.8	11.1	–
Hydraulic fracturing	Vertical borehole	–		10.0
	Horizontal borehole	–		12.1

(2012). According to Olovjannyj (2012), in ductile clayey rocks (that is true for the rocks of Western Donbas mines) the stress ratio λ can reach a value of more than 0.7 and up to 1.

This is confirmed by the results of earlier in-situ measurements (Khalymendyk & Meshchaninov, 2000). In the conditions of the "Zapadno-Donbasskaya" mine (depth 480 m, siltstone rocks with UCS = 25 MPa), the stress components in the rock mass were determined using three methods.

The first method was based on the Kaiser effect – a phenomenon that is defined as the absence of detectable acoustic emissions until the previously applied stress level is exceeded (Ljunggren Chang, Janson, & Christiansson, 2003; Stavrakas, 2017). Six rock samples taken from the roadway were tested.

The second method was the overcoring of borehole-bottom cells (Ljunggren et al., 2003). Two boreholes that were drilled from the same roadway were examined. One was vertical and the other horizontal.

The third and final method was hydraulic fracturing (Ljunggren et al., 2003) in two boreholes that were drilled from the same roadway.

The average results of the rock mass components' determination are presented in Table 2.

According to the obtained results, it is fair to say that in soft laminated clayey rocks under the high stress "deep mine" conditions the stress ratio λ will be approximately equal to 1.

Thus, when $r = \rho$ (i.e. on the contour of the circular roadway) and $\lambda = 1$ there is only a circumferential stress of $\sigma_\theta = 2\gamma H$ present (eqs. (2)–(4), Fig. 4).

According to equations (2)–(4), the stress on the contour of the circular roadway does not depend on the elastic properties of the rock mass, its strength properties and the cross-sectional area of the roadway. However, strength properties, i.e. the anisotropy of strength parameters, determine the weakest place on the contour, where destruction takes place and the system loses its equilibrium state. In other words, the position of the initial point of destruction on the contour is predetermined by the strength properties and conditions of rocks bedding.

In laminated rocks, the coefficient of the anisotropy of the rock mass properties varies from 1.3 to 2.0. The UCS of a mudstone and a siltstone perpendicular to the lamination is about 20–30 MPa and the value of an anisotropy coefficient varies from 1.2 to 5 in conditions of Western Donbas mines (Vlasov & Vlasov, 2015).

For example, the hypothetical circular roadway that is driven in laminated rocks is considered (Fig. 6).

The UCS of the rocks perpendicular to the lamination is $\sigma_{\updownarrow}^{UCS} = 30$ MPa, along the lamination – $\sigma_{\longleftrightarrow}^{UCS} = 20$ MPa, so the value of the anisotropy coefficient is $\sigma_{\updownarrow}^{UCS}/\sigma_{\longleftrightarrow}^{UCS} = 1.5$. These properties are of typical siltstones and taken from the results of laboratory studies of the rock samples available from the geological departments of Western Donbas mines. The stress ratio is $\lambda = 1$, vertical stress is $\gamma H = 12$ MPa ($\gamma = 0.025$ MN/m^3, $H = 480$ m), which is typical for the conditions of Western Donbas.

Calculated with equation (3) compressive circumferential stress is $\sigma_\theta = 2\gamma H = 24$ MPa at the sides of the contour of the roadway, and this acts perpendicular to the lamination of rock mass. The UCS of the rock in this direction is greater than the stress value, so no destruction takes place there. But in the roof and floor the stress σ_θ acts parallel to the lamination. At these points rock is destroyed because the UCS in this direction is lower than the stress value $\sigma_{\longleftrightarrow}^{UCS} < 2\gamma H$. Therefore there is no natural pressure arch (typical for tensile stresses and "shallow depth") but a so-called "wedge of rock extrusion" is formed (Fig. 7).

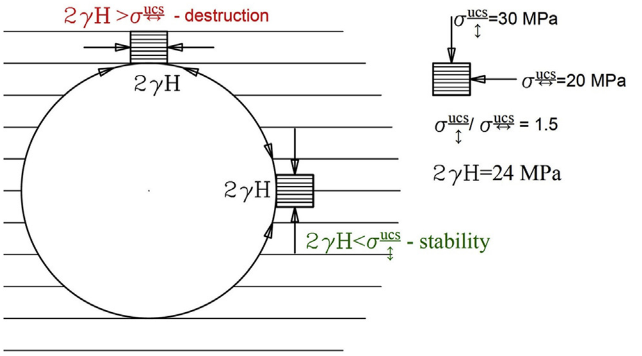
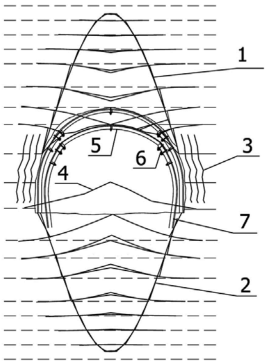


Fig. 6. The mechanism of the roadway rock contour deformation.



1 – the wedge of rock extrusion in the roof;
2 – the wedge of rock extrusion in the floor
3 – the destruction of the roadway sides, which develops after the formation of rock extrusion wedges;
4 – the floor heave;
5 – the roof sag;
6 – the yielding of the arch support joints;
7 – the support racks penetration into the floor.

Fig. 7. The sketch of the "support – rock mass" system deformation.

Destroyed rocks make it easier for the support rack to penetrate the floor. This leads to losses in support rebuff in the roof and the overall intensification of the convergence process. The support rack moves along the borderline between destroyed and relatively stable rocks (Fig. 7).

This kind of laminated rock mass deformation occurs around the roadways in all deep coal mines in Ukraine (Figs. 8–12).

Below the data obtained as a result of in-situ observations over the displacement of the roof and the floor of the roadways of "deep mines" is shown (Fig. 13).

It can be seen from the graph (Fig. 14) that there is a linear relationship with a high correlation coefficient (close to 1) between the roof sag and the floor heave in the roadways of deep mines.

Similar results can be obtained by processing measurements that were carried out by other researchers in deep mines. For example, Zaslavskij (1966) presented the results of roadway roof and floor displacement. Western haulage roadway (WHR) and Eastern haulage roadway (EHR) of "Krasnaya Zvezda" mine and Eastern ventilation roadway (EVR) of "Mushketovskaya-Zaperevalnaya" mine are considered (Zaslavskij, 1966). For these roadways $K_z = 0.4$ and the UCS of roof and floor rocks = 42–57 MPa. WHR and EVR had rectangular and arch cross-section respectively, whereas EHR had a circular cross-section. The results of the measurements are presented in Fig. 15.

It can be seen from the graph (Fig. 16) that the linear correlation

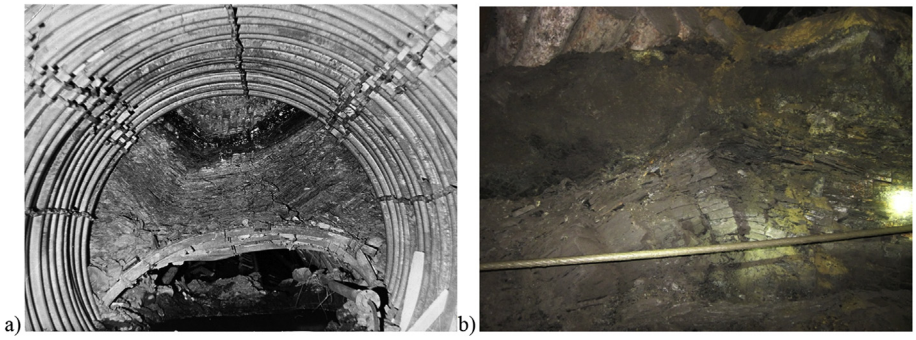


Fig. 8. The wedge of rock extrusion in the conditions of the “Zapadno-Donbasskaya” mine.

Fig. 9. The wedge of rock extrusion in the conditions of the “Svyato-Andreyevskaya” mine. The 13th Eastern roadway.

Fig. 11. The roof fall in the 163th roadway in the conditions of the “Stepova” mine.

between the roof sag and the floor heave can also be traced.

4. Discussion

According to investigations, the mechanism of roadway deformation in the conditions of laminated rocks and “deep mine” is characterized by the formation of rock mass extrusion wedges in the roof and floor.

The description of rock deformation which is similar to the proposed term “extrusion wedge” has appeared in the works of different authors, for example Oldengott (1981) (Fig. 17).

The wedge-like formation and subsequent rock fall was recorded during tunneling in layered rocks (Perras, 2009).

It should be highlighted that the axis of the wedge is perpendicular to the bedding of rock layers (and the lamination plane) which can clearly be seen in Figs. 10(b), 12 and 17. This is explained by the simple theoretical approach that included Kirsch equations and took into account the strength anisotropy of the rock mass. It should also be clarified that the computations using the simple elastic model were carried out to explain the qualitative side of the formation of the extrusion wedges at the points on the roadway contour where the resistance of the rocks to the stresses is minimal. From this point of view, the simple model convincingly explains the orientation of wedge axis being perpendicular to the bedding.

According to results of in-situ measurements, the displacement of the floor is greater than the displacement of the roof. Theoretically, if simple theoretical approach is used (Figs. 3 and 5) and the weight of the rocks in the extrusion zones is neglected (in the roof and floor), then these processes can be considered symmetrical, both quantitatively and qualitatively. In fact, the intensity of the rocks mass extrusion in the floor is usually greater than in the roof. This is due to the shape of the roadway cross-section and the absence of support rebuff in the floor –

Fig. 10. The wedge of rock extrusion in the conditions of the “Belozerskaya” mine. Incline #1 (a) and Northern roadway (b) of l8 seam.

Fig. 12. The wedge of rock extrusion in the conditions of the "Sukhodolskaya-Vostochnaya" mine.

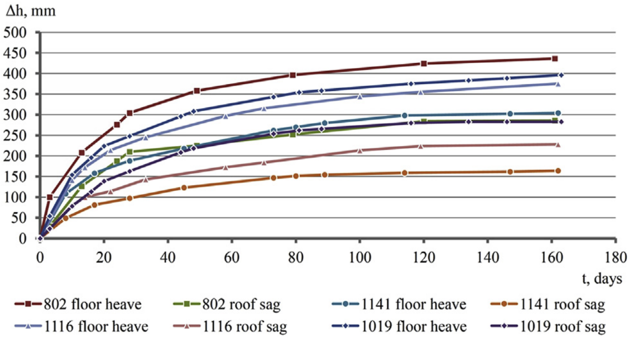


Fig. 13. The displacement (Δ*h*) of roof and floor in the roadways. Represented data was analyzed and the floor heave as a function of the roof sag was plotted (Fig. 14).

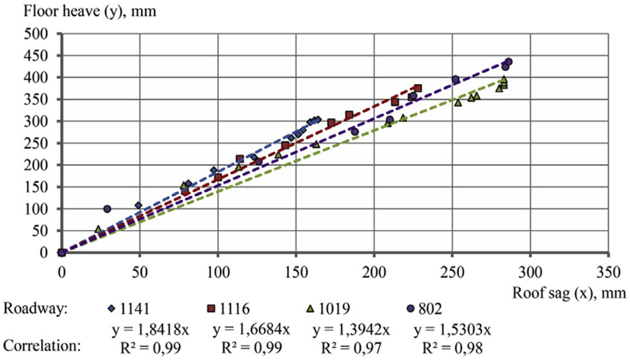


Fig. 14. The relation between the roof sag and the floor heave of the "deep" roadways.

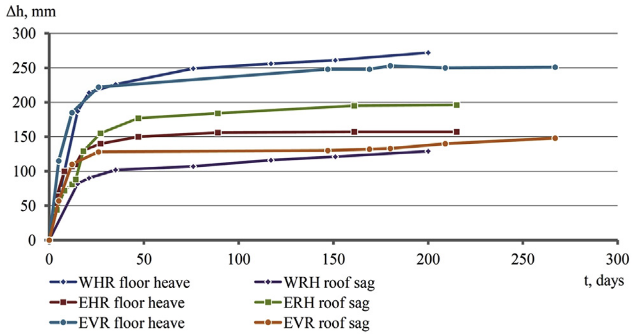


Fig. 15. The displacement (Δ*h*) of roof and floor in the roadways (Zaslavskij, 1966). This data was analyzed and the floor heave as a function of the roof sag was plotted (Fig. 16).

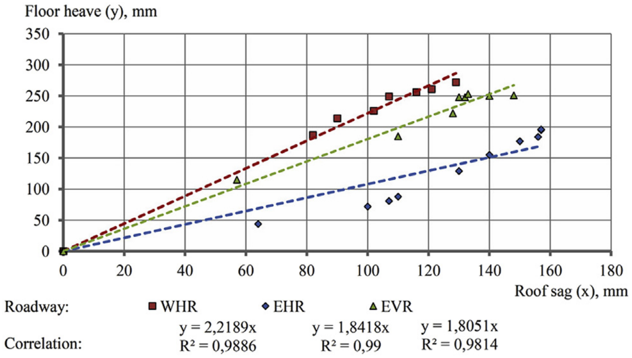


Fig. 16. The relation between the roof sag and the floor heave in the WHR, EHR and EVR.

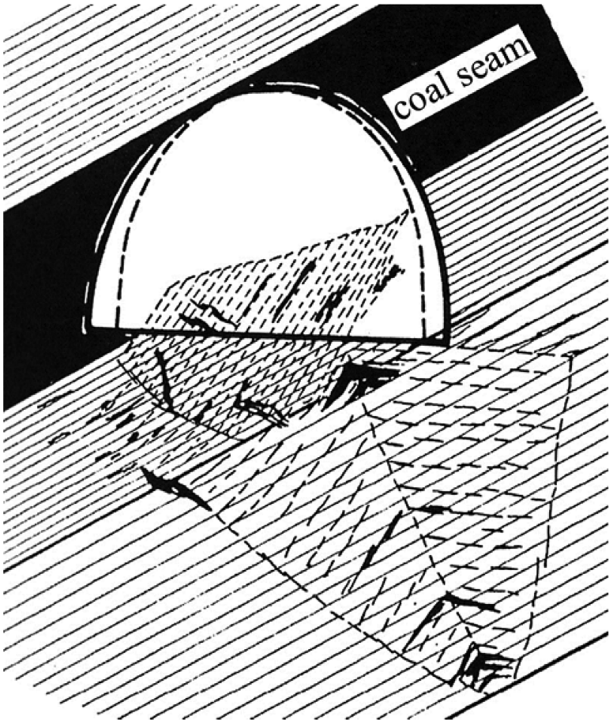


Fig. 17. A sketch of the rock mass deformation around the gateroad. The dotted line shows the position of the rock layers and support after their deformation. (Oldengott, 1981).

the roadways were supported with steel arch support. Additionally, only the measurements in EHR (Fig. 16) showed quantitatively equal displacement of the roof and floor because there was a circular shape and support.

The reduction of floor rock heave (extrusion of floor rocks) is a very difficult task (Chaoke et al., 2017; Hucke et al., 2006; Hui, Freifei, Yuguo, & Hongmin, 2017; Zaslavskij, 1966). To complete this task the causes of the geomechanical processes that occur and their relationship to each other need to be determined. The problem of determining the pressure on the support from the floor of the roadway was solved by Cimbarevich (1948) and then analyzed by Khalymendyk and Baryshnikov (2012) and Hui et al. (2017). It was assumed that the mechanical aspect of the floor heave phenomenon is identical to the extrusion of loose soil under the action of a load transmitted to the floor through two presses. As a result, a linear relationship between the height of the destroyed rocks zone in the roof and the magnitude of the floor heave was established. Although the mechanical model proposed by Cimbarevich (1948) is greatly simplified, it explains why the roof sag (as a result of increasing the height of the destroyed rocks zone in the roof) is the initial factor that entails the intensification of floor rock deformation. According to the established relations (Figs. 13 and 16), the increase in the extrusion of roof rocks may lead to an increase in floor extrusion. Therefore, it can be assumed that the prevention of roof sag also counteracts the extrusion of the floor rock.

The phenomenon of the floor heave reduction was described by Tully (1987). At the Ruffod Colliery mine the 206th main roadway was deformed due to vertical convergence. To improve the condition of the roof, roofbolting was made. Unexpectedly, the roofbolting not only lowered the roof sag but also reduced the floor heave. A similar effect was obtained later on physical models made of equivalent materials. Some authors, for example Hui et al. (2017), show reduction in size, obtained on numerical models, of the plastic deformation zone around the roadway when support rebuff is applied. As a result, the total contour displacements, as well as floor heave, are reduced. However, in the physical model (Tully, 1987) floor heave significantly decreased only after roofbolting. Furthermore, most numerical models do not take into account the strength anisotropy of rocks. That is why the overwhelming majority of numerical models do not show wedges of rock extrusion. Taking into account the weakening planes, in order to bring some anisotropy in to the virtual rock mass, makes it possible to reflect the formation of extrusion wedges and this works quite well (Hucke et al., 2006; Perras, 2009). However, the phenomenon of floor heave reduction was not studied on these physical models and strength anisotropy was not taken into account because these tasks were not set. Therefore, the studying of anisotropic rock mass behavior around a roadway on the numerical models has not been fully completed and needs further investigations.

5. Conclusions

The “deep mine” is characterized by the value of the ratio of in-situ stress to the strength of rock mass being more than 0.3–0.4 and the stress ratio being close to 1. Under such conditions a simple approach to the analysis of stress distribution around the roadway was used in order to explain the phenomenon of rock extrusion wedge formation. The anisotropy of strength parameters plays an important role in the determination of the weakest place on the roadway contour, where destruction occurs. The analysis of the in-situ observations over the displacement of the roof and the floor of the “deep mine” roadways has shown linear correlation between roof sag and floor heave. Therefore, it is fair to say that the roof sag must be prevented in order to effectively counteract the extrusion of the floor rocks.

Conflict of interest

None declared.

Ethical statement

Authors state that the research was conducted according to ethical standards.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jsm.2018.03.004.

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