DOI: https://doi.org/10.68732/7c825c8540a37bab

ISBN: 978-9989-2053-7-8

Assessment of mine stability during selective coal seam extraction with backfill into the mined-out space

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Abstract

This article is devoted to studying the effect of backfilling the mined-out space during selective extraction of a thin coal seam on mine stability. The aim of the research is to develop a geomechanical model and assess the stress-strain state of the rock mass, considering the formation of a backfill massif in the mined-out space of the longwall. The research object is the mining and geological conditions of seam C8n at the "Zakhidno-Donbaska" mine, PJSC "DTEK Pavlogradvuhillya", Ukraine.

Numerical modeling was conducted using the ANSYS software package, which allowed for identifying the patterns of vertical and horizontal stress distribution in the coal-bearing massif and evaluating the reduction in stress concentration zones. Stress field diagrams around the longwall entry were obtained for traditional extraction technology with full caving and selective extraction technology with backfill into the mined-out space.

The results showed that the use of backfill material reduces vertical stresses by up to 1.8 times, horizontal stresses by up to 2.7 times, and decreases the stress-strain zones by 60-80%. This contributes to reduced deformations of mine workings, improved stability, and the creation of conditions for their reuse.

Keywords

Backfill, mine rock, Rock mass, Mine working, Stress-strain state.

1 Introduction

Modern mining industries face significant challenges related to improving the efficiency of mineral resource utilization, enhancing the quality of extracted products, and minimizing environmental impacts. One of the critical problems in Ukrainian mines is the development of thin coal seams (less than 0.8 m thick), which are characterized by low economic efficiency when using traditional technologies (Malashkevych et al., 2022). The extraction of such seams necessitates increased waste rock removal, leading to higher operational ash content in the coal and complicating its further utilization. Moreover, the high intensity of ground pressure manifestations makes it difficult to maintain adjacent mine workings, increasing the costs of reinforcement and repair.

An innovative approach to addressing this issue is the implementation of selective mining technology with backfill into the mined-out space. This technology not only improves the quality of the extracted coal but also utilizes waste rock from the longwall face as backfill material, minimizing waste generation and creating conditions for the reuse of longwall entries (Smoliński et al.,2022).

Research on mine stability and the application of selective mining technology is conducted both in Ukraine and internationally. Ukrainian scientific literature focuses on optimizing backfill parameters to enhance mine stability. For instance, studies (Malashkevych et al., 2018) confirm the effectiveness of backfill technologies in reducing ground pressure manifestations. Similar results are presented in studies (Luan et al., 2017), which emphasize geomechanical processes occurring during longwall operations in complex geological conditions. International researchers (Zhang et al., 2019) investigate backfill material applications to prevent surface subsidence and collapses, highlighting its role in reducing rock mass deformation. These studies provide successful examples of selective mining technology implementation in Chinese mines, where advanced approaches to coal seam development are actively employed (Duan et al., 2020)

Significant contributions to this topic include studies on modelling the stress-strain state of rock masses (Li et al. 2017), which examine the impact of backfill material on mine stability. Furthermore, research (Petlovanyi et al., 2020) highlights the ecological benefits of backfill technologies in minimizing the environmental footprint of mining operations. The scientific community also actively investigates new types of backfill materials to enhance mine stability. For example, studies (Petlovanyi et al., 2021) focus on analysing the granulometric composition of rocks used as backfill and their impact on reducing geomechanical processes. Additionally, monitoring and control of ground pressure are essential research areas, identifying key parameters of stress distribution in rock masses when using backfill technologies (Gautam and Yadu, 2021).

Selective coal seam mining technology with backfill has significant potential to enhance mine stability and reduce costs. However, optimizing backfill material parameters, predicting the stress-strain state of the rock mass, and adapting the technology to specific deposit conditions remain relevant challenges.

The goal of this study is a comprehensive assessment of mine stability during selective coal seam extraction with backfill into the mined-out space. The research aims to develop a geomechanical model, study the impact of backfill material on mine stability, and determine optimal conditions for the industrial implementation of this technology

2 Research methodology

2.1 Characteristics of the research object

To achieve the objectives of the study, the mining and geological conditions of the “Zakhidno-Donbaska” mine (Ukraine) were selected. The selective coal extraction technology with backfill into the mined-out space is considered the most promising for this mine due to the limited coal reserves in its seams. An analysis of geological data from the minefield indicates that the majority of coal reserves are concentrated in seams with a thickness of less than 0.8 m (69.7% of industrial reserves). For example, 58.7% of reserves in the seam being worked occur within the thickness range of 0.55-0.8 m. This implies that an increased inclusion of surrounding rock to 0.45 m could lead to a rise in the operational ash content of the coal in the longwall face to over 60% when using traditional bulk extraction methods.

The geomechanical model of the coal-bearing massif was developed based on the conditions at the "Zakhidno-Donbaska" mine during the extraction of longwall 861 in seam C_8^n. The initial position in this research was to provide the most accurate and reliable representation of the mining and geological conditions of seam extraction when developing the geomechanical model.

The selected area of the 861st longwall is considered hazardous in terms of high-intensity ground pressure manifestations. It was chosen for modeling through computational experiments to evaluate the effect of backfill strip formation in the mined-out space on the stability of longwall entries under intense ground pressure conditions, which presents significant scientific interest.

2.2 Justification of the geomechanical model

Computational experiments were conducted using the ANSYS software package, which provides extensive capabilities for solving geomechanical problems based on the finite element methods. The selected software for stress-strain state (SSS) analysis, together with the adopted methodological approach to the development of the geomechanical model, ensured reliable results with a high degree of agreement with in-situ observation, as confirmed by numerous studies (Zhang et al. 2016: Bondarenko et al. 2023; Wang and Li 2019).

The methodological framework of the study involved the development of two numerical models: the first representing the conventional mining technology (for comparative evaluation), and the second representing selective coal seam extraction with backfilling of the mined-out space. The difference between the models lies in the presence of a backfill strip located in the mined-out space adjacent to the extracted seam.

The SSS calculations were performed using an elastoplastic formulation. In the numerical simulations, negative stress values correspond to compressive stresses, whereas positive stress values correspond to tensile stresses. The same sign convention is adopted for all stress contour plots presented in this study. The behavior of the rock mass and support elements was described by bilinear stress-strain relationships. Within the elastic range, the relationship between stresses and strains was governed by Hooke`s law. The transition of materials into the plastic state was controlled by their strength properties. Yielding and failure of both the rock mass and support elements were simulated by approximating their deformation diagrams using bilinear constitutive functions separately for rock materials and steel support components, post-yield behavior was represented by a significant reduction in material stiffness after reaching the strength limit.

The model dimensions were 55 m along the dip/rise direction of the seam (x-axis) and 60 m in the vertical direction (y-axis), with a seam dip angle of 3º.The applied boundary conditions of the geomechanical model are shown in Fig. 1.

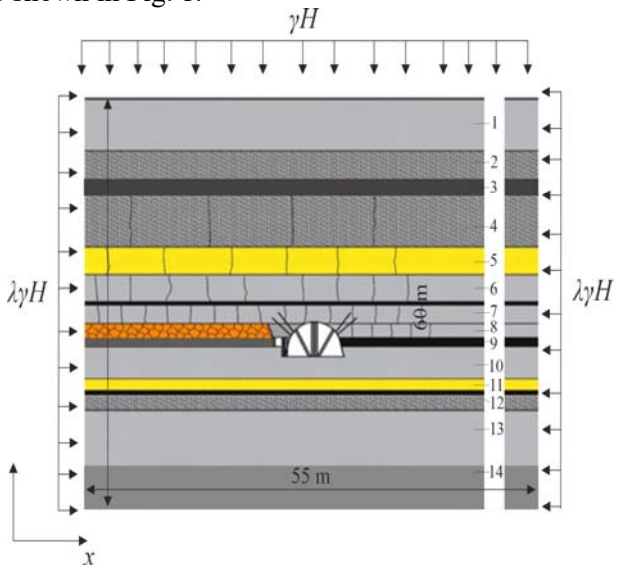


Fig. 1 Geomechanical model for assessing the condition of the surrounding rockmass around the gathering roadway. Layer numbering corresponds to the lithological sequence and properties presented in Table 1.

The upper boundary was subjected to the load generated by the weight of the overlying strata, the lateral boundaries were constrained against horizontal displacements, and the bottom boundary was fixed in both horizontal and vertical directions. The main mechanical properties of the coal-bearing strata used in the model are presented in Table 1.

Table 1. Mechanical characteristics of coal-bearing rock strata.

№	Thickness, m	Type of rock	σ_c, MPa	σ_r, MPa	γ, kg/m^3	E·10^4, MPa
1	0-0.72	Siltstone	26.8	2.2	2.33	1.0
2	0-0.60	Argillite	11.0	0.7	2.7	0.5
3	1.02	Coal seam	26.0	1.3	1.24	0.3
4	3.05-7.2	Siltstone	26.8	2.2	2.33	0.2
5	6.0-9.0	Sandstone	40.0	2.7	2.6	2.0
6	3,0-5,4	Siltstone	26.8	2.2	2.33	2.0
7	5.6-12.4	Argillite	11.0	0.7	2.7	0.1
8	1.5-2.0	Argillite	11.0	0.7	2.7	0.1
9	0.74-0.8	Coal seam C_8^n	31.0	1.3	1.24	0.3
10	0.95-2.2	Argillite	10.0	0.81	2.22	0.1
11	1.31-1.8	Sandstone	37.9	2.7	2.6	2.0
12	0.1-0.3	Coal seam	27.0	1.3	1.26	0.25
13	2.4-15.0	Siltstone	26.8	2.2	2.33	0.2
14	11.6-14.3	Argillite	10.0	0.8	2.2	0.15

In Table 1, σ_c denotes the uniaxial compressive strength of the rock, $\sigma_r$denotestheuniaxial tensile strength, γ is the volumetric weight (density) and E is the deformation modulus. The mechanical characteristics of lithological variations were obtained from geological and mining forecasts for the 861st longwall gathering roadway. The influence of weakening factors such as rock fracturing, water saturation, and rheology was accounted for in accordance with regulatory documents (SOU 10.1.00185790.011:2007; KD 12.01.201-98)and the results of studies (Bondarenko et al. 2023; Dychkovskyi et al. 2020). The mechanical properties of support materials were included in the calculations based on reference data (Feng and Zhang 2018). The deformation properties of granular backfill materials formed from mine rocks (Li et al. 2022; Kovalevska et al. 2020) were assumed to correspond to the compression load period. The deformation properties of the backfill material after settlement were accepted as follows: deformation modulus E = 50 MPa, poisson's ratio $\mu = 0.4$.

In the cross-section of the roadway model, a KSHPU-14.4 steel-polymer support system (profile SVP-27) was installed, featuring four rows of wooden beams with a cross-section of 0.1 m×0.15 m and a length of 3.2 m. The frame support spacing was 0.8 m. Along the caving side of the longwall, three rows of wooden props (diameter 0.2 m, length 2.3 m) and one row of wooden props (diameter 0.2 m, length 1.2 m) were installed on the floor of the roadway.

The anchoring system consisted of four anchors, each 2.4 m long and 22 mm in diameter, installed into the rock mass between the frames at 0.8 m intervals. The SSS calculations were performed in an elastoplastic formulation.

This approach allowed for accounting for plastic deformations within the geomechanical system and avoiding significant calculation errors, thereby enhancing the reliability of the analysis.

3 Results of numerical modeling

The most intensive manifestations of ground pressure occur after the longwall face passes, making this section of the roadway critical for potential reuse. The analysis of the geomechanical system included an evaluation of abnormal zones and the distribution of vertical and horizontal stresses, with results corresponding to modern models of rock mass behavior.The obtained vertical stress diagrams are presented in Fig. 2.

On the side of the mined-out space, there is a large area of unloaded roof and floor rocks of seam C_8^n, with a vertical stress range of σ_y = 2.3 MPa-6.7 MPa. Relative to the initial non-hydrostatic state of the undisturbed massif ($\sigma_y = \gamma H$), the unloading degree is 0.21-0.61. Thisarea extends up to 16.6 m into the roof, reaching the upper sandstone layer, which forms the boundary between the block-hinge deformation zone and the smooth bending zone without layer integrity violations. In the floor of the seam, the unloading zone extends throughout the entire model depth, exceeding 18.4 m. Within this area, within the thickness of the block-hinge deformation zone, centres of complete unloading ($\sigma_y \approx 0$) emerge, transitioning to tensile stresses of up to 2 MPa. This phenomenon aligns with existing understandings (Bazaluk et al. 2022) of coal-bearing strata movement near the longwall face.

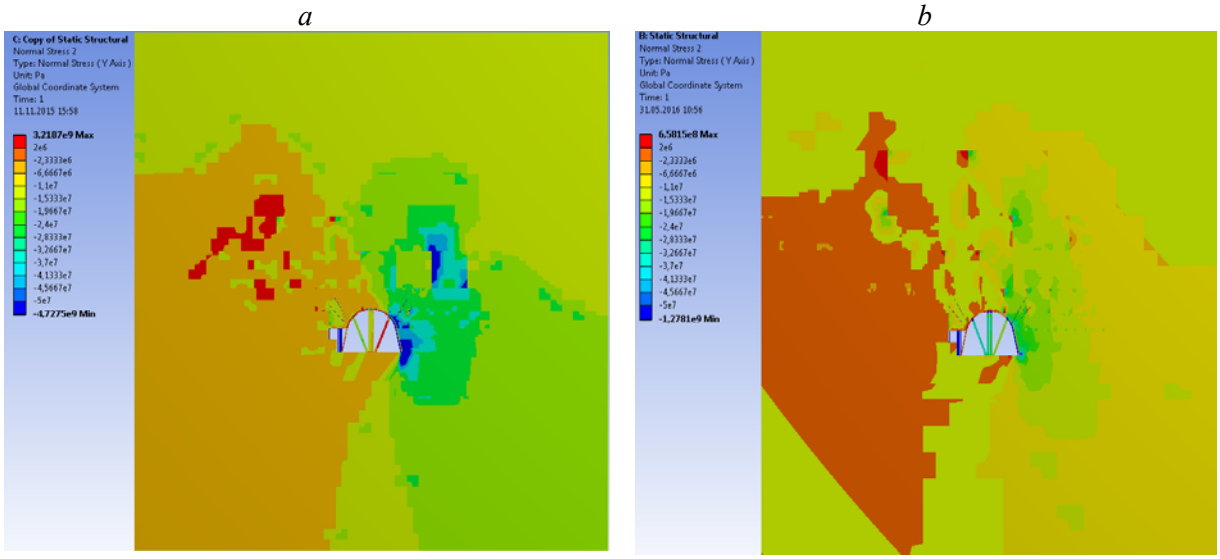


Fig. 2 Vertical stress diagrams σ_v in the coal-bearing rock mass around the gathering roadway under conventional extraction technology(*a*) and selective extraction with backfill technologies (*b*).

The weight of the delaminated and caved roof rocks creates some stress concentration in the areas of support and reinforcement elements that resist the deformation process, including single-row timber supports and rows of side and central props for additional reinforcement (Kovalevska et al. 2018). However, the magnitude of these concentrations is relatively small ($\sigma_v/\gamma H$ = 1.40-1.79), attributed to the low response of the entire row of wooden props and the compliance of the additional reinforcement props. This stress concentration zone extends up to 14.2 m into the roof and through the entire model depth into the floor.

Stress concentrations of $\sigma_y/\gamma H$ = 3.4-6.0 definitively destroy the contour rocks, extending up to 1.8 m in width and 4.5 m in height from the roadway contour. Particularly hazardous is a localized area with $\sigma_v/\gamma H \geq$ 4.5-5.0, with dimensions of 1.9 m in height and 0.8 m in width. Its negative impact lies in its location under the coal seam near the support bases of the frame props.

In terms of floor rock stability (based on vertical stress factors), increased floor heave intensity can be predicted from the undisturbed massif side, where lateral abutment pressure plays a significant role in this process. All these features of σ_y distribution indicate the necessity of substantially reinforcing the roadway's frame support.

When using selective seam extraction technology with backfill into the mined-out space, the distribution of vertical stresses significantly differs from the baseline scenario. Particular attention was paid to the areas of stress concentration, which are of the greatest interest regarding the load formation on the support and protection systems of the gathering roadway. The general conclusion is reduced concentrations and smaller areas of their influence due to decreased deformation of the roof rock layers, which descend onto a wide backfill support.

On the side of the mined-out space, the concentration of compressive σ_v in the immediate roof above three rows of side wooden props for additional reinforcement completely disappeared. This can be explained by the fact that, despite the sufficient rigidity of the wooden props, their total resistance to the descending roof layers is dozens of times lower compared to the total resistance of the backfill massif constructed in the mined-out space. For the same reason, the sizes of the minimum $\sigma_v/\gamma H \leq 1.4$ concentrations in the immediate roof above the row of single-row timber supports have sharply decreased (in height by 95% and in width by 3.2 times); higher concentrations have disappeared altogether.

The sizes of areas with moderate stress concentrations $\sigma_y/\gamma H$ = 1.40-1.79 have significantly reduced. Previously, under the baseline technology, such concentrations formed a single large area, while under selective extraction technology, they are divided into two parts: in the main roof, with a height of up to 4.8 m and a width of up to 2.1 m; and in the immediate roof and floor, with a combined height of 11.4 m and a width of up to 4.2 m. Compared to the baseline technology, the areas affected by

moderate σ_v concentrations have been significantly reduced. It should be noted, however, that this stress level can only weaken soft argillite.

The positive effect of forming a backfill massif in the mined-out space becomes evident when comparing the above-mentioned areas of $\sigma_v/\gamma H = 1.79\text{-}2.18$ concentrations with those under the baseline technology: their spread into the roof is reduced to 10.0 m, into the floor to 5.3 m, and along the strike to 6.6 m. This represents a significant reduction in the areas affected by σy concentrations capable of weakening the softest lithotypes in the coal-bearing massif. As for concentrations that weaken or completely destroy stronger lithotypes (coal and sandstone), they practically disappear under the selective seam extraction technology.

Thus, regarding vertical stress factors, a substantial reduction in hazardous concentrations and the shrinkage of their areas of influence can be observed. Further analysis focused on the distribution of horizontal stresses σ_x with diagrams presented in Fig. 3.

Horizontal stress components σ_x vividly reflect the bending of rock layers and its direction, which is clearly observed in the main roof of the roadway. Intensely loaded sandstone layers, as more rigid and durable lithotypes, are particularly affected.

For example, in sandstone located 5.0-5.5 m above the roof contour, a large area of compressive σ_x concentration forms, exceeding the original state of the undisturbed massif by 8.7-13.2 times. This area extends up to 1.8 m in thickness and up to 8.4 m along the bedding plane. The bending of the sandstone layer is directed toward the roadway, and the high concentration of σ_x indicates its active resistance to ground pressure. In the event of sandstone instability, the underlying siltstone (likely water-saturated) may also weaken significantly due to the lack of underlying support, potentially causing the development of the roof failure height up to the next sandstone layer above.

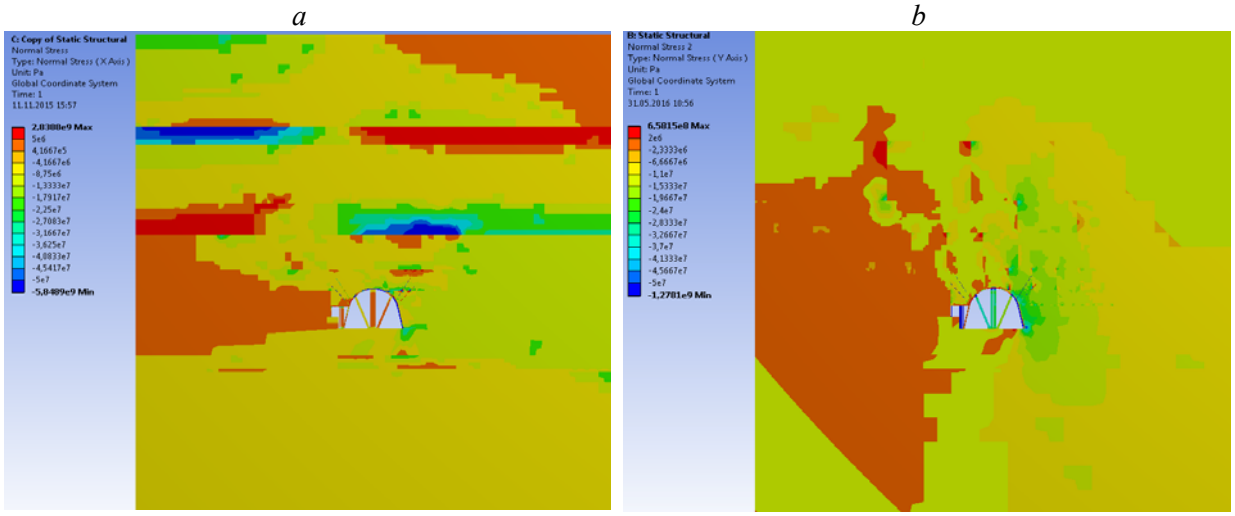


Fig. 3 Horizontal stress diagrams σ_x in the coal-bearing rock mass around the gathering roadway under conventional extraction technology (*a*)and selective extraction with backfill technologies (*b*).

On the side of the mined-out space, an area of nearly fully unloaded rocks with tensile σ_x stresses of 3-5 MPa is formed. Given that this area includes zones of chaotic caving and hinge-block deformation, the tensile stresses further exacerbate rock disintegration, forming a large-sized rubble zone. Thus, the hypothesis of provoking the caving of the immediate and lower layers of the main roof to create support as the roof descends has merit. This is supported by the relatively small gradient of σ_x changes in the roof height (from the mined-out space side) up to the coordinates of sandstone bedding at the boundary with the zone of smooth bending layers without integrity violation.

This relative homogeneity of σ_x distribution (excluding rigid sandstone) indicates mild bending of the main roof layers. As a result, the rubble zone of caved rocks partially fulfills its function of providing adequate support. On the undisturbed massif side of the roadway, there are two localized areas of σ_x concentration (1.0-2.8 range) within an overall weak concentration background. The upper area is located in the arch region (frame hinge joints), while the lower area is located near the prop bases of the frame supports.

Stress concentrations in the more distant sandstone, which likely marks the upper boundary of the hinge-block deformation zone, have been significantly reduced. On the mined-out space side, the compressive σ_x concentration decreased by 1.65-2.7 times with a relatively small (10-15%) reduction in their spatial extent. The absolute value of these concentrations is no longer sufficient to weaken the sandstone. On the massif side, the extent of tensile σ_x regions ≥ 5 MPa has been limited to 15-20%, although this does not improve the block separation situation within the sandstone, as its tensile strength is much lower (σ_r = 1.6 MPa). Simultaneously, the penetration depth of tensile σ_x(through the sandstone thickness) has been reduced to 60%, suggesting an increase in the stability of the sandstone block support system.

Processing the results of numerical modelling established patterns of rock contour changes (Fig. 4) for both traditional and selective seam extraction technologies with backfill in the mined-out space.

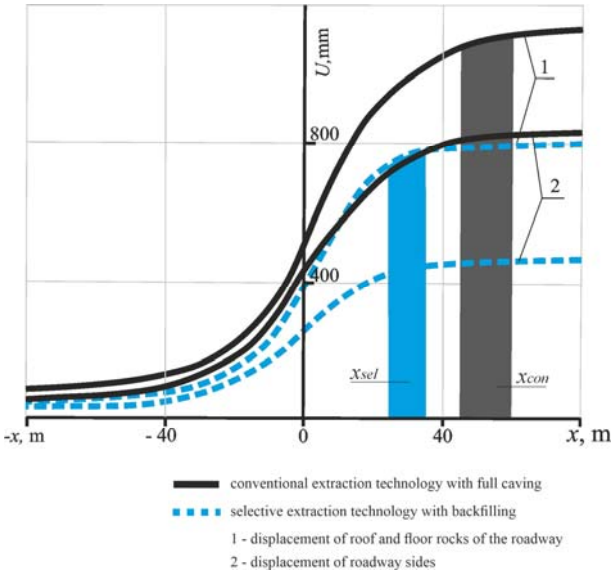


Fig. 4 Patterns of displacement *U* development in the rock contour of the roadway depending on the distance *x* from the longwall face and seam extraction schemes.

Figure 4 illustrates the development of roadway contour displacements depending on the distance from the longwall face. The obtained results indicate that the general pattern of displacement development remains similar for both mining technologies. As the longwall face approaches, roof-to-floor convergence and roadway side displacement gradually increase, reaching their maximum values in the vicinity of the powered support, after which the deformation rate decreases and the displacements stabilize. However, the formation of a backfill massif significantly reduces the intensity of rock mass deformation. Under selective extraction with backfill, the stabilization distance decreases from 45-60 m to 25-35 m. In addition, roof-to-floor convergence is reduced by approximately 1.42 times and does not exceed 790 mm, while roadway side convergence decreases by about 1.84 times and remains below 450 mm. These results confirm the positive influence of backfilling on roadway stability and support performance.

In summary, based on the SSS analysis of the coal-bearing massif around the gathering roadway, several positive changes in its condition can be observed when backfill massifs are formed in the mined-out space:

– hazardous concentrations of vertical stresses σ_y are reduced by up to 1.8 times, and their areas of influence are significantly decreased;

– horizontal stresses σ_x form stable block systems in nearly all layers of the main roof, capable of actively resisting ground pressure;

– these factors contribute to reducing the intensity of ground pressure manifestations and enhancing the stability of the gathering roadway.

Steel-polymer anchors show a reduction in the σ_x component, particularly on the massif side. For instance, tensile σ_x stresses completely disappear in the upper anchor and are reduced by 1.9-2.2 times in the lower anchor. This is attributed to the decreased deformation intensity in the immediate roof

layers under selective coal seam extraction technology with backfill in the mined-out space. In other support system elements, the stress distribution field remained virtually unchanged.

Thus, a comparative analysis of the gathering roadway support system condition has identified several positive changes when selective seam extraction technology with backfill is employed:

– the plastic deformation zones in frame supports and steel-polymer anchors are reduced by 60–80%, or they are entirely eliminated;
– side wooden props of the additional reinforcement system transition into a stable state, providing maximum resistance to the deformation of the immediate and lower layers of the main roof;
– these factors collectively enhance the overall stability of the roadway.

3 Conclusions

A comparative analysis of longwall roadway stability under traditional and selective extraction technologies with backfill confirmed significant improvements. Reduced concentrations of vertical stresses σ_y enhance the stability of support elements, effectively counteracting multi-directional ground pressure. Horizontal stresses σ_x improve frame supports and steel-polymer anchors, while reducing roof and floor convergence by 1.42 times and roadway side convergence by 1.84 times. These deformations slightly exceed KSHPU support compliance but can be managed through reinforcement. The findings highlight that backfilling improves roadway stability, enabling reuse, reducing costs, enhancing safety, and minimizing environmental impact.

References

Bazaluk, O., Rysbekov, K., Nurpeisova, M., Lozynskyi, V., Kyrgizbayeva, G., &Turumbetov, T. (2022). Integrated monitoring for the rock mass state during large-scale subsoil development. *Frontiers in Environmental Science*, *10*, 852591.https://doi.org/10.3389/fenvs.2022.852591

Bondarenko, V., Salieiev, I., Kovalevska, I., Chervatiuk, V., Malashkevych, D., Shyshov, M., &Chernyak, V. (2023). A new concept for complex mining of mineral raw material resources from DTEK coal mines based on sustainable development and ESG strategy. *Mining of Mineral Deposits*, *17(*1), 1-16. https://doi.org/10.33271/mining17.01.001

Bondarenko, V., Kovalevska, I., Sheka, I., &Sachko, R. (2023, April). Results of research on the stability of mine workings, fixed by arched supports made of composite materials, in the conditions of the PokrovskeMine Administration. *IOP Conference Series: Earth and Environmental Science*, *1156*(1), 012011. https://doi.org/10.1088/1755-1315/1156/1/012011

Duan, H., Sun, M., & Li, Q. (2020). A new gob-side entry retaining approach with reinforced filling gangue wall in thin coal seam. *Geotechnical and Geological Engineering*, *38*(1), 883-895.https://doi.org/10.1007/s10706-019-00874-5

Dychkovskyi, R., Saik, P., Lozynskyi, V., Falshtynskyi, V., Shavarskyi, I., & Cabana, E. (2020). Research into stress-strain state of the rock mass condition in the process of the operation of double-unit longwalls. *Mining of Mineral Deposits*, *14*(2), 85-94.https://doi.org/10.33271/mining14.02.085

Feng, X., & Zhang, Q. (2018). The effect of backfilling materials on the deformation of coal and rock strata containing multiple goaf: A numerical study. *Minerals*, *8*(6), 224.https://doi.org/10.3390/min8060224

Gautam, A.D., & Yadu, L.K. (2021). Study on the characteristics of overburden dump of the coal mines. In *Transportation, Water and Environmental Geotechnics: Proceedings of Indian Geotechnical Conference 2020 Volume 4* (pp. 63-71). Springer Singapore. https://doi.org/10.1007/978-981-16-2260-1_6

KD 12.01.201-98. (1998).*Location, protection and maintenance of mine workings during coal seam extraction in mines. Methodological guidelines* (*Raspolozhenie, okhranaipodderzhaniegornykhvyrabotokpriotrabotkeugolnykhplastovnashakhtakh)*. Metodicheskieukazaniya. Kyiv, Ukraine: UkrNIMI, 149 s.

Kovalevska, I., Samusia, V., Kolosov, D., Snihur, V., &Pysmenkova, T. (2020). Stability of the overworked slightly metamorphosed massif around mine working. *Mining of Mineral Deposits*, *14*(2), 43-52. https://doi.org/10.33271/mining14.02.043

Kovalevska, I., Barabash, M., &Snihur, V. (2018). Development of a research methodology and analysis of the stress state of a parting under the joint and downward mining of coal seams. *Mining of Mineral Deposits*, *12*(1), 76-84. https://doi.org/10.15407/mining12.01.076

Li, M., Zhou, N., Zhang, J., & Liu, Z. (2017). Numerical modelling of mechanical behavior of coal mining hard roofs in different backfill ratios: a case study. *Energies*, *10*(7), 1005. https://doi.org/10.3390/en10071005

Li, M., Zhang, J., Guo, Y., Pu, H., & Peng, Y. (2022). Influence of particle size distribution on fractal characteristics of waste rock backfill materials under compression. *Journal of Materials Research and Technology*, *20*, 2977-2989.https://doi.org/10.1016/j.jmrt.2022.08.056

Luan, H., Jiang, Y., Lin, H., & Wang, Y. (2017). A new thin seam backfill mining technology and its application. *Energies*, *10*(12), 2023.https://doi.org/10.3390/en10122023

Malashkevych, D., Petlovanyi, M., Sai, K., & Zubko, S. (2022). Research into the coal quality with a new selective mining technology of the waste rock accumulation in the mined-out area. *Mining of Mineral Deposits*, *16*(4).https://doi.org/10.33271/mining16.04.103

Malashkevych, D., Sotskov, V., Medyanyk, V., & Prykhodchenko, D. (2018). Integrated evaluation of the worked-out area partial backfill effect of stress-strain state of coal-bearing rock mass. *Solid State Phenomena*, *277*, 213-220.https://doi.org/10.4028/www.scientific.net/SSP.277.213

Petlovanyi, M.V., Zubko, S.A., Popovych, V.V., & Sai, K.S. (2020). Physicochemical mechanism of structure formation and strengthening in the backfill massif when filling underground cavities. *Vopr. KhimiiKhimicheskoi Technol.6*(6), 142-150. https://doi.org/10.32434/0321-4095-2020-133-6-142-150

Petlovanyi, M., Malashkevych, D., Sai, K., Bulat, I., &Popovych, V. (2021). Granulometric composition research of mine rocks as a material for backfilling the mined-out area in coal mines. *Mining of Mineral Deposits*, *15*(4), 122-129. https://doi.org/10.33271/mining15.04.122

Smoliński, A., Malashkevych, D., Petlovanyi, M., Rysbekov, K., Lozynskyi, V., & Sai, K. (2022). Research into impact of leaving waste rocks in the mined-out space on the geomechanical state of the rock mass surrounding the longwall face. *Energies*, *15*(24), 9522.https://doi.org/10.3390/en15249522

SOU 10.1.00185790.011:2007. (2008).*Development workings in flat coal seams. Selection of support systems, protection methods and means(Pidhotovchivyrobkynapolohykhplastakh. Vybirkriplennia, sposobivizasobivokhorony).* StandartMinvuhlepromuUkrainy. Donetsk, Ukraine: DonVUHGI, 114 s.

Wang, Z., & Li, L. (2019). Study of energy release in failure of coal and rock near fault on ANSYS. *Geotechnical and Geological Engineering*, *37*(10), 2577-2589. https://doi.org/10.1007/s10706-018-00779-9

Zhang, J., Li, M., Taheri, A., Zhang, W., Wu, Z., & Song, W. (2019). Properties and application of backfill materials in coal mines in China. *Minerals*, *9*(1), 53.https://doi.org/10.3390/min9010053

Zhang, J., Sun, Q., Zhou, N., Haiqiang, J., Germain, D., & Abro, S. (2016). Research and application of roadway backfill coal mining technology in western coal mining area. *Arabian Journal of Geosciences*, *9*, 1-10. https://doi.org/10.1007/s12517-016-2585-5