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An experiment to determine the width of coal pillar when mining seams under hard-to-cave main roof conditions

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ABSTRACT

Ensuring roadway stability is one of the keys to determining production efficiency and labor safety in Vietnam's underground coal mines. However, it is difficult to determine the reasonable width of coal pillars to protect the roadway and roadway deformation therefore usually occurs. Especially when exploiting coal seams in the deep and hard main roof conditions, the deformation of the roadway becomes even more serious, affecting labor safety. Using the mining data of Seam #10 at Ha Long Coal Company as the reference case of this research, a scale model of equivalent materials has been conducted. The stability of the roadway has been simulated and analyzed in different widths of coal pillars. The results show that, when exploiting coal seams under a hard-to-cave roof, very thick and long roof consoles are formed in the gob. The stability of the coal pillar and roadway is influenced by the sagging, rotation, and fracturing of the main roof in the gob. Under the impact of static and dynamic loads of the main roof, a coal pillar of less than 40 m width is not stable enough to protect the roadway. As the width of the coal pillar decreases, more apparent cracks in the roadway roof appear, and the coal blocks on the walls of the roadway are broken and wider. Visual monitoring results show that a coal pillar of more than 40 m in width can ensure the stability of the roadway. However, it causes a much more loss of coal in the pillars, a challenge for further research.

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1. Introduction

In underground coal mines, the longwall mining system is the main method used in the mining of coal seams. In this method, ensuring roadway stability requires solving many geotechnical problems, which is the key to ensuring safe and efficient exploitation (Zubov and Le, 2022). In the process of implementation, the longwall mining method is applied with two schematics, including (1) one-entry and (2) two-entry of fresh air to the working face.

In the first schematic (1), the tailgate of the next panel is excavated after the roof rock collapses stably in the gob of the previous panel. This causes significant disruption and prevents continuous mining. As the mining depth increases, the challenges in ventilation and gas control are also becoming increasingly apparent. This affects significantly the production efficiency of mining enterprises. In the second schematic (2), the tailgate of the next panel is pre-excavated, allowing for continuous extraction and solving challenges related to transportation, ventilation, and gas control. In addition, in this schematic, the headgate and the tailgate of two adjacent panels are excavated in pairs and parallel to each other, creating efficient space for mining equipment and coal transportation. Therefore, the second type (2) is more commonly applied in most of Vietnam's underground coal mines (Figure 1). However, there is a big challenge that the second type (2) faces in the application process. That is to leave a considerable amount of coal in the coal pillars (coal pillar width of 10-25 m). In addition, the tailgate is inevitably subjected to the disturbance of increased mine pressure from the main roof during the excavation of both panels, causing a lot of problems, including unstable coal pillars, and deformation or damage of the tailgate. These incidents are especially serious when mining the coal seams under hard roof conditions (Figure 2).

In Vietnam's underground coal mines, the width of the coal pillar is an issue that can't be ignored. It plays an important role in safe and efficient mining. Based on analyzing the influence of dynamic loads caused by the main roof collapse

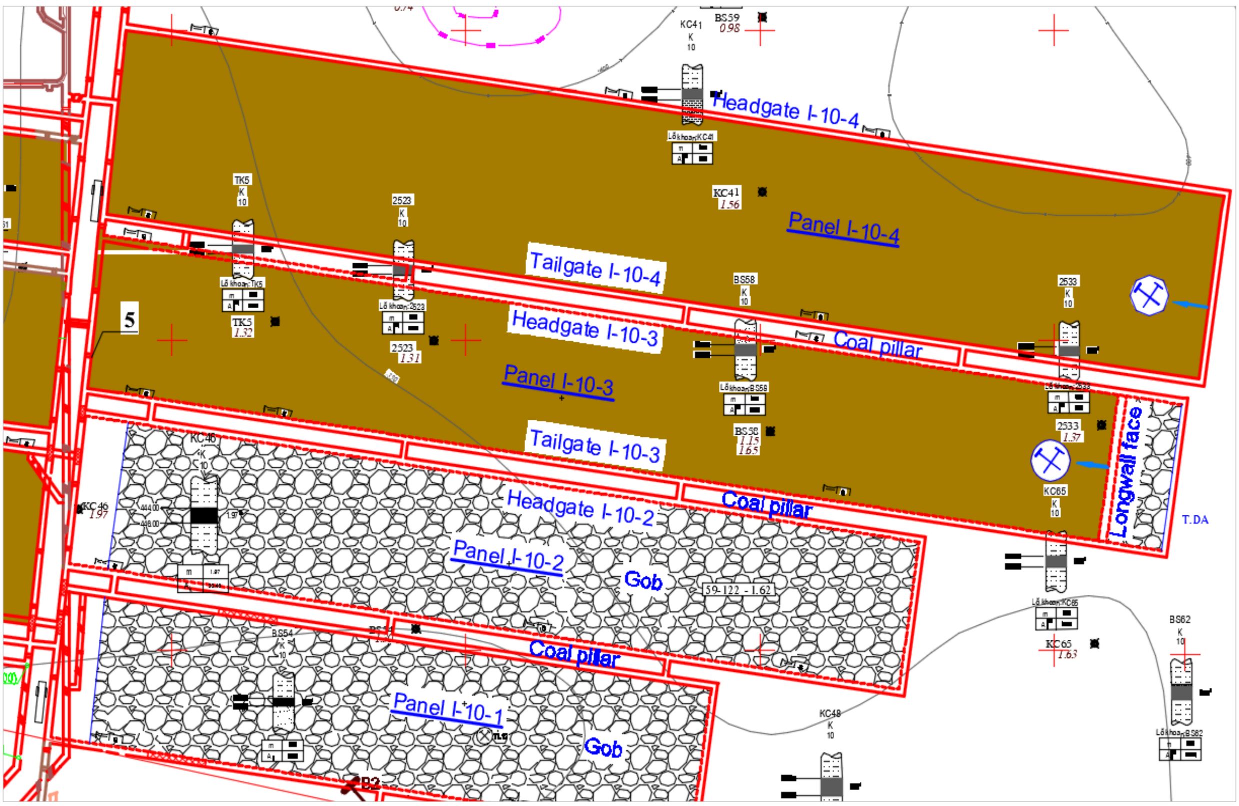


Figure 1. Diagram of longwall mining method applied in underground coal mines in Vietnam (The typical panels at seam #10 of Halong Coal Company).

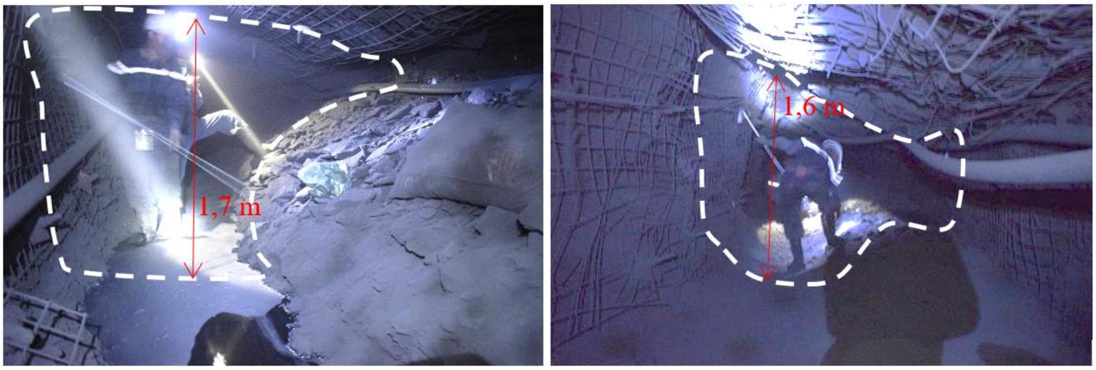


Figure 2. Deformation of roadway in longwall mining method (photograph of field survey at Halong Coal Company).

in rock, the impact intensity and distribution of abutment pressure in the coal pillar will increase. Therefore, the deformation and development of cracks in the surrounding rocks of the roadway will take place seriously, making it difficult to stabilize the roadway. It can be said that the determination of the coal pillar width and appropriate roadway support parameters will be the key to ensuring the stability of the rock surrounding the roadway, exploiting more coal resources, and saving costs. A study of the law and deformation intensity of the roadway corresponding to different widths of coal pillars has great scientific significance and technical application value.

By using different methods, many scholars have studied the deformation law of the roadway corresponding to different widths of coal pillars. Fan et al. (2020) performed a numerical simulation by using the FLAC3D program to determine the size of coal pillars in super-thick seams. After combining with the field survey, the authors found that a coal pillar of up to 24 m wide meets the requirements of retained roadway protection. The research results confirmed that during the retreat of the working face, the internal stress of the coal pillar changes from a single peak to a double asymmetrical peak, and the plastic region gradually develops from the sides to the middle of the coal pillar and creates a certain elastic core region. This elastic zone is the basis to ensure the stability of coal pillars and retained roadways. Yang et al. (2020), through equivalent materials models and numerical simulation, identified the law of vertical stress distribution, surrounding rock deformation, and the law of plastic destruction corresponding to different coal pillar widths in thick coal seams. Together with the results of field observations, the authors confirmed that a 5 m narrow coal pillar may suffer plastic failure without losing bearing capacity. When considering the transverse fracture characteristics of the main roof above the coal pillar, Pang et al. (2022) used numerical simulation and determined that the sagging and rotation of the main roof cause more loads on the coal pillar and roadway. As a result, the roadway and coal pillar are subjected to great stress, causing serious instability. Xingliang et al. (2016) proposed that the coal pillar is stabilized when there is a neutral surface in it. At this surface, the horizontal displacement is zero. The neutral surface is a good fixing point for rock bolts. Hongtao et al. (2017) carried out a study on the variation of principal stress and the distribution of plastic regions in coal pillars during the excavation of adjacent panels. They concluded that the stress angle could determine the extended azimuth of the plastic region in the coal pillar. The fracture and collapse processes of the hard main roof in the gob cause asymmetric expansion of this plastic region. At that time, the retained roadway is deformed asymmetrically accordingly. Liu et al. (2023) studied the relationship between the structural features of the upper rock layers and the asymmetrical damage to the immediate roof on the roadway along the gob. The authors concluded that high transverse abutment pressure would be generated directly on the roof of the roadway, following the law of rotation and sagging of the broken roof rock. This high stress causes severe compressive strain in the coal pillars and eventually leads to an asymmetric stress distribution along the roadway.

Other studies on the coal pillar width focused on the abutment pressure distribution. Some studies used the theory of the limited equilibrium region. Hou et al. (2001) deduced the corresponding abutment pressure distribution formula. The authors proposed a method to calculate the width of the limit equilibrium zone and applied it to setting coal pillars in typical mining areas. Based on the analysis of motion characteristics of the rock layers above gob, Zhang et al. (2015a) clarified the load transmission mechanism of the roof rock on a coal pillar. Then, a technical solution to optimize the residual stress of the coal pillar was proposed. Wang et al. (2013a) analyzed the relationship between the geological-mining conditions and the deformation of rock surrounding the roadway. They found that the factors that affect the stability of coal pillars include: the strength of the coal, the thickness and slope angle of the coal seam, the depth of mining, the characteristics of the immediate roof, the effect of roof fracture, the support of roadway, and coal pillar width.

Thus it can be seen that the width of the coal pillar determines the stress conditions around of retained roadway. The decrease in coal pillar strength is considered a coefficient of reduction in the width and height of the coal pillar (Zhang et al., 2018). When the main roof of the coal seam is difficult to collapse, a small coal pillar puts the working in a stress-relieving state, while a wide coal pillar puts it in a stress-concentration state (Esterhuizen et al, 2010). Shabanimashcool & Li (2013) found that stresses in a wide coal pillar fluctuate up and down due to periodic roof collapse in goaf. Wang et al. (2013b) suggested that the risk of retained roadway collapse is significantly increased when there is no elastic zone in the coal pillar. Mohammadi et al. (2016) analyzed the failure mechanism of the roof above the retained roadway in the longwall mining method. They argued that the development of stress determines the stability of the coal pillar and roadway. The study concluded that the roadway is stable only when the width of the coal pillar is less than 5 m or more than 22 m, and it depends on the development of stress in the coal pillar. Shen et al. (2018a) concluded that a weak flat in the roof rock will lead to slippage when the width-to-height ratio of the coal pillar is less than eight. Some other studies on the correlation between the coal pillar width and the stability of the retained roadway are also mentioned in several studies (Shen et al., 2018b; Zhang et al., 2015b; Jiang et al., 2016 and 2017).

The above studies have contributed many reliable results when determining the width of coal pillars for ensuring roadway stability. However, most results are tied to a specific geotechnical condition. It would be an omission and not fully understood when studying hard roof conditions in underground coal mines in Vietnam.

In this paper, the authors focus on a case study of coal seam #10 of Ha Long Coal Company. A model of equivalent materials was created under plane stress conditions to simulate the stability mechanism of the roadway and to determine the coal pillar width for coal seam excavation under hard-to-cave main roof conditions.

2. Research Method

In this paper, a laboratory-scale study is carried out with the use of equivalent materials model. In our analysis, we use the typical geological conditions of Ha Long Coal Company in the Quang Ninh coal basin, which has all the typical roof rock features of Vietnam's underground coal mines.

Coal seam #10 of Ha Long Coal Company is used as an example in this study. The average thickness and depth of coal seam #10 is 3.0 m and 400 m, and the dip angle is 9° (Le and Van, 2021). Figure 1 shows the diagram of the longwall mining method. The physico-mechanical properties of the rock and coal layers are shown in Table 1.

A model of equivalent materials was carried out by a system of physical models in the laboratory. As shown in Figure 3, the simulation system consists of an air cushion load control system at the top of the model, a high-rigidity load frame, and two monitoring systems. The size of the physical model reaches 2.8 m in length, 0.2 m in width, and 1 m in height. Under geological and technical conditions, the rock layers in the model were created to simulate the mechanical behavior

Table 1. Physical and mechanical characteristics of rocks at field and in models.

Type rock	Tensile strength (MPa)	Cohesion (MPa)	Friction angle (degree)	Uniaxial compressive strength (MPa)		Density (kg/m^3)	
				Field value	In model	Field value	In model
Sandstone	1.6	3.22	34.2	83.2	0.64	2785	1853
Mudstone	0.9	2.14	30.1	50.6	0.39	2552	1700
Siltstone	1.2	1.83	26.4	16.5	0.21	2253	1500
Coal	0.4	1.54	19.3	14.5	0.21	1454	967

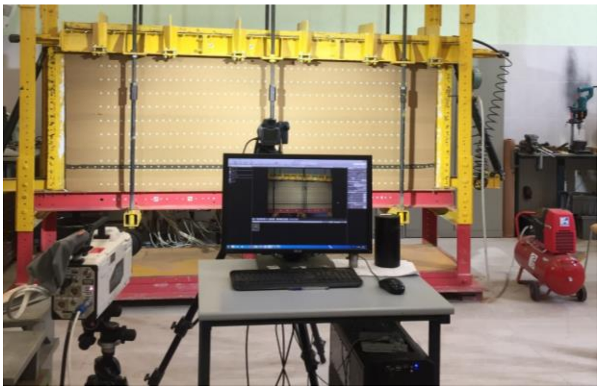


Figure 3. Research model and monitoring system.

of coal mining. The boundary pillar of the model has a width of 48 m. According to the similarity theory (Zubov and Le, 2022), the geometry, density, and strength depend on a certain relationship.

For this study, the similarity factor between prototype and model geometry, Poisson's ratio, density, and uniaxial compressive strength were defined as 100, 1.0, 1.5, and 130, respectively.

Materials used in the model (equivalent material)

As shown in Figure 4, four materials with

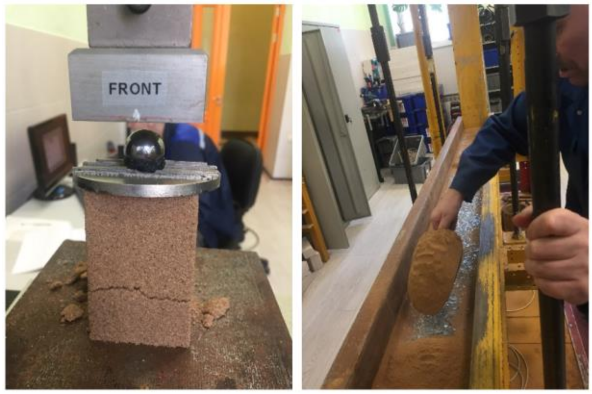


Figure 4. Material testing and model building.

different strains and strengths are used to model the mechanical properties of rock and coal (including mudstone, coal, siltstone, and sandstone). The material of each layer is formed by mixing sand, polyethylene polyamine, and synthetic chemical resin in different proportions. Micanite powder is used to simulate the separation of layers. For uniaxial compression and equivalent strength ratio tests, the proportions of the material components were determined based on the results available (Zuev et al., 2019; Shabarov et al., 2018; Shklyarsky and Zuev, 1999; Monozov et al., 2019; Le et al., 2019). Table 1 presents the four types of materials used in the study.

The process of model building and simulation is shown in Figure 5.

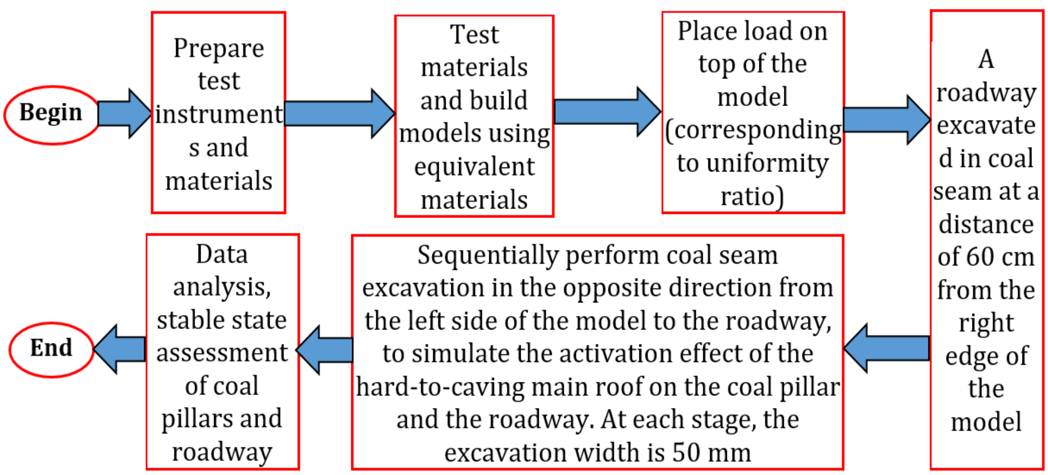


Figure 5. The diagram of model building and simulation.

3. Results and discussion

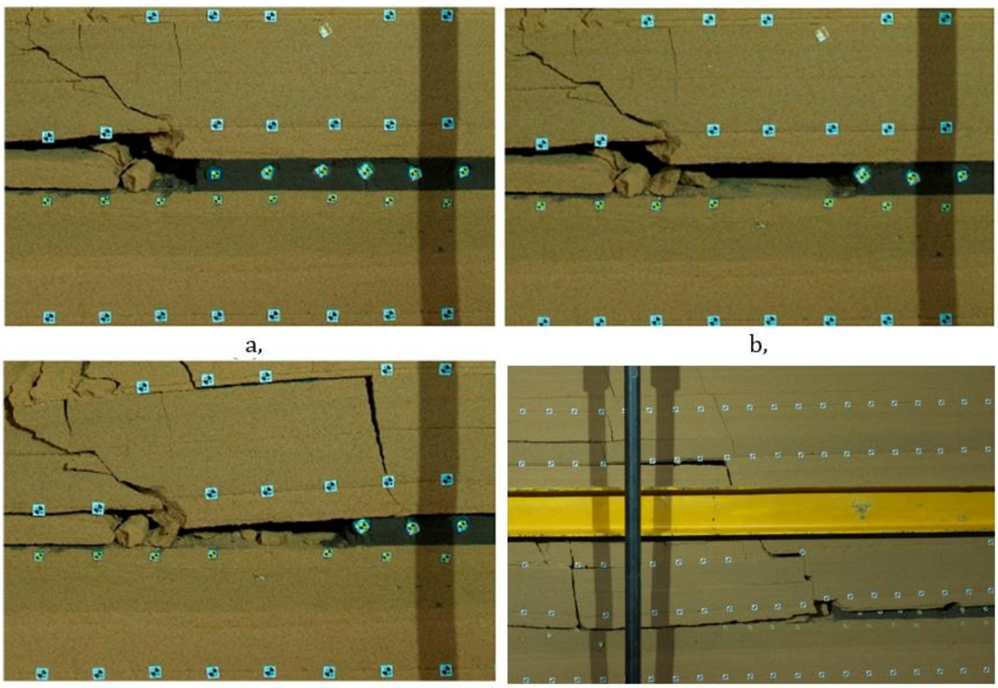
3.1. Collapse characteristics of the hard-to-cave main roof

Underground coal excavation creates gaps. At the top of the coal seam, the hard main roof forms a console hanging above the gob. Studies show that it only collapses when given enough time and when the length of the console is large enough. Between the time before and after the main roof collapse in the gob, the static load on the coal pillars changes significantly. The dynamic load generated from the roof rock collapse will cause a negative impact on the stability of the adjacent roadway. As a rule, it will reduce the cohesiveness of the surrounding rock. As shown in Figure 6, the main roof console bends, breaks, and collapses when its area is large enough. During this process, the console structure will increase the load on the coal pillar until it breaks and collapses. Figures 6(c), and 6(d) show the main roof console structure breaking and then collapsing into the gob, with one side being abutted by a coal pillar.

3.2. The dependence of the deformation state of the roadway on different widths of coal pillars

The sagging of the hard-to-cave main roof console will induce the part of the coal pillar adjacent to the gob to be compressed. This compression depends on the rotation angle of the console. This state is the cause of the weakening of the coal pillar and the reduction of roadway protection. The process of deformation and collapse of the roadway, corresponding to different widths of coal pillars, is shown in Figure 7.

The simulation results show that there is a significant change in the steady state of the roadway when changing the coal pillar width. Figure 6a shows the steady state of the roadway with a coal pillar width of more than 60 m. It shows that the roadway is stable with no signs of deformation. When reducing the width of the coal pillar to 40÷45 m, a horizontal crack appeared on the roof of the roadway (Figure 7b). In addition, there is slight damage on the left side of the roadway (the coal pillar side). However, according to the assessment, the roadway is still in a good and stable state. When the coal pillar is 35 m wide, more cracks appeared on the roadway



a, b, c, d,

Figure 6. Breaking and collapsing mechanism of hard-to-cave main roof in gob. a - before forming main roof console; b - forming and sagging of main roof console; c - breaking of main roof, d - correlation between main roof breaking, coal pillar, and roadway.

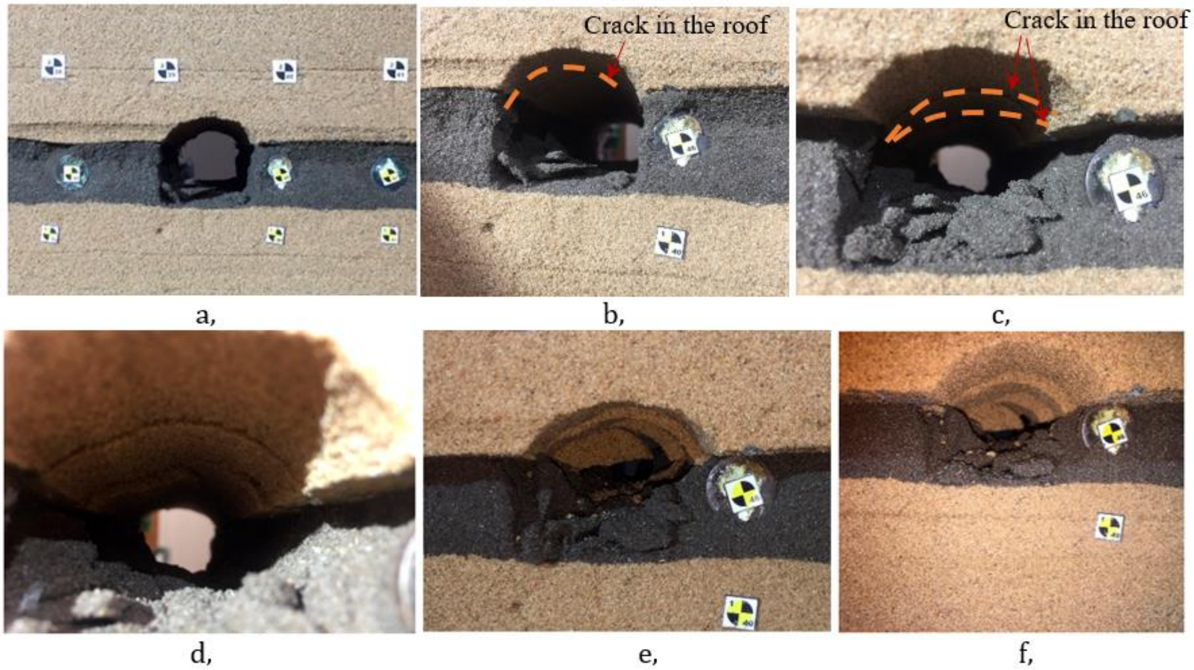


Figure 7. The deformation of roadway corresponds to different coal pillars widths: (a) 60 m; (b) 40÷45 m; (c, d) 35 m; (e)25 m; and (f) 20 m.

roof (Figures 7c and 7d). At this time, the two sides of the roadway's walls were severely eroded, and coal blocks fell into the roadway. This has a significant impact on the usable space on the roadway. Visual assessment results show that, in this case, the roadway has been greatly deformed and is relatively weak.

When the coal pillar is 25 m wide (Figure 7e), the roof of the roadway begins to collapse into coal blocks. On both sides of the roadway's walls, the collapse of coal blocks develops deeper inside. Continuing the mining until the coal pillar width is 20 m; the roadway can be seen as almost completely deformed (Figure 7f). Visual assessment results show that the roadway cannot function appropriately.

The results of visual monitoring on the simulation model show that the conditions of the hard-to-cave main roof with a considerable console length have a significant influence on the stability of the retained roadway. Especially when it is protected by a coal pillar of a small width. Therefore, when there is a coal pillar in the longwall mining method, the stability of the roadway is determined by the width of the coal pillar. This has been proven by the research results in Figure 7. In this study, the stability of the roadway is determined by a coal pillar of more than 40 m wide.

4. Conclusions

In this paper, with the requirement to determine the coal pillar width to ensure the stability of retained roadway in a longwall mining system, an experimental study using a similar material model was performed. The research object is taken according to the actual mining data at coal seam No.10 at Ha Long Coal Company, where the main roof is hard-to-cave. The results of the experimental study are as follows:

- The mining process of coal seams under a hard-to-cave main roof will aggravate the instability of coal pillars and seriously affect the deformation of the roadway. The hard main roof will create a large console in the gob. Its sagging, rotation, and collapse will place great stress on the coal pillar and increase the area of the plastic deformation zone in it. Therefore, a narrow coal pillar will be easily destroyed, making it unsafe for the roadway to be reused.

- The combined effect of static and dynamic loads in the process of the main roof collapse is the cause of the formation of cracks around the roadway. Therefore, limiting this impact is key to ensuring roadway stability. According to the results of the case study, a coal pillar of more than 40 m wide should be selected to ensure the stability of the retained roadway.

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Contributions of authors

Phuc Quang Le - forming ideas, building models and simulations, structuring articles, writing, review & editing; Chi Van Dao - data analysis and editing; Tung Manh Bui - data analysis; Hung Phi Nguyen - data analysis; Dung Tien Thai Vu - review & editing, supervision.

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