EXPERIMENTAL TESTS OF CONCRETE MEANS OF PROTECTION FOR COAL MINES DISTRICT ROADWAYS

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ABSTRACT. The current paper is devoted to experimental tests of working protection means in the construction of which concrete in liquid state is used. Such means of protection are most vulnerable to irreversible deformations during the period of their hardening, which coincides with the period of intensive growth of pressure on them from the side of the rock massif. Studies have shown that the pressure of fake rocks on the working protection means depends significantly on the depth of its location and the category of collapse of the roof of the coal seam. The maximum pressure is reached at the moment before the collapse of the roof, that is, at the maximum values of the length of the console of fake rocks, which hangs over the produced longwall space and rests on the working protection means. It was established that the pressure of the fake roof of the coal seam and the relative vertical deformation of the district roadway protection means increase according to the logarithmic dependence of the distance to the longwall outcrop and the time of concrete hardening. With heavy and medium roof collapse, these processes are divided into two stages: in the first stage (the length of which corresponds to the step of the roof collapse), as the longwall moves, the pressure increases intensively, at the moment of collapse it drops by 15-20%, and in the second stage again increases, but 6-8 times more slowly than in the first one, and, provided the relative vertical deformation of the protective device stabilises, passes into a stable mode. With an easily collapsed roof, the step of its collapse does not have a significant effect on the growth and stabilisation of the stress-deformed state of the protective device. The mechanism was revealed and the regularities of loading and deformation of district roadway protection means from a quick-setting mixture depending on the time of its hardening and the distance to the outcrop of longwall, taking into account the category of stability of the roof of the coal seam, were established. Implementation of recommendations for the parameters and technology of the construction of a guard-isolation wall in the conditions of the "Chervonogradska" and "Lisova" mines of the SE "Lvivvugilya" made it possible to reduce the costs of cement-mineral mixture by 27% and save the belt roadways No. 562 and No. 166 for reuse in the production as ventilation during the working out of the adjacent trench column.

Key words: means of protection of district roadways, quick-setting mixtures, concrete packaged protection wall, load intensity of protection means.

Introduction

The efficiency and safety of coal mines largely depend on the operational condition of the district roadways (NPAOP, 2010; Rotkege and Bock, 2015; Nekache et al, 2015; Zhao and Zhang et al., 2017; Xing et al., 2019). These productions are carried out along the bottom of the coal seam. Therefore, the support under the forged rocks of the roof is eliminated in the side of the working after the coal seam has been worked out. A means of its protection is being built to replace the extracted seam near the contour of the working. It takes on the pressure of the roof rocks. In case of significant vertical deformation or destruction of the protective device, the frame fastening of the working is subjected to asymmetric loading. From the side of the worked longwall space, the pressure on it increases due to the weight of suspended artificial rocks. As a result, the frames in the locks sag, and after the limit of yielding is exhausted, their destruction occurs (bending of the special steel profile of the tops and legs of the frame mount and the rupture of the locks connecting them). This increases the danger of miners' work. In addition, there is a significant reduction in the cross-sectional area of the working. This complicates the transportation of fastening materials, rock and mined coal, as well as conditions the deterioration of the ventilation of the mining area and the reduction of the allowable speed of the longwall outcrop due to the gas factor (NPAOP, 1994). As a result, the safety and efficiency of mine operation is reduced.

The use of reliable means for their protection contributes to the preservation of the proper operational condition of district roadways. Among them, concrete guard walls made of fast-hardening mixtures have gained considerable popularity (Bulat et al, 2004; Bulat, 2014; Zhang et al, 2017). They have high compressive strength without significant vertical deformation under pressure. This contributes to the acceleration of the collapse of the rocks above the worked longwall space and, thereby, reduces the load on the means of protection of the working and its fastening. In addition, protective walls made of quick-setting mixtures isolate the field workings from the longwall space produced. This prevents the leakage of fresh air from the workings and the ingress of methane into them.

When constructing such means of protection of products, concrete is used in a liquid state, which is most vulnerable to irreversible deformations during its hardening period. It is at this time that there is a deflection of the rock massif forged by longwall and an intense increase in pressure on the protective wall, which depends on the geological conditions of the location of the mine. In work (Stadnychuk et al., 2023), we proposed a method for calculating the growth of the strength of concrete protective walls over time, taking into account the properties of the mixture and the factors that form the mine conditions of their construction.

Therefore, the purpose of these studies is to reveal the mechanism and establish the regularities of loading and deformation of the means of protection of district roadways from a quick-setting mixture depending on the time of its hardening and the distance to the longwall outcrop to justify the parameters of the means of protection and the properties of the mixture in different geological conditions.

The main research material

Experimental studies were carried out in the coal mines of the Lviv Coal State Enterprise.

The "Chervonogradska" mine is worked out at the n_8^b coal seam, the depth of which is 500 m, the dip angle is 2-3^0, the geological thickness is 1.05-1.35 m. The immediate roof of the coal seam is siltstone with a thickness of 2-4 m, with a strength *f* = 5-6. The main roof is sandstone with a thickness of 8-14 m, with a strength *f* = 6-7. According to the classification of DonVUGI, the roof belongs to heavy and medium-collapsed category A3-A2. The sole of the layer belongs to low-resistant and stable - P2-P3.

The research was carried out in the conditions of the 562nd belt roadway, in which arched fastening AKP-3/11.2 (SVP profile 22) was used, the frame installation pitch was 0.5 m. The basic version of the mounting passport as a means of protection of working involved the use of a wall of vertical chock support.

At first, vertical chock support created a stiff resistance to the lowering of the false roof. But already at a distance of 20-30 m behind the longwall, the racks were destroyed from the side of the created space. Following them, the racks close to the working of the rows were destroyed. The surviving racks were pressed into the sole, destroying the berm of the district roadway. That is, vertical chock support was not able to work as a single system. Their tying with steel ropes also did not give positive results. Therefore, at a distance of about 100 m behind the longwall, this means of protecting the working finally lost its bearing capacity. As a result, the frame fastening of the working was subject to asymmetric loading. From the side of the developed space of the longwall, the fastening exhausted the limit of its flexibility, its locks broke and the special profile bent.

The Institute of Geotechnical Mechanics (IGTM) of the National Academy of Sciences proposed a concrete packed wall (Bulat et al., 2014) to replace the vertical chock support (Figure 1).

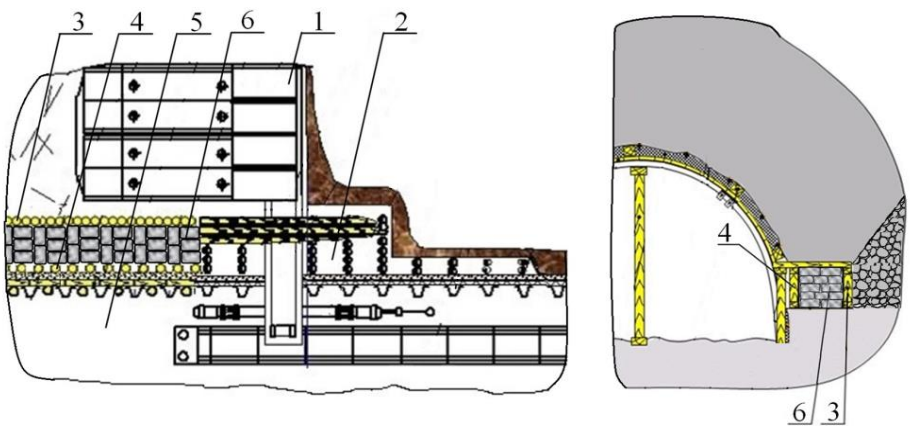

Fig. 1. Technological diagram of the construction of a packaged wall: 1 – mechanised longwall fastening, 2 – excavation longwall, 3 – organic fastening from the side of the produced space of the longwall, 4 – organic fastening from the side of the district roadway, 5 – district roadway, 6 – packaged wall

This type of means of working protection is constructed as follows. After the cycle of movement of the mechanised fixture 1 in the excavation longwall 2, at the level of the rear row of the risers of the first section, an organ attachment is installed: 3 – from the side of the produced space of the longwall and 4 – from the side of the district roadway 5. Between the rows of the organ attachment, a security wall is constructed 6. It is formed according to the height of the excavation capacity of the seam from elastic bags of rectangular shape, filled with a dry, fast-hardening mineral mixture, and laid in layers. Packages of each subsequent layer are placed close to each other, with the intersection of the packages of the previous layer. Then, mine water is supplied to each bag of the formed wall 6, starting from the bottom layer, through a needle injector, which is introduced into the bag by pushing it through. The wall is built close to the fake roof of the coal seam, which prevents stratification of the rocks of the roof and ensures the isolation of the working from the produced longwall space.

Research methodology

The pressure of the rocks of the fake roof on the concrete guard wall was measured by specially made hydraulic devices, which consisted of metal containers filled with oil and equipped with a high-pressure hose with a pressure gauge. During the construction of the bagged wall, during the stacking of bags with a dry mixture, these devices were placed under the last upper layer of bags. Rock pressure measurements were carried out at different distances from the contour of the district roadway, which allowed to study the mechanism and patterns of load distribution along the width of the wall. Also, during the construction of the concrete wall, benchmarks were set on its upper and lower borders, the distance between which measured the deformation of the wall in relation to the time and position of the longwall outcrop. The stress-strain state of the concrete wall was evaluated by the criterion of its relative vertical deformation under the pressure of the rocks of the false roof at different time stages of concrete hardening (Stadnichuk, 2023).

Results and discussion

The results of studies of the state of the packed wall in the conditions of heavy-medium collapse of the roof of the coal seam (Chervonogradska mine) are presented in Figure 2.

The concrete wall is a rigid protective structure. Its strength limit for uniaxial compression, taking into account the weakening factors in mine conditions, is at least 20 MPa. However, during the period of concrete hardening (1 < τ ≤ 28, days), this means of working protection is most vulnerable to destruction (Stadnychuk et al, 2023)..

Ultimate strength of the concrete wall for uniaxial compression at the moment of time τ is as follows,

$$R_{cw(\tau)} = k_{str} \cdot k_{rel} \cdot k_{mw} \cdot k_m \cdot R_{(28)} \cdot \lg(\tau \cdot k_t)/\lg 28, \quad (1)$$

Coefficients for the equations (1) were as follows:

k_{str} – attenuation coefficient of the concrete wall under the influence of its structure;

k_{rel} – attenuation coefficient of the concrete wall under the influence of topography irregularities of forged and crushed rocks;

k_{mw} – coefficient of influence of aggressiveness of mine waters on concrete strength;

k_m – coefficient of influence of the power of the extracted coal seam on the strength of the concrete wall;

k_t – coefficient of influence of the temperature of the mine environment on the intensity of strength gain by concrete in the time period 1 < τ ≤ 28, days.

Just in this period, as a result of the distance of the longwall outcrop, and therefore the increase of the cantilever overhanging the rock over wall, the load on it increases intensively. Therefore, it is important to establish the mechanism and regularities of this process.

In the case of heavy and medium collapsed roofs, in the first period, in the interval of 4-20 m from the cleaning outcrop, the build-up of stresses in it has an intensive character (Figure 2, curves 1 and 3). At the same time, the pressure on the part of the concrete wall far from the district roadway (on the side of the produced longwall space) is 4-5 times higher than the pressure on its near part. This is due to the stationary support pressure from the cantilever of fake rocks, which hangs over the produced longwall space and rests on the means of protection of the working. During this period, the relative vertical deformation of the wall intensifies according to the logarithmic dependence (Figure 2, curve 6).

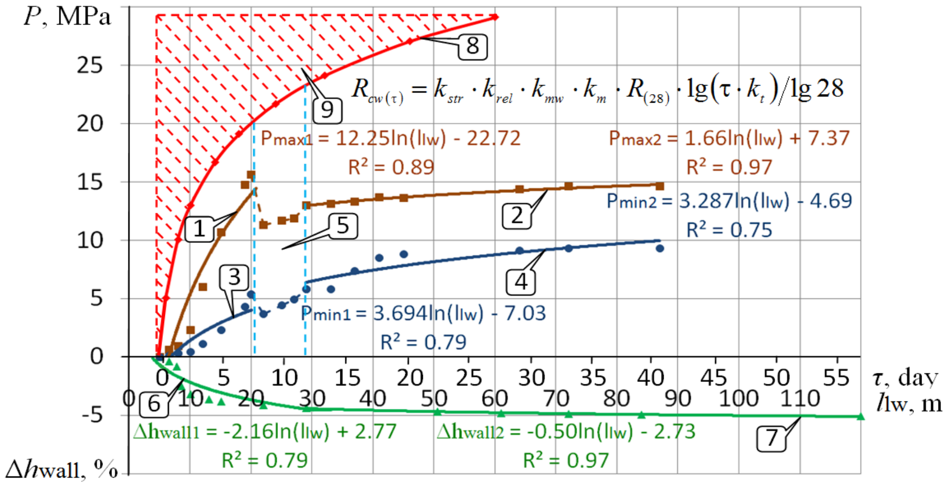

Fig. 2. Dependence of the stress-strain state of the concrete wall on the time of concrete hardening and the distance to the longwall outcrop in the case of a heavy-medium collapsed roof: 1, 2 – the maximum pressure P_{max} (MPa) on the concrete wall, according to and after the collapse of the roof; 3, 4 – minimum pressure P (MPa) on the concrete wall, according to and after the collapse of the roof; 5 – pressure stabilisation period after roof collapse; 6, 7 – relative vertical deformation Δh_{wall} (%) of the concrete wall, respectively, before and after the collapse of the roof; 8 – compressive strength limit of the concrete wall $R_{cw(\tau)}$ (MPa) in the corresponding period of time τ, days; 9 – zone of destructive pressure for the concrete wall

When the longwall outcrop is further removed, the cantilever of the false roof of the coal seam collapses (Table 1) (KD 12.01.01.503, 2001), the pressure on the concrete wall decreases sharply and is redistributed more evenly across its entire width (Figure 2, curves 2 and 4). As a result, the relative vertical deformation of the wall is stabilised according to the logarithmic dependence (Figure 2, curve 7).

The relative vertical deformation of the concrete wall over the entire observation period did not exceed 13%. The main part of the deformation (more than 80%) occurs during the initial period of removal of the cleaning outcrop (from 4 to 20 m). This is explained by the technology of the construction of the wall, which involves mixing the mixture with water directly at the junction of the district roadway with the longwall. Therefore, in the initial period of time (up to 7 days), the concrete wall is most prone to inelastic deformations (Stadnichuk, 2023).

The criterion for assessing the stability of cast or packaged walls is the correspondence between the rate of strength gain by concrete $R_{cw(\tau)}$ (Figure 2, curve 8) and the increase in pressure P_{max} on it (Fig. 2, curves 1, 2) - in the normal mode

$$R_{cw(\tau)} > P_{max}. \quad (2)$$

Thus, according to the results of observations in the conditions of roof categories A2-A3, the growth of the compressive strength limit of the concrete wall $R_{cw(\tau)}$ by 25-50% was ahead of the growth of the pressure P_{max} on the wall in any time interval τ (Figure 2, curves 1, 2 and 8). The criterion of stability of the concrete wall is fulfilled, therefore the parameters of the means of protection of working recommended by the IGTM of the National Academy of Sciences meet the geological and technological conditions. After the longwall was worked out, the 562nd belt roadway was saved for reuse.

Table 1. *Extract from the classification of rock collapse of DonVUGI* (KD 12.01.01.503, 2001)

Roof collapse category	The step of the primary collapse of the roof	The step of further roof collapses
A1	$S_o \leq 10$ m	does not appear
A2	$S_o = 25$ m	$S_r \leq 15$ m
A3	25 m < $S_o \leq 50$ m	15 m < $S_r \leq 30$ m

The next stage of research was carried out in the conveyor section of the "Lisova" mine during the development of the seam n_7^n "Sokalsky" with longwall No. 166. The thickness of the coal seam is m = 1.4-2.0 m, the angle of incidence is α = 6^0. The direct roof of the coal seam is argillite with a thickness of m = 1.9-6.4 m, strength factor f = 3. The main roof of the seam is siltstone with a thickness of m = 3.7÷7.1 m, strength factor f = 5-6. The immediate bottom of the coal seam is sandstone with a thickness of m = 2.1-10.0 m, strength coefficient f = 8. The depth of the development is 265 m. The analysis of mining and geological conditions showed that according to the classification of the DonVUGI, the main roof of the seam n_7^n "Sokalsky" is lightly crushed (A1), direct sole – rack (P3).

The results of the research in the conditions of an easily collapsed roof ("Lisova" mine) are presented in Figure 3. In this case, in contrast to the conditions of a roof with heavy and moderate collapse (see Figure 2), the growth and stabilisation of the pressure on the concrete wall and its relative vertical deformation occur more evenly in time and space, according to logarithmic dependencies. This is explained by the lack of influence of the pitch of the roof collapse (see Table 1). At the same time, two stages of loading and deformation of the protective wall are also observed: first, it is more intense, and after the longwall moves away, it is slower.

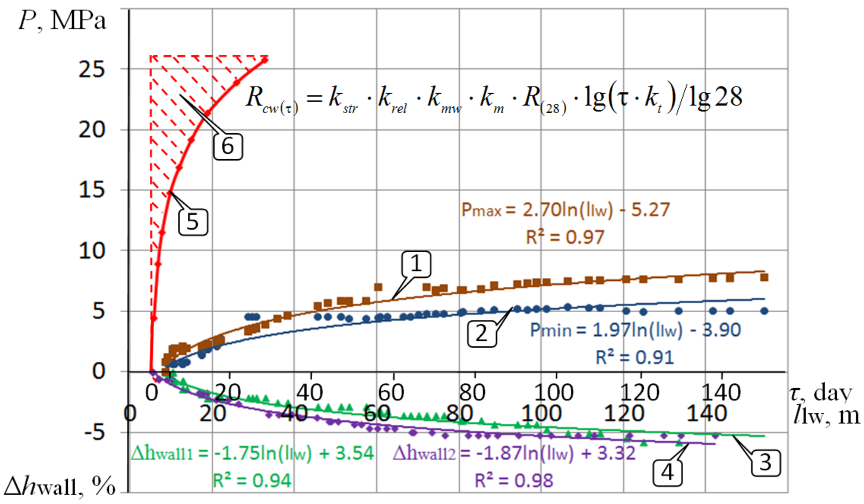

Fig. 3. Dependence of the stress-strain state of the concrete wall on the time of concrete hardening and the distance to the eruption of longwall in the case of an easily collapsed roof: 1, 2 – maximum and minimum pressure P (MPa) on the concrete wall, respectively; 3, 4 – relative vertical deformation Δ*h*$_{wall}$, (%) of different types of protective means, respectively packaged and combined walls; 5 – compressive strength limit of the concrete wall $R_{cw(\tau)}$ (MPa) in the corresponding period of time τ, days; 6 – zone of destructive pressure for the concrete wall

Thus, in the conditions of an easily collapsed roof (category A1), at any time interval τ, the increase in the compressive strength limit of the concrete strip $R_{cw(\tau)}$ was at least 5 times ahead of the increase in the pressure P_{max} on the wall (Figure 3, curves 1 and 5). Therefore, in order to save money, changes were developed and applied to the product's fastening passport. The width of the concrete wall was reduced, as well as a combined wall made of sections of concrete and rolled walls made of timber alternating along the length of the working was used (Figure 3, curve 4).

In the case of a low-collapse roof, the load on the means of protection of working is smaller than in the case of a medium-heavy collapse roof, but the rate of their growth over time is greater. Therefore, the sections of the wall rolled from the timber, accepting the load at the initial time, give the concrete in the sections with the packed wall an opportunity to harden under the conditions of non-destructive loading (2). Because of that, the relative vertical deformation of the combined wall is somewhat smaller than the deformation of the concrete wall and also corresponds to the logarithmic dependence (Figure 3, curve 3).

After working out the longwall, the 166th belt roadway was saved for reuse.

Conclusion

1. According to the results of observations in the conditions of roof categories A2-A3, the increase in the compressive strength limit of the concrete wall $R_{cw(\tau)}$ by 25-50% was ahead of the increase in the pressure P_{max} on the wall in any time interval τ. The criterion of stability of the concrete wall is fulfilled, therefore the parameters of the working protection tool proposed in the Recommendations satisfy the geological and technological conditions. After the longwall was worked out, the 562nd belt roadway was saved for reuse.

2. In the conditions of an easily collapsed roof (category A1), at any time interval τ, the growth of the compressive strength limit of the concrete wall $R_{cw(\tau)}$ was at least 5 times ahead of the growth of the pressure P_{max} on the wall. Therefore, for the purpose of saving money, changes to the passport of fastening were developed and applied to the Recommendations. The width of the concrete wall was reduced, and a combined wall of sections of concrete and rolled timber strips alternating along the length of the product was used. After working out the longwall, the 166th belt roadway was saved for reuse.

3. The pressure of the fake roof of the coal seam and the relative vertical deformation of the means of protection of the district roadway increase according to logarithmic dependences on the distance to the longwall outcrop and the time of concrete hardening. With heavy and medium roof collapse, these processes are divided into two stages: in the first stage (the length of which corresponds to the step of the roof collapse), as the longwall moves, the pressure increases intensively, at the moment of collapse it drops by 15-20%, and in the second stage again increases, but 6-8 times more slowly than on the first one, and, provided the relative vertical deformation of the protective device stabilises, passes into a stable mode. With an easily collapsed roof, the step of its collapse does not have a significant effect on the growth and stabilisation of the stress-deformed state of the protective device.

4. The scientific novelty of the obtained results lies in the disclosure of the mechanism and the establishment of dependencies of loading and deformation of concrete means of protection of district roadway depending on the distance to the longwall outcrop, taking into account the category of stability of the coal seam roof.

5. The reliability of the results and conclusions is confirmed by the scientific validity and approbation of the research methodology used; preparation and testing in the laboratory of measuring equipment for conducting mine experiments. The reliability of the approximation of the results is not lower than 0.75.

6. The practical significance of the obtained results lies in the development and implementation of recommendations regarding the parameters and technology of the construction of a guard-isolation wall in the conditions of the Chervonogradska and Lisova mines of the Lviv Coal State Enterprise, which allowed to reduce the costs of cement-mineral mixture by 27% and save the belt roadways No. 562 and No. 166 for reuse as ventilation when working out the adjacent trench column.

References

Bulat, A. F., Iljashov M. A. & Usachenko B. M. (ed.), (2004). *Temporary Technological Regulations for the Protection of Development Workings of Coal Mines with Cast Strips of Hardening Materials,* RIA Dnepr-VAL, Dnepropetrovsk, Ukraine.

Bulat A. .F. (2014). Advanced Technologies for Tunnel Supporting in Ukrainian Coal Mines, *Visnyk of the National Academy of Sciences of Ukraine*, 1, 74-79, https://doi.org/10.15407/visn2014.01.074.

Bulat A. F., Smirnov A. V., Kurnosov S. A., Vozijanov V. S., Tsikra A. A., Zaderiy V. V. & Averkin D.I.(2014). The Method of Working Protection, UA Patent 92305, Patented on 11 August 2014.

KD 12.01.01.503, (2001). *Roof Control and Fastening in Longwalls on Coal Seams with Dip Angle up to 35⁰*, Kyiv, Ukraine.

Nekache, R., Boukelloul M. & Fredj M. (2015). Stability Analysis of Underground Mining and their Application on the Mine Chaabte El Hamra, Algeria. *Procedia Earth and Planetary Science*, 15, 237-243, https://doi.org/10.1016/j.proeps.2015.08.058.

NPAOP 10.0-7.08-93, (1996). *Coal Mine Ventilation Design* Guide, Kyiv, Ukraine.

NPAOP 10.0-1.01-10, (2010). *Safety Rules in Coal Mines*, Kyiv, Ukraine.

Rotkegel, M & Bock S. (2015). Impact of Plates Dimensions on Interaction of Mine Workings Support and Rock Mass, *Journal of Sustainable Mining*, 14 (1), 12-20, http://doi.org/10.1016/j.jsm.2015.08.003.

Stadnychuk, M. M., Kurnosov S. A., Makeiev, S.Y. Justification of the conformity of the quick-setting mmixture parameters to the conditions of using safety means for the district workings, Szkoła Eksploatacji Podziemnej 2023: Materiały Konferencyjne, Kraków, 27.02–1.03.2023, Kraków: Instytut Gospodarki Surowcami Mineralnymi i Energią Polskiej Akademii Nauk, (pp. 632-636). https://szkolaeksploatacji.pl/wp-content/uploads/2023/02/materialy_sep_2023.pdf.

Xing, Y., Kulatilake, P. & Sandbak, L. (2019). *Rock Mass Stability Around Underground Excavations in a Mine.* CRC Press, London, UK, https://doi.org/10.1201/9780429343230.

Zhang, Z., Shimada, H., Sasaoka, T. & Hamanaka A. (2017). Stability control of retained goaf-side gateroad under different eoof conditions in deep underground Y type longwall mining, *Sustainability*, 9(10), 1671, https://doi.org/10.3390/su9101671.

Zhao J-J, Zhang Y. (2017). Studies on rock failure of layered rocking underground mining-face and control techniques. *Geomech Geophys Geo-Energy Geo-Resour,* 3, 405-414, https://doi.org/10.1007/s40948-017-0068-0.