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Numerical simulation on effect of coal pillar width on stability of retained roadway: A case study of Khe Cham Coal Mine, Vietnam

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When extracting coal seams in Vietnam underground mines, coal pillars are often left unmined for the protection of retained roadways in the longwall mining method. During longwall mining operations, coal pillars are often placed where high-stress concentrations occur in the abutment pressure zone of adjacent panels, especially when extracting seams under hard-to-cave main roof conditions. The instability of coal pillars under the loading of the main roof may cause the roadway to collapse, threatening the safe operation of a coal mine. This paper presents a detailed numerical investigation of the effect of coal pillar width on the stability of retained roadway under hard-to-cave main roof conditions, which has not been fully understood in previous studies. The results indicate that as the width of the coal pillar increases, the peak stress gradually moves from the virgin coal side to the pillar side, and an elastic zone will gradually be formed in the center of the pillar. A pillar width of less than 40 m coal pillars is easily destroyed under the great pressure caused by the hard main roof. A pillar width greater than 40 m creates a safe condition and has enough bearing capacity to maintain the stability of retained roadways. Based on these results, this paper proposes to use an improved longwall mining method where the coal pillars should be mined together with the adjacent panel to reduce coal loss in pillars.

Keywords

FLAC3D numerical simulation; coal pillar; stress distribution; roadway deformation; retained roadway; hard-to-cave roof

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Numerical Simulation on Effect of Coal Pillar Width on Stability of Retained Roadway: A Case Study of Khe Cham Coal Mine, Viet Nam

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Abstract

When extracting coal seams in Vietnam underground mines, coal pillars are often left unmined for the protection of retained roadways in the longwall mining method. During longwall mining operations, coal pillars are often placed where high-stress concentrations occur in the abutment pressure zone of adjacent panels, especially when extracting seams under hard-to-cave main roof conditions. The instability of coal pillars under the loading of the main roof may cause the roadway to collapse, threatening the safe operation of a coal mine. This paper presents a detailed numerical investigation of the effect of coal pillar width on the stability of retained roadway under hard-to-cave main roof conditions, which has not been fully understood in previous studies. The results indicate that as the width of the coal pillar increases, the peak stress gradually moves from the virgin coal side to the pillar side, and an elastic zone will gradually be formed in the center of the pillar. A pillar width of less than 40 m coal pillars is easily destroyed under the great pressure caused by the hard main roof. A pillar width greater than 40 m creates a safe condition and has enough bearing capacity to maintain the stability of retained roadways. Based on these results, this paper proposes to use an improved longwall mining method where the coal pillars should be mined together with the adjacent panel to reduce coal loss in pillars.

Keywords: FLAC3D numerical simulation, coal pillar, stress distribution, roadway deformation, retained roadway, hard-to-cave roof

1. Introduction

For safe and efficient production in an underground coal mine, it is vital to control the deformation of roadways, to increase the degree of coal extraction, and to reduce the costs of production [1]. In Vietnam's underground coal mines, the longwall mining method with U-shaped (Fig. 1a) is widely used due to its high performance. However, as the mining depth increases, the advantage of this system clearly decreases because it is necessary to leave large coal pillars unmined, which leads to great coal loss. To reduce coal loss, a longwall mining method with the construction of artificial strips of pillars for the protection of retained roadways was studied (Fig. 1b). With this system, the problem of coal loss was solved, leaving no coal in the pillar. However, excessive material consumption, strict requirements for material, difficult construction conditions and high-cost limit the popularity of the mining system.

To solve the problem of coal loss, another modified longwall mining method was proposed, as shown in Figure 1c [2,3]. In this scheme, the ventilation roadway is retained beside a coal pillar; so that the costs can be reduced in comparison with the construction of an artificial pillar. In addition, coal pillar, after fulfilling its function, will be extracted together with the adjacent longwall face. This accordingly reduces the coal loss in the pillars. The modified mining system can thus solve the problems associated with the "U" type system when mining at great depth and under a hard-to-cave main roof.

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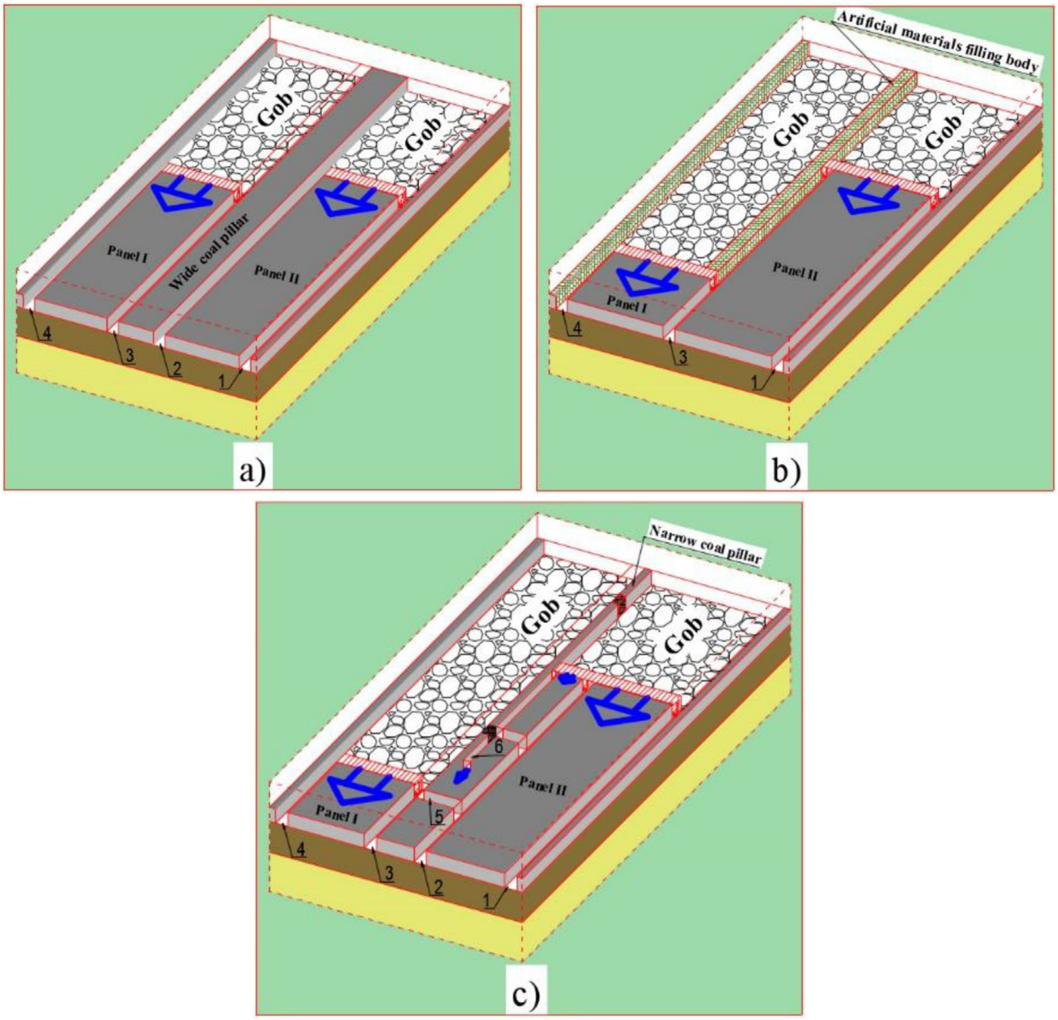


Fig. 1. 3D model of longwall mining methods: a — wide coal pillars; b — protective pillar using artificial materials; c — narrow coal pillars; 1 — II headgate; 2 — II tailgate; 3 — I headgate; 4 — I tailgate; 5 — crosscut; 6 — gob-side entry driving.

The modified mining technology, however, encounters the problem of maintaining the stability of roadways and pillars. That is, the coal pillars and roadways are located in the area affected by progressive mining with impacts such as dynamic loading from collapsing or settlement and fracturing of roof rock layers. At the same time, static stress in the surrounding rocks of the gob is redistributed until the movement of the upper strata ceases [4]. The combination of dynamic loading during roof strata collapse, and high static stress can easily cause dynamic catastrophes such as rock bursts, especially when mining at great depth and under a hard-to-cave main roof. The catastrophes can be minimized by increasing the width of the coal pillar, but this at the same time increases coal loss. Therefore, the determination of a proper coal pillar width is a key requirement when applying the modified mining system.

The width of the coal pillar in the longwall mining method was previously investigated by many authors. Liu et al. [5] confirmed that the determination of coal pillar width is the key to ensuring safe production in deep coal seams. In their studies, the authors found that the coal pillar is influenced by the roof rocks in the form of static loading, dynamic loading and stress superposition. Zhang et al. [6] determined the width of coal pillars for ultra-thick seams (17 m). In their study, the coal pillar stability was evaluated through the field survey and stress analysis in deep boreholes. Xie et al. [7] conducted field measurements and used the FLAC3D program to determine the rule of stress distribution and pillar width when mining multiple seams. Wu et al. [8] studied the propagation rules of shear and tensile cracks in coal pillars with different widths in a fractured 5.5 m thick coal seam. Shi et al. [9]

investigated the crack development mechanism in the roof strata above coal pillars and proposed optimal supporting parameters combined with a roof rocks cutting solution. He et al. [10] studied the characteristics of stress distribution and plastic zones in the surrounding rocks of roadway corresponding to different coal pillar widths when mining ultra-thick coal seams. Li et al. [11] determined coal pillar width for gob-side roadway under multilayer hard roofs in deep mines. Ma et al. [12] conducted a study on the stress distribution of narrow coal pillars with different top coal caving heights. They suggested that the thick top coal is not conducive to the control of roadways. Yu et al. [13] and Nguyen et al. [14] determined the proper width of narrow coal pillars along gob-side driving entries in coal seams having gas outbursts.

The above studies have contributed to a better understanding of coal pillar width stability and its failure mechanisms under various geo-mining conditions in the longwall mining method. However, there has been very limited research on pillar stability under the condition of hard-to-cave roof strata. The instability of coal pillars under the loading of hard-to-cave rocks' main roof may cause roadway collapse and safety incidents that have not been studied to satisfactory level in previous studies. Therefore, it is necessary to research this issue to ensure labor safety and production efficiency of the mine.

This paper presents a detailed study on the stress distribution and coal pillar stability corresponding to different widths under hard-to-cave rocks main roof' in the longwall mining method. Stable coal pillars lead to stable retained roadways, and this reduces the repair cost of the roadways. The research method was carried out with a numerical simulation model, FLAC3D. This is a computer program built by Itasca Corporation to specialize in research on the stress-strain state of rock mass. It is therefore suitable for use in this study. The paper's results can be consulted for better design of pillar for safe and productive longwall mining.

2. Materials and methods

2.1. Site of study

In this paper, the geological conditions of the Khe Cham coal mine in Quang Ninh province, Vietnam, are selected for study due to the typical hard-to-cave roof strata. The coal seam No. 11 is used as an example in this study. The seam has an average thickness of 3.0 m and a depth of 400 m, with a dip angle of 9°. The physico-mechanical properties of coal and rock units are shown in Figure 2.

2.2. Construction of numerical simulation

A numerical simulation is constructed based on the computer program FLAC3D [15] to study the stability of the retained roadway and stress distribution when the coal pillar width varies. FLAC3D is a computer program for the numerical modelling of continuum media to investigate the stress-strain state of a rock mass. FLAC3D uses an explicit finite volume method to represent complex behaviors of rock mass, experiencing large displacements and deformations and considering non-linear material behavior. The program is capable of modelling material failure over large areas.

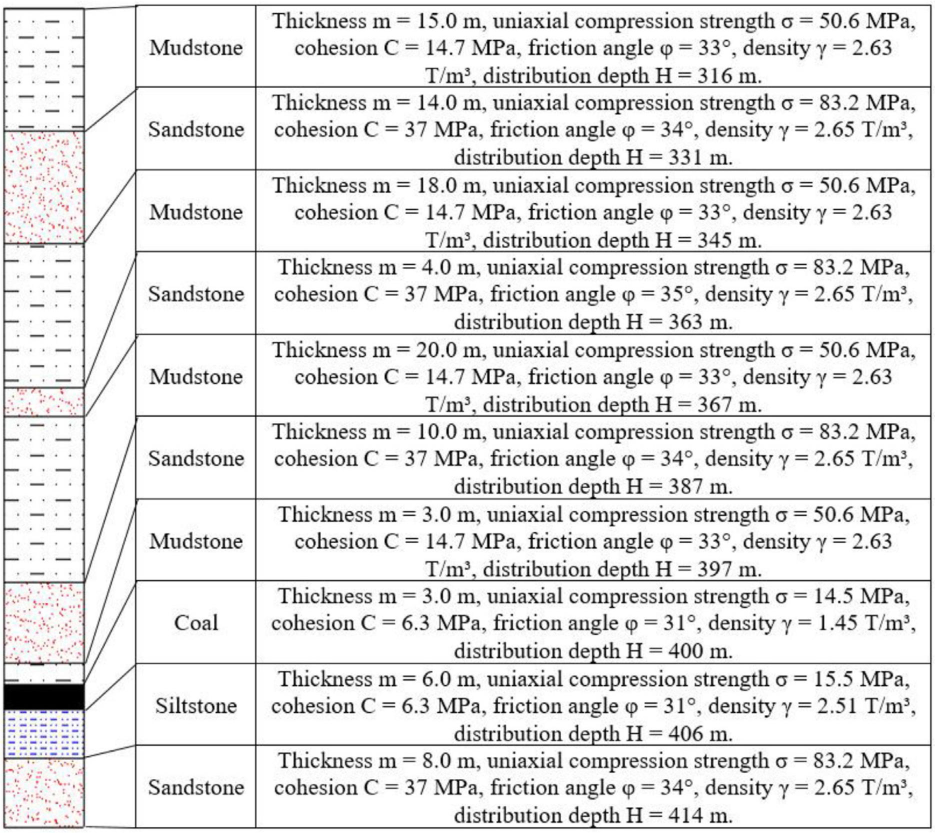
The model has a length of 310 m, a width of 200 m, and a height of 150 m, as shown in Figure 3. This model size was determined through a trial-and-error process considering the size and density of finite volume. Panels #11.1.1 and Panel #11.1.3 and associated roadways are included in the model. The roadway's width and height are 4.0 and 3.0 m, respectively. For parametric study, the coal pillars are built with widths of 15, 20, 30, 40 and 50 m. The overburden stress is 7.0 MPa applied to the top boundary. The specific gravity of rocks is 2500 kg/m^3 with a gravity of 10 m/s^2 [16]. The horizontal boundaries of model are fixed in the X direction, while the bottom boundary is fixed in the Y direction. The Mohr-Coulomb constitutive law is used for materials.

The numerical model was constructed and run as follows: (1) calculating initial stress caused by gravity; (2) driving roadways 11.1.1 and 11.3.3; (3) extracting panel 11.1.1; and (4) extracting panel 11.1.3. The model has five options for pillars of different sizes. Depending on the mining conditions and characteristics of the coal seam, the height of the coal pillar is set to 3.0 m, and its width is modelled with dimensions of 15, 20, 30, 40 and 50 m, respectively. The algorithm flowchart of the simulation is shown in Figure 4.

The physical-mechanical properties of coal and rocks used in the model are based on the stratigraphic characteristics of panels 11.1.1 and 11.1.3 at the Khe Cham coal mine. The input properties for the model are listed in Table 1.

3. Results and discussion

The results of numerical modelling and determining the influence of coal pillar width are shown in Figure 5. The position of the monitoring cross-section on the model is at a distance of 20 m in front of longwall face #11.1.3. In these figures, the white



Mudstone	Thickness m = 15.0 m, uniaxial compression strength σ = 50.6 MPa, cohesion C = 14.7 MPa, friction angle φ = 33°, density γ = 2.63 T/m³, distribution depth H = 316 m.
Sandstone	Thickness m = 14.0 m, uniaxial compression strength σ = 83.2 MPa, cohesion C = 37 MPa, friction angle φ = 34°, density γ = 2.65 T/m³, distribution depth H = 331 m.
Mudstone	Thickness m = 18.0 m, uniaxial compression strength σ = 50.6 MPa, cohesion C = 14.7 MPa, friction angle φ = 33°, density γ = 2.63 T/m³, distribution depth H = 345 m.
Sandstone	Thickness m = 4.0 m, uniaxial compression strength σ = 83.2 MPa, cohesion C = 37 MPa, friction angle φ = 35°, density γ = 2.65 T/m³, distribution depth H = 363 m.
Mudstone	Thickness m = 20.0 m, uniaxial compression strength σ = 50.6 MPa, cohesion C = 14.7 MPa, friction angle φ = 33°, density γ = 2.63 T/m³, distribution depth H = 367 m.
Sandstone	Thickness m = 10.0 m, uniaxial compression strength σ = 83.2 MPa, cohesion C = 37 MPa, friction angle φ = 34°, density γ = 2.65 T/m³, distribution depth H = 387 m.
Mudstone	Thickness m = 3.0 m, uniaxial compression strength σ = 50.6 MPa, cohesion C = 14.7 MPa, friction angle φ = 33°, density γ = 2.63 T/m³, distribution depth H = 397 m.
Coal	Thickness m = 3.0 m, uniaxial compression strength σ = 14.5 MPa, cohesion C = 6.3 MPa, friction angle φ = 31°, density γ = 1.45 T/m³, distribution depth H = 400 m.
Siltstone	Thickness m = 6.0 m, uniaxial compression strength σ = 15.5 MPa, cohesion C = 6.3 MPa, friction angle φ = 31°, density γ = 2.51 T/m³, distribution depth H = 406 m.
Sandstone	Thickness m = 8.0 m, uniaxial compression strength σ = 83.2 MPa, cohesion C = 37 MPa, friction angle φ = 34°, density γ = 2.65 T/m³, distribution depth H = 414 m.

Fig. 2. Lithological profile and physical-mechanical properties of rocks in the study area.

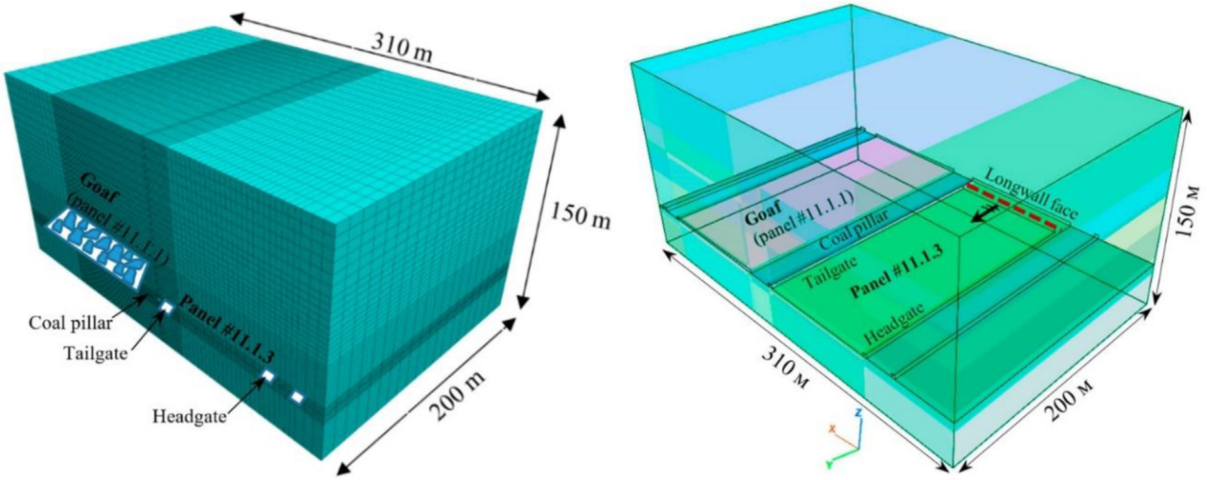


Fig. 3. Configuration of longwall model using FLAC3D.

area represents the elastic state, and the remaining colors represent the state of plasticity (inelastic). The two curves to the right and the left of the roadway represent the vertical stress distributed in the coal pillar and in the virgin coal rib, respectively.

The maximum vertical stress values in the coal pillar and the virgin coal rib are denoted by σ_p and σ_s, respectively (Fig. 5). The stress values for both the coal pillar and the surrounding rocks were recorded as the maximum stresses achieved.

When the coal pillar width is 15 m (Fig. 5a), the pillar may be crushed, and the roadway cannot be stable. In this case, the width of the destruction zones in the roof, virgin coal rib and floor reaches

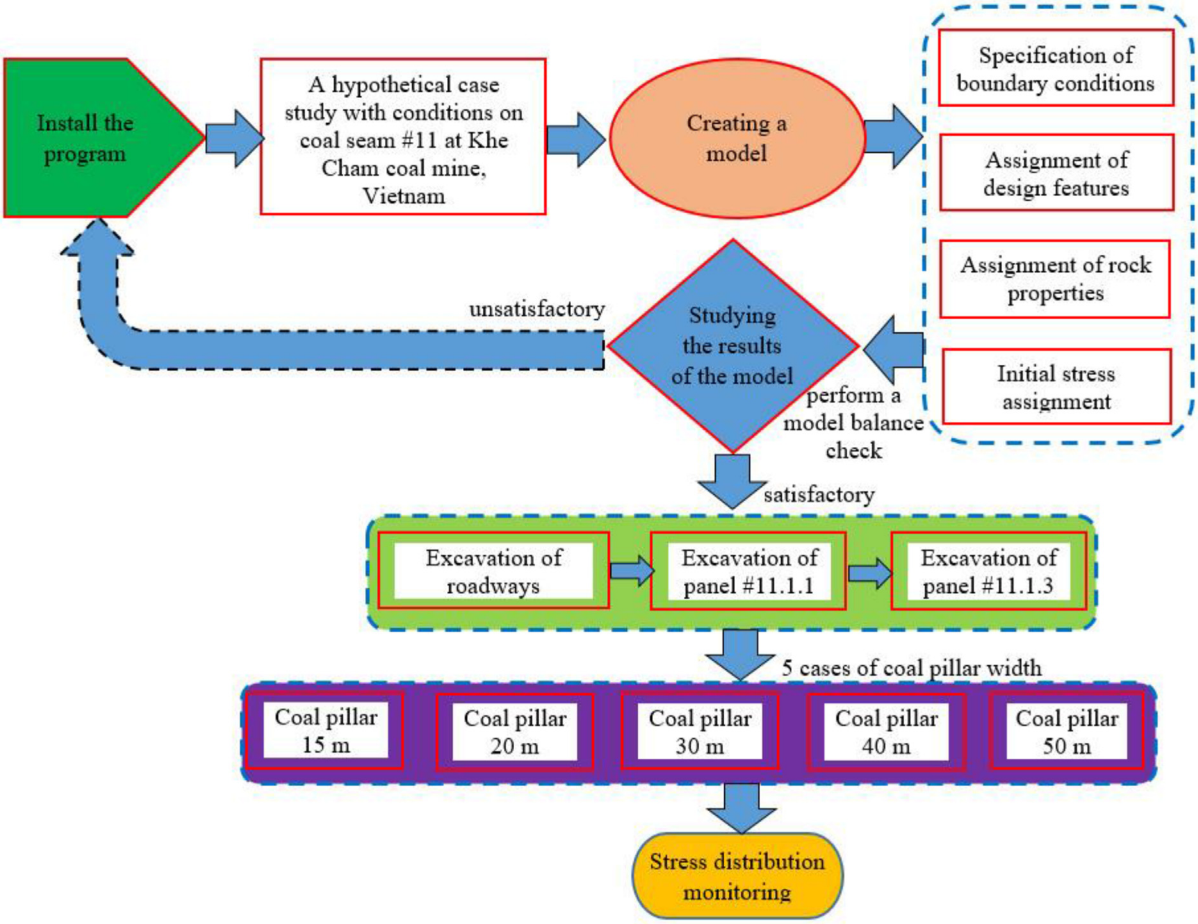


Fig. 4. Block diagram of algorithm for numerical simulation in FLAC3D.

Table 1. Physical-mechanical properties of rocks [16].

Type rock	Tensile strength (MPa)	Bulk modulus (GPa)	Shear modulus (GPa)	Poisson's ratio	Cohesion (MPa)	Friction angle (degree)	Density (kg/m^3)
Sandstone	1.62	7.46	3.24	0.313	3.22	34.2	2785
Mudstone	0.93	2.33	0.96	0.324	2.14	30.1	2552
Siltstone	1.22	1.82	0.61	0.352	1.83	26.4	2253
Coal	0.41	0.75	0.48	0.261	1.54	19.3	1454

3 m, 22 m, and 4 m, respectively. The value of vertical stresses in the coal pillar (σ_p) is 25.03 MPa, and the stresses in virgin coal rib (σ_p) are equal to 50.28 MPa. These values indicate that the maximum concentration of vertical stress is in virgin coal rib.

With an increase in the coal pillar width from 15 to 20 m (Fig. 5b), the coal pillar remains in a state of inelastic deformation. The width of the destruction zone in the roof and in the virgin coal rib is reduced to 2.5 and 17 m, respectively. In addition, the stresses in the coal pillar (σ_p) sharply increase to 47.35 MPa and exceed the stresses in the virgin coal rib. This shows that the rock pressure is mainly acting on the coal pillar. It should be noted that the stress in the virgin coal rib also increased to a great value of 41.59 MPa.

When the coal pillar width is 30 m (Fig. 5c), the stress in the virgin coal rib is 29.62 MPa, and in the coal pillar the maximum stress is 42.68 MPa. The stresses are unevenly distributed over the width of the coal pillar, and the peak stress values on both sides of the roadway significantly decreased, although still high in magnitude. The stress distribution in the coal pillar changes: signs of the formation of two maximum peaks of stress concentration are clearly visible, but the zones of

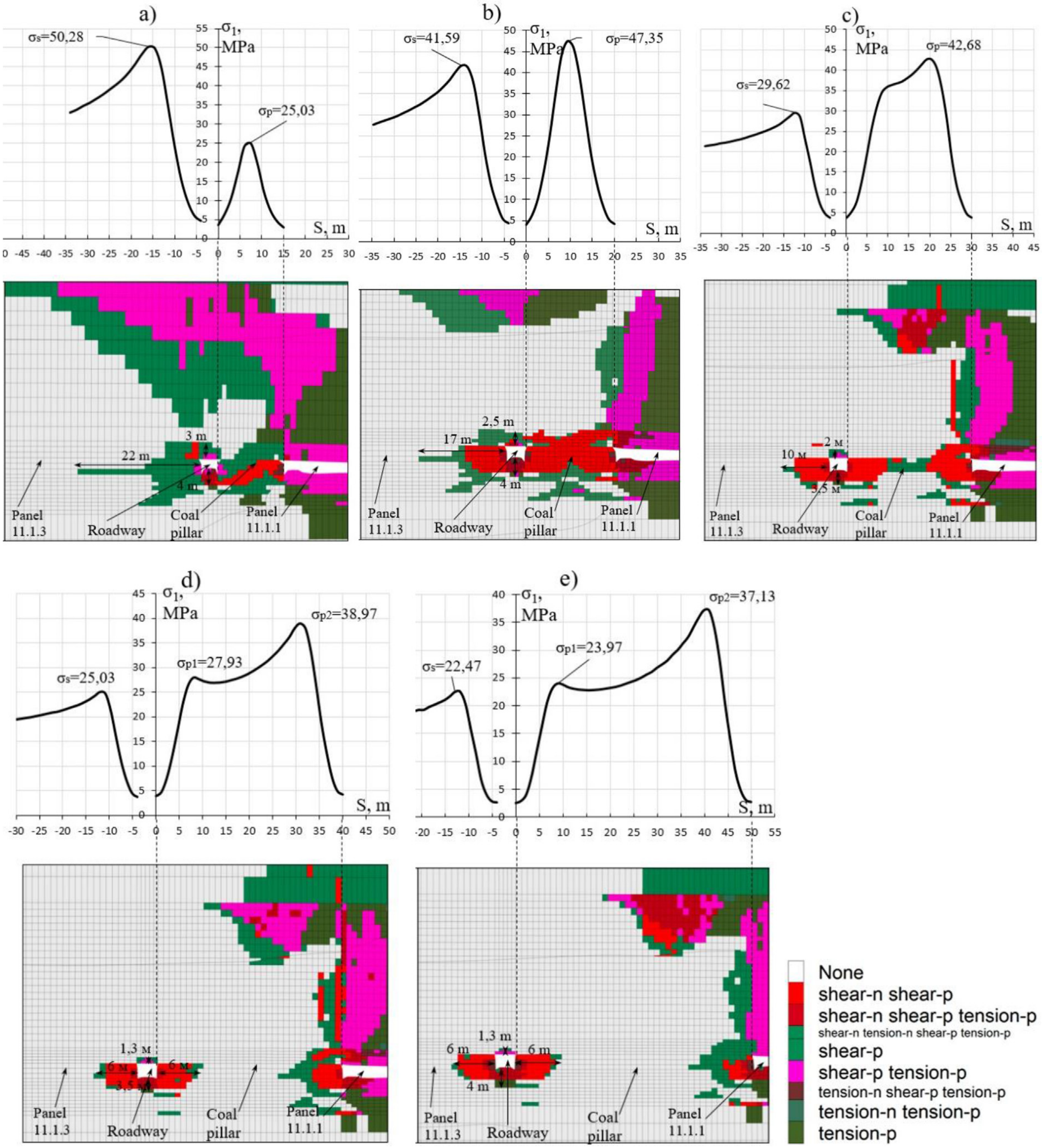


Fig. 5. Distribution of vertical stress and elastic zone around a roadway with different coal pillars widths: a) – coal pillar 15 m; b) – coal pillar 20 m; c) – coal pillar 30 m; d) – coal pillar 40 m; e) – coal pillar 50 m.

inelastic deformations still extend to the entire coal pillar. The area of plastic deformation zone (inelastic) in the roof, virgin coal rib and floor is reduced to 2 m, 10 m and 3.5 m, respectively.

With a coal pillar width of 40 m (Fig. 5d), an elastic zone with a width of about 14 m remains in this pillar. At this time, on the coal pillar, two stress peaks are formed on both sides, and the values of σ_p and σ_s slightly decrease.

When a coal pillar width is 50 m (Fig. 5e), the width of the elastic zone increases to 24 m in the pillar. The zone of destruction in the surrounding rocks of the roadway has not changed significantly. The distribution of vertical stresses on the coal pillar with double peaks expands, and the stress values continue to decrease slightly. The stress distribution in the coal pillar changes: signs of the formation of two maximum peaks of stress concentration are clearly visible, but the zones of inelastic deformation still extend to the entire coal pillar. The area of plastic deformation zone (inelastic) in the roof, virgin coal rib and floor is reduced to 2 m, 10 m and 3.5 m, respectively.

The above numerical results indicate that the bearing capacity of the coal pillar gradually increases with an increase in its width, and the position of the maximum stress gradually shifts from the virgin coal rib to the coal pillar. Therefore, it is possible to control the stresses in the surrounding rocks of the roadway by changing the width of the coal pillar.

3.1. Determine the width of the coal pillar

The principle of stress change in the surrounding rock mass is shown in Figure 5: the magnitude and distribution of stresses in the coal pillar and in the virgin coal rib change significantly as the width of coal pillar increases. This is the result of the stress redistribution caused by mining activity in the area. In a real mining environment at a coal seam with a hard-to-cave roof, due to changes in the stress distribution in the vicinity and from the influence of mining panels, as well as due to the extraction of the adjacent panels, coal pillars are subjected to a complex process of loading with a hard-to-cave roof. When a coal pillar is formed in the coal seam, stresses will develop on it. The abutment pressure is transferred from the immediate roof to the coal pillars and the virgin coal rib. When the rock pressure exceeds the tensile strength of coal at the edge of the coal pillar, destruction occurs from small to deep cracks. At the same time, pressure from the roof rocks is moved further into the coal seam.

If the coal pillar width is large, the pillar has enough bearing capacity to withstand the loading from the roof rocks during the extraction (Fig. 5d, e). Conversely, if the coal pillar is narrow, the bearing capacity of this pillar is too small and cannot withstand the loading from hard-to-cave roof rocks during extraction, and the stresses are transferred further into the coal mass (Fig. 5a). When the coal pillar has an average width (Fig. 5b and c), it has a certain bearing capacity, but the stresses in the coal pillar and virgin coal rib are great, and this distribution is uneven. A high concentration of stresses in a coal pillar under certain conditions results in a rock burst [17,18]. Therefore, the formation of a wide coal pillar is also a condition of safety. Considering the proposed scheme of the longwall mining method in which the coal pillar is extracted along with the adjacent longwall face, it is possible to determine the optimal width of the coal pillar by the criterion of ensuring the stability of the retained roadway.

Thus, regarding the stress distribution, the analysis of the simulation results showed that with a pillar width of 40 m, two stress peaks appear on it, and an elastic zone is formed in its center part. The elastic zone is the key to the stability of the coal pillar, as well as its ability to protect the retained roadway. The rock around the roadway is in relatively low stresses so that the stability of the roadway can be ensured using conventional supports. Moreover, the coal pillars will be extracted together with the adjacent longwall face, making it possible to significantly increase the coal recovery rate [19,20].

When considering the deformation of the roadway, as discussed earlier in this section, a narrow pillar of 20 m and normal support cannot guarantee the stability of the retained roadway and the safety of production. The destabilization mechanism of the roadway can be described as follows. During the mining of the panel, there is a continuous redistribution of stresses in the surrounding rock mass. With the movement of roof strata, coal is destroyed in the marginal part of the seam, heaving off the floor rocks and squeezing from the sides of the roadway. That is, the rocks strongly deform and gradually turn into a plastic state with large inelastic deformations. The metal support of the roadway is severely damaged along the boundary of the roadway. The stresses in the coal pillar are reduced and less than those in the virgin coal rib. It can be concluded that the roadway will be crushed and destroyed simultaneously with the destruction of the coal pillar. This result is evidenced by the survey image at the Khe Cham coal mine (when the coal pillar width is 15–20 m) (Fig. 6).

When the coal pillar width is 30 m, the convergence of roof, floor and roadway ribs is small and decreased compared to those caused by a coal pillar width of 15 m and 20 m. However, the width of inelastic deformation zones still occupies up to 10 m at the virgin coal rib and extends to a depth of 3.5 m on the roadway floor. It is important to note that the inelastic deformation zone still extends to the entire width of the coal pillar. The stress on the coal pillar is distributed continuously and forms a single peak with a higher stress concentration than that on virgin coal rib. That is, the coal pillar now plays the main load-bearing role. The problem with ensuring the stability of the roadway remains. Both sides of the roadway are in the area of high stresses ($\sigma_p = 42.68$ MPa and $\sigma_s = 29.62$ MPa) that adversely

Fig. 6. The roadway is deformed when the coal pillar width is 15–20 m at Khe Cham coal mine.

affects the stability of the roadway (Fig. 5c). In combination with the effect of front abutment pressure of longwall face 11.1.3, there is a high risk of large deformations of the support and destruction of the retained roadway 11.1.3.

Based on the numerical analysis, the correlation between coal pillar width and roadway convergence is obtained and shown in Figure 7.

Figure 7 shows that as the width of the coal pillar increased, the deformation of the roadway was markedly reduced. When the coal pillar is narrow (15 m), the loading from the hard-to-cave main roof causes the coal pillar to be destroyed. The displacement of the roadway of the coal pillar side is 800 mm, and especially the floor heaving is 1000 mm. The roof sagging is 460 mm, and the displacement on the solid coal side is 268 mm. In this case, the incidents of roadway deformation are similar to the results of the field survey at the Khe Cham coal mine (the coal pillar width is 15–20 m), as shown in Figure 6. It proves that a narrow coal pillar should not be selected for protecting the retained roadway. With the expansion of the coal pillar to 40 m, the convergence of the roadway decreases linearly to an acceptable value for the protection of the roadway stability and reduction of repair costs. As a result, the parameters of the corresponding roadway convergence are: 163 mm of roof sagging, 71 mm of displacement of the solid coal side, 384 mm of displacement of the coal pillar side, and 249 mm of floor heaving.

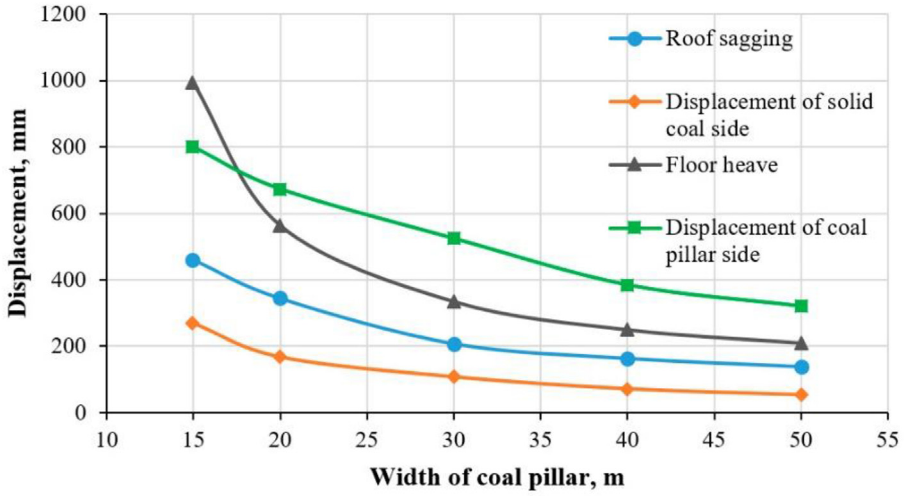


Fig. 7. Convergence of the roadway with different coal pillar widths.

4. Conclusions

This paper investigated the relationship between the coal pillar width and the retained roadway stability by using numerical simulation and comparing it with practice. Based on the numerical results, the conclusions of the study are summarized as follows.

(1) A 3D numerical simulation was built using FLAC3D to study the width of coal pillars in medium-thick seams and a hard-to-cave main roof. Numerical calculations were performed to obtain the stress distribution and the plastic zone evolution of the surrounding rock with different pillar widths. The results show that the increased pillar size leads to a gradual change in the maximum stress in the virgin coal rib and in the coal pillar. A coal pillar width of less than 20 m is not sufficient for bearing capacity, leading to instability of the retained roadway.

(2) Because the retained roadway adjacent to the gob-side is severely affected by mining, it is necessary to consider the design of the coal pillars' width to ensure the safety in production. The research results show that there is a significant difference between the observed plastic deformation area and the stress distribution of the rock mass surrounding two sides of the roadway. In the condition that the coal seam has a hard-to-cave main roof, the roadway is greatly deformed when the coal pillar width is 15 m and 20 m. In this case study, a coal pillar of greater than 40 m wide ensures the stability of the retained roadway adjacent to the gob-side. The proposed mining system (Fig. 1c) will effectively improve the stability of the retained roadway at the Khe Cham coal mine.

Ethical statement

The authors state that the research was conducted according to ethical standards.

Funding body

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Conflicts of interest

The authors declare no conflict of interest.

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