JOURNAL OF
HYDRO-METEOROLOGY

Rerearch Article

Stress distribution under coal pillars in the case of multi-seam mining: A case study at Thong Nhat Coal Mine, Vietnam

Phuc Quang Le[1,2], Ha Thu Thi Le[1,4], Long Quoc Nguyen[1,3]*

[1] Hanoi University of Mining and Geology, Hanoi, Vietnam; lequangphuc@humg.edu.vn; lethithuha@humg.edu.vn; nguyenquoclong@humg.edu.vn
[2] Research Group: Sustainable Development of Mining Science, Technology and Environment (SDM), Hanoi University of Mining and Geology, Hanoi, Vietnam; lequangphuc@humg.edu.vn
[3] Innovations for Sustainable and Responsible Mining, Hanoi University of Mining and Geology, Hanoi, Vietnam; nguyenquoclong@humg.edu.vn
[4] Geomatics in Earth Sciences Research Group, Hanoi University of Mining and Geology, Hanoi, Vietnam; lethithuha@humg.edu.vn

*Corresponding author: nguyenquoclong@humg.edu.vn; Tel.: +84–916196336

Received: 27 March 2024; Accepted: 9 May 2024; Published: 25 September 2024

Abstract: The presence of an overlying coal pillar (OCP) strongly influences the stress distribution and deformation of the surrounding rock of the roadway and working face. In this paper, the stress distribution characteristics under the coal pillar are analyzed through numerical simulation using the FLAC3D program. Multi-coal seam mining conditions at Thong Nhat coal mine were selected as the technical foundation. Research results show that the presence of coal pillars acts as a bridge to transfer loads from the roof rock strata to the floor, and therefore it forms a high-stress concentration zone with an oval shape under the coal pillar. Caused by stress superposition, abutment stress distribution rules are affected by the distance from the roadway or working face to the OCP. In the concentrated stress zone of the OCP, the abutment pressure at the roof and floor of the roadway increases by 2 times and puts the road into a dangerous deformation condition. Meanwhile, when the working face approaches the OCP, the front abutment pressure value increases 1.3 times, and the range of the high-stress zone increases 2 times. Thus, the presence of OCP has changed the stress distribution law in the direction of increasing the value and distribution range of the maximum stress area, and it affects the roadway and working face of the coal seam below. The research results of this article will be an important document as a basis for researching technical solutions to meet the requirements for safe mining in underground coal mines.

Keywords: Coal pillar; Stress distribution; Abutment pressure; Multi-seam mining; Roadway; Longwall face.

1. Introduction

In the realm of coal mining, particularly in multi-seam operations, the stress distribution beneath coal pillars is a critical factor influencing mine stability. The coal pillars, acting as primary support structures, bear the overburden pressure and redistribute stresses within the seam. In multi-seam mining, the interaction of stresses between seams adds complexity to this distribution. The stress concentration around the pillars can lead to pillar failure and ground control problems, posing significant safety risks. Therefore, understanding and accurately predicting the stress distribution under these conditions is crucial for safe and efficient mining operations.

In underground coal mining, the success of a mining enterprise is determined by many factors. One of them is the stability of roadways and longwall faces. This task becomes even more complicated when multi-coal seams mining. In the mining plan of underground coal mines in Vietnam, the mining order is carried out sequentially from the upper seam to the lower seam. In this case, the longwall face or roadway in the lower coal seam is placed under the gob or coal pillar of the upper coal seam. Production practice and theory have proven that the coal pillar of the upper coal seam will become a place where stress from the roof rock strata is concentrated, and this can increase abutment pressure to a seriously threatening level to the safe production of coal mines [1, 2]. Studies on the influence and control of OCP on roadway stability and the exploitation of the lower coal seam have been the focus of many scientific works. Liu et al. combined theoretical analysis with field testing, allowing them to detect abnormal magnitudes of abutment pressure when mining coal seams under the OCP [3]. The study [4] used numerical simulation and theoretical analysis to obtain the asymmetric stress distribution law under the coal pillar. With this result, they research and design the optimal location of the roadway to increase roadway control and labor safety. The study [5] studied the stress distribution law in the upper coal pillar according to soil mechanics principles and numerical analysis. They discovered an abnormal increase in the value stress on the roof of the roadway and longwall face when their position is under the stress concentration zone of OCP. Xia, Huang et al. focused on studying the influence of the OCP on the cracking of hard strata, and the abutment pressure under the coal pillar in case of dual effect when multi-seam mining [6–8].

In addition, there are some other notable projects such as Investigation of strong strata behaviors in the close-distance multiseam coal pillar mining [9], this study delves into the behaviors of strong strata in the context of close-distance multiseam coal pillar mining, providing valuable insights into the dynamics of such environments. Coupling control on pillar stress concentration and surface cracks in shallow multi-seam mining [10], it focuses on the interplay between pillar stress concentration and surface cracks in shallow multi-seam mining, offering a comprehensive understanding of the factors influencing these phenomena when applying technical solutions of coal mining and gas extraction without coal pillar in multi-seam with low permeability [11]. These studies investigate the failure mechanisms of gob-side roadways under the pressure of overlying coal pillars in multiseam mining, as well as the design considerations for multi-seam mines intended for coal extraction [12, 13]. Implementing a rational coal pillar design in multi-seam mining, and achieving the coupling control of underground concentrated stress and surface fractures [14]. In order to boost underground coal production in India, supports are essential. Longwall mining, which involves an array of chain pillars, is used in multi-seam longwall mining panels in India’s deepest coal mine. This method helps in maintaining the stability of the mine and ensures the safety of the miners while maximizing the extraction of coal [15]. In the research [16], the authors first obtained the rock by using a coal mine with multi-seam mining in Datong as a case study. Then, based on the geological conditions, we proceeded with the physical analysis. This approach allows us to understand the complexities of multi-seam mining and provides valuable insights for improving mining efficiency and safety. The next steps of the study would likely involve further analysis and testing based on these physical conditions. The extensive and interconnected movements of multi-seam goaf have exacerbated issues when the longwall is mined under the edge of mining panels and remnant pillars within the mine. This situation presents significant challenges in maintaining the stability of the mine and ensuring the safety of the miners. It underscores the need for careful planning and robust support structures in multi-seam mining operations. Further research and development are required to mitigate these issues and enhance the efficiency and safety of longwall mining under such complex conditions [17]. The study [18] aims to understand the dynamics of coal pillar positions and their impact on the stability and safety of mining operations. It provides valuable insights into the optimal positioning of coal pillars to prevent potential hazards and improve the efficiency of multi-seam mining operations. Further details would likely involve the specific methodologies used and the findings from the Research.

The studies related to the coal pillars mentioned above focus on the instability of coal pillars and the law of stress propagation through the coal pillar to the floor. However, in small slope angles areas of the coal seam, OCP may be perpendicular to the longwall face and the lower roadway. In this case, studies on the stress distribution characteristics in the OCP that affect the roadway and longwall face under are not much. The resonance effect of stress in the OCP and the abutment stress in front of the longwall face is very complicated. To clarify this issue, the article takes the mining conditions at coal seams 4C and 3C in the Thong Nhat coal mine as the research object.

2. Materials and Methods

The technical foundation for this study is mining conditions at 4C and 3C coal seams in the Thong Nhat coal mine, Quang Ninh region, Vietnam. Coal seam 3C is located under and the distance between the two seams is 7.5 m. Coal seam 4C was mined first, in which a 25 m-wide coal pillar was left in the gob. The roadway and longwall faces at coal seam 3C are perpendicular to the coal pillar of seam 4C. The relationship of the coal pillar at seam 4C with the roadway and longwall face at seam 3C is presented in Figure 1. Coal seams 4C and 3C are in depth 313 m and 320.5 m, respectively. They have a slope angle of 70 and a thickness of 3m and 4.5 m, respectively. The surrounding rocks are respectively layers of claystone, siltstone, and sandstone. See Figure 2 for map of the research area and stratigraphic columns in the study area. For the physical and mechanical properties of surrounding rocks, see Table 1.

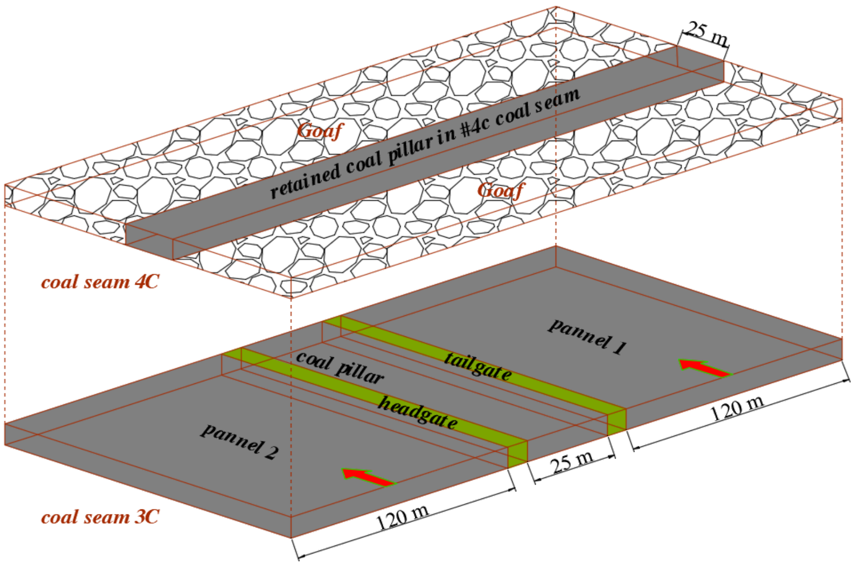
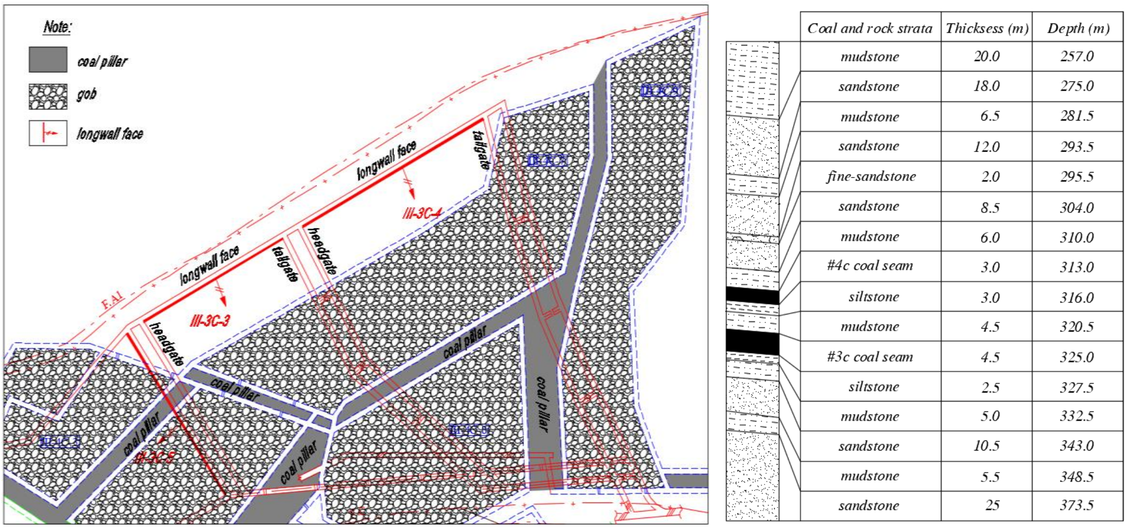


Figure 1. Three-dimensional diagram of the relative position of the OCP with roadways and longwall faces.

Table 1. Properties of rocks and coal in the study area.

Type rock	Tensile strength (MPa)	Bulk modulus (GPa)	Shear modulus (GPa)	Poisson's ratio	Cohesion (MPa)	Friction angle (deg.)	Density (kg/m^3)
Fine-sandstone	1.75	8.120	3.642	0.30	3.15	38	2840
Sandstone	1.63	7.451	3.240	0.31	3.21	34	2775
Mudstone	0.98	2.342	0.950	0.32	2.16	30	2556
Siltstone	1.25	1.826	0.609	0.34	1.83	26	2250
Coal	0.5	0.755	0.486	0.26	1.45	19	1460



Coal and rock strata	Thicksess (m)	Depth (m)
mudstone	20.0	257.0
sandstone	18.0	275.0
mudstone	6.5	281.5
sandstone	12.0	293.5
fine-sandstone	2.0	295.5
sandstone	8.5	304.0
mudstone	6.0	310.0
#4c coal seam	3.0	313.0
siltstone	3.0	316.0
mudstone	4.5	320.5
#3c coal seam	4.5	325.0
siltstone	2.5	327.5
mudstone	5.0	332.5
sandstone	10.5	343.0
mudstone	5.5	348.5
sandstone	25	373.5

Figure 2. Map of the research area, stratigraphic and petrographic column.

The numerical modeling research method with the Flac3D program is used in this study: FLAC3D (Fast Lagrangian Analysis of Continua in 3 Dimensions) is numerical modeling software for geotechnical analyses of soil, rock, groundwater, constructs, and ground support. FLAC3D utilizes an explicit finite volume formulation that captures the complex behaviors of models that consist of several stages, show large displacements and strains, exhibit non-linear material behavior, or are unstable (including cases of yield/failure over large areas, or total collapse). This is a finite element model with construction materials such as coal and stone considered elastic materials that meet the Mohr-Coulomb durability criteria [19]. The model dimensions are 350 m long, 265 m wide, and 140 m high. The side boundaries of the model have been fixed to displacements in the horizontal direction, and the bottom boundary has been fixed to displacements in the horizontal and vertical directions. The top boundary of the model is not constrained in displacement. Natural load is applied to the upper boundary of the model with a vertical stress of 6.5 MPa. The upper specific gravity is assumed to be 0.025 MN/m^3, and gravity is also applied. The stratigraphic and rock mechanical parameters used in the model are similar to the study area conditions at seams 4C and 3C of the Thong Nhat coal mine (Table 1). The model structure diagram is presented in Figure 3.

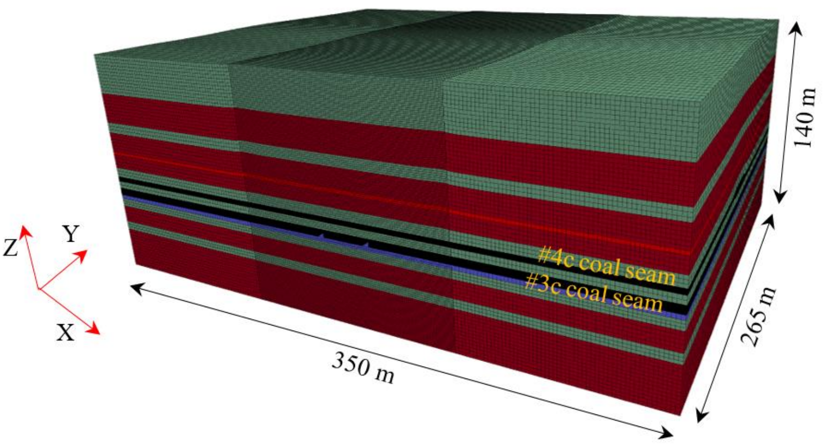


Figure 3. Structure diagram of the simulation model.

In this model, the 4C coal seam is exploited first. During the exploitation of seam 4C, coal pillars with a width of 25 m are formed in the gob. Next, two roadways were excavated in the 3C coal seam in a direction perpendicular to the coal pillar. Finally, panels on the 3C coal seam are mined in a direction perpendicular to the coal pillar. The distance between coal seams and their distribution depth is similar to Figure 2. During model implementation, stress data is extracted at the location of coal pillars, roadways, and longwall faces. Model's research structure diagram, see Figure 4.

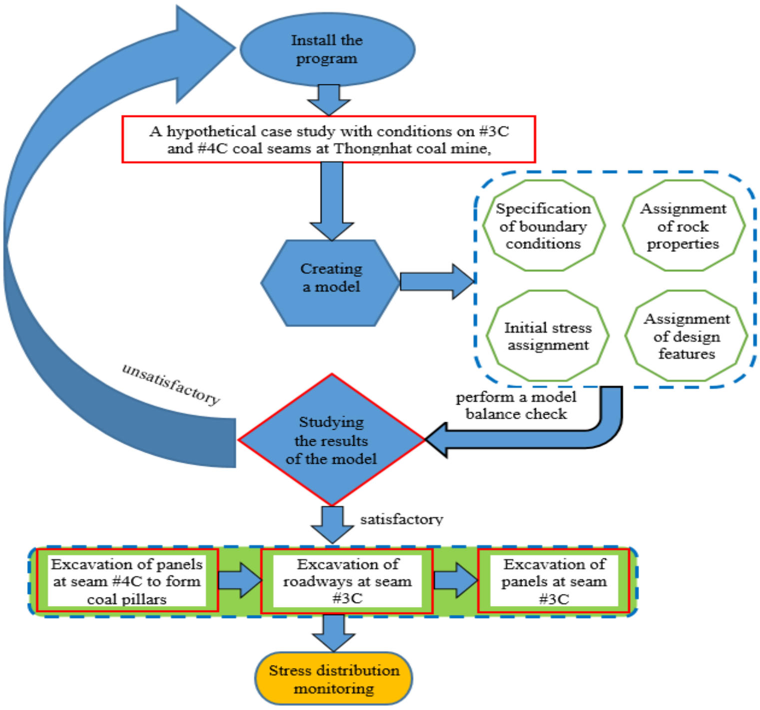


Figure 4. Research structure diagram.

3. Results and Discussions

3.1. Stress distribution under the coal pillar

When there is no OCP, crack development occurs under the gob of the 4C seam to a certain extent. Therefore, when mining coal seam 3C, the integrity of the coal seam and its roof is broken, it causes a certain pressure drop during the mining of the coal seam. In the presence of OCP, stress concentrations are formed in the coal pillar [20]. The coal pillar then acts as a bridge to transfer stress to the coal seam 3C (Figure 5).

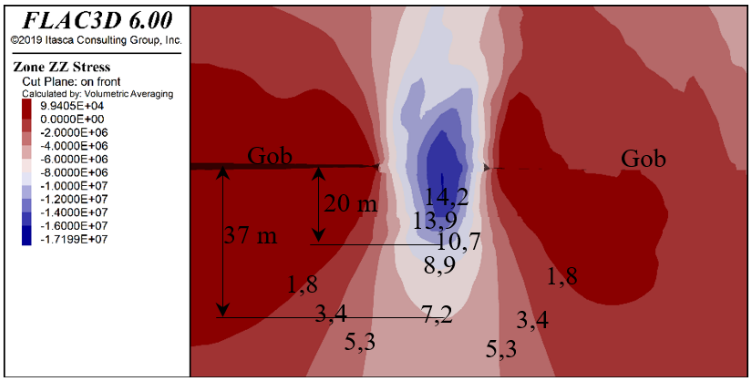


Figure 5. Vertical stress distribution under the coal pillar.

Figure 5 shows that the coal pillar completely bears the load of the roof rock strata. Therefore, there is quite a high stress concentration in the coal pillar. The stress at the center of the coal pillar is 17.2 Mpa and then gradually decreases to the two sides. Under the gob area, the vertical stress is quite small, only 1.8-3.4 Mpa. However, near the coal pillar, stress increases rapidly. The high-stress zones under the coal pillars are oval and appear to extend vertically. At a distance 37 m under OCP, the vertical stress is 7.2 Mpa, nearly equal to the initial static stress. And then, the vertical stress increases rapidly when approaching the coal pillar. The vertical stress is 10.7 Mpa at a distance of 20 m under the coal pillar. This value is respectively 15.5 Mpa and 16.3 Mpa when distances 10 m and 5 m, correspond.

Production practice shows that high stress in the surrounding rock is an unfavorable working environment for underground coal mining. In this condition, the risk of rock burs can occur and threaten labor safety. Especially when mining coal seams at close distances, the status of roadway deformation and support destruction often at the Thong Nhat coal mine. Therefore, it is necessary to eliminate OCP when multi-seam mining.

3.2. Stress distribution when the roadway is excavated under the coal pillar

Corresponding to the research conditions at seams 4C and 3C at the Thong Nhat coal mine (the distance between the two seams is 7.5 m), the stress distribution when excavating the roadway under the coal pillar is shown in Figure 6.

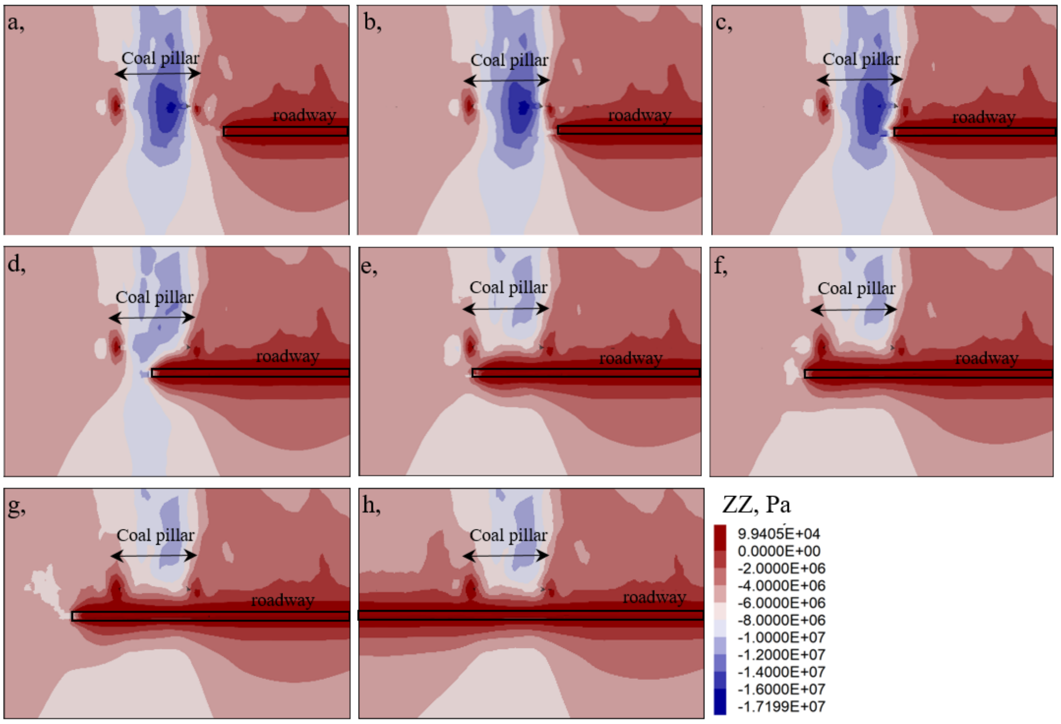


Figure 6. The stress distribution under the coal pillar corresponds to the distance to the working face of the roadway: (a) 20 m from the coal pillar; (b) 10 m from the coal pillar; (c) meet the coal pillar; (d) in the middle of the coal pillar; (e) when starting to pass the coal pillar; (f) pass 10 m coal pillar; (g) pass 20m coal pillar; (h) completely surpasses the coal pillar.

Figure 6 shows a significant change in stress distribution when excavating the roadway under the coal pillar. When the roadway is far from the coal pillar, the stress distribution in the surrounding rock of the roadway follows the normal law. However, when the roadway approaches the coal pillar, the superposition of stress from the coal pillar and the abutment pressure in front of the working face of the roadway increases. Specifically, when the distance between the coal pillar and the working face of the roadway is 20 m, the front abutment pressure is 6.2 Mpa and increases to 9.6 Mpa at a distance of 10 m. When the roadway begins to enter the area under the coal pillar, the superposition of stress from the coal pillar causes the maximum stress value to increase to 13.1 Mpa. When the roadway was excavated to the middle of the coal pillar, the maximum stress value began to decrease to 10.6 Mpa. However, almost all the stress from the coal pillar is transmitted to the roof of the roadway, the stress value reaches 10.5 Mpa. This can be explained by the failure of the surrounding rock mass the effect of eliminating the stress concentration in front of the roadway, and the roadway under the coal pillar would bear the entire load loaded of OCP. Therefore, there is a high risk of rock bursts on the roof of the roadway. As the roadway begins to pass the coal pillar, the abutment stress in front of the roadway decreases to 8.2 Mpa and is stable at 6.0 Mpa. The stress area from the coal pillar loading on the roadway remains unchanged compared to the previous case.

Figures 6e-6g, 6h show a large stress area from the coal pillar with a stress value of 10-10.5 Mpa acting on the roof of the roadway. At the same time, a high-stress zone with a stress value of about 8.3 Mpa is also formed on the floor of the roadway. These stress values are almost 2 times higher than in other areas. At this location, the roadway is pressed from both roof and floor, causing the phenomenon of falling roof rocks and floor heave. This explained the deformation of roadways that frequently occurred when excavating them under coal pillars. According to statistics at the Thong Nhat coal mine, the frequency of repairing these roadways is every 4-5 months. Frequent roadway repairs have hurt production efficiency and labor safety.

3.3. Stress distribution when mining panels under coal pillars

The stress distribution in front of the longwall face when performing panel mining under the influence of coal pillars is shown in Figure 7.

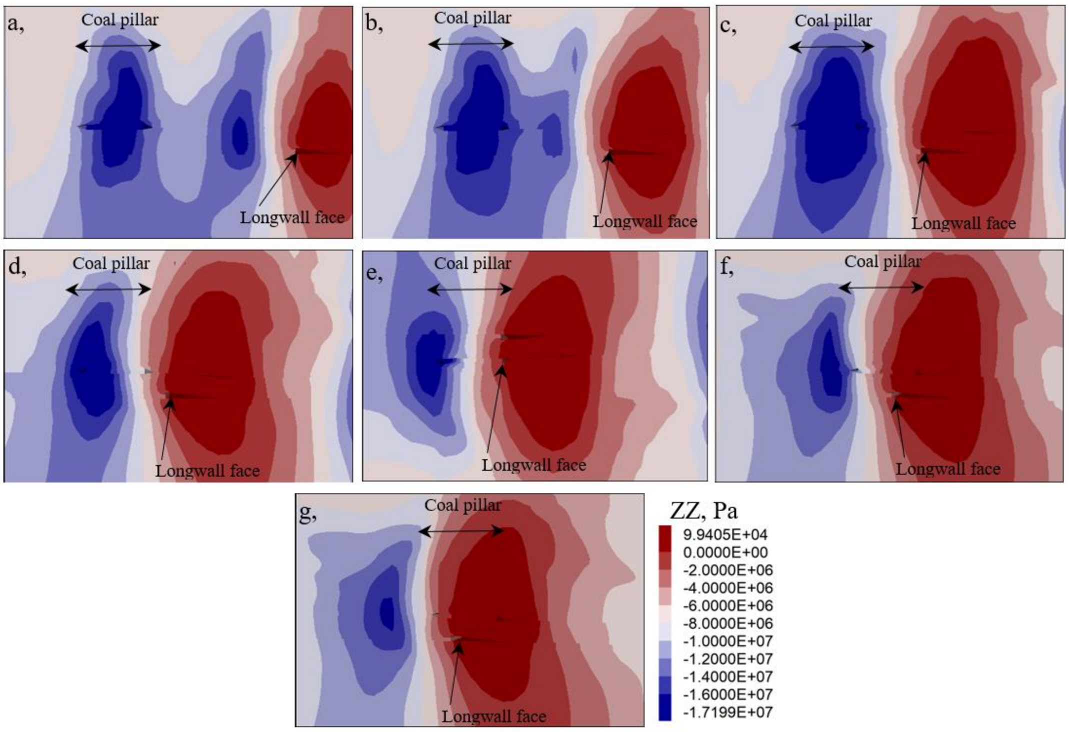


Figure 7. Stress distribution in front of the longwall face under the influence of the OCP, when the distance between the longwall face and the coal pillar: (a) 70 m, (b) 50 m, (c) 30 m, (d) 10 m, (e) approaching OCP, (f) in the middle of OCP, (g) passing the OCP.

As seen in Figure 7, the stress distribution in front of the working face differs greatly in the cases of the absence or presence of the OCP. When the distance between the longwall face, and the OCP is 70 m, the abutment stress in front of the longwall face increases, then decreases and increases again due to the stress concentration under the OCP. In Figure 7a, the abutment stress is formed in the form of two peaks in front of the longwall face. A maximum stress of 15.3 MPa was observed at a distance of 15 m from the longwall face, while the maximum stress under the coal pillar was 17.2 Mpa. As the longwall face advances, the abutment stress peak in front of the longwall face decreases to 13.8 Mpa at a distance of 50m. The main reason is that the gob area next to the coal pillar of the upper seam has been unloaded and reduced the stress concentration, so the stress of the surrounding rock is significantly reduced. As the longwall face continues to excavate forward and at a distance of 30 m from the coal pillar, the abutment stress in front of the longwall face only remains a single peak under the coal pillar. The maximum value of abutment stress does not change much, however, under the interference of the stress in front of the longwall face and the stress under the pillar, the high-stress area is expanded 1.5 times compared to the coal pillar. It can be seen that OCP strongly impacts the longwall face within a range of less than 50 m and a rapid increase in stress in the coal seam. When the longwall face is at a distance of 10 m and approaches the coal pillar, the front abutment stress area gradually narrows and shifts to the opposite side. The maximum stress value remains at 17.2 Mpa. When the longwall face is in the middle of the OCP, the abutment stress peak begins to move away from the coal pillar, and the maximum stress value is 16.3 Mpa. When the longwall face passes the OCP, the abutment stress in front of the longwall face returns to normal with a maximum stress value of 13.3 Mpa at a distance of 15m and then stabilizes at 12.6 Mpa.

Figure 7 implies in the absence of OCP, the maximum stress in front of the longwall face is lower. In the presence of OCP, the maximum stress value is higher and the distribution range is wider. As the longwall face approaches the OCP, the abutment stress increases sharply and maintains a high value. The area affected by stress concentration in OCP is larger and stable control of the longwall face becomes more difficult.

4. Conclusion

- Simulation results show that the appearance of OCP will form an oval-shaped enhanced stress concentration zone. The coal pillar acts as a bridge to transmit the entire load of the roof rock strata to the coal seam below, significantly affecting the stress distribution when excavating the roadway and mining panels. In the presence of OCP, the maximum stress will be higher and spread across the width of the OCP. Residual stress from the coal pillar will compress the roadway vertically from the roof and floor. Therefore, if not well supported and corresponding technical solutions are applied, the roadway will deform and be destroyed.
- The presence of OCP affects the stress distribution in front of the longwall face. When the longwall face in the lower coal seam is far from the coal pillar, the stress distribution in front of the longwall face is relatively stable and follows the law of abutment pressure. When the longwall face approaches the OCP, the superposition of the coal pillar's stress and the abutment stress causes the maximum value of the stress to increase significantly and expand the influence area by 1.5 times. With this condition, the scope of overburden collapse in the roof and working face expands and causes rockburst safety risks.
- The result of the research found the law of stress distribution under the coal pillar. This is an important factor in finding solutions to ensure safety when excavating roadways and mining longwall faces of the adjacent seam below. The main gap in the research is that the model can only simulate a specific geological case. The variation in thickness and slope angle of the rock layers has not yet been considered. However, this is also the basic foundation for developing subsequent research projects according to different parameters of coal seam thickness, distance between coal seams, and other parameters. The research results will be the basis for mine managers to develop plans and operate mines safely.

Author contribution statement: Generating the research idea; statement of the research problem; analysis of research results and data preparation; wrote the draft manuscript: P.Q.L., H.T.T.L.; Analyzed and interpreted the data, wrote the draft manuscript: L.Q.N.

Acknowledgements: This research was funded by the Viet Nam Ministry of Education and Training, grant No: B2024–MDA–03 (Research, evaluate influencing factors, and propose technical solutions to ensure roadway stability in the case of multi-coal seam mining, with gentle slopes in the Quang Ninh region).

Competing interest statement: The authors declare no conflict of interest.

References

1. Zhang, Z.; Deng, M.; Bai, J.; Yan, S.; Yu, X. Stability control of gob-side entry retained under the gob with close distance coal seams. *Int. J. Min. Sci. Technol.* **2021**, *31(2),* 321–332.
2. Ju, J.F.; Hu, G.L. Influence of leading instability in the upper dip coal pillar boundary to the strong strata behaviors during the working face out of the pillar. *J. China Coal Society*. **2012**, *37(7),* 1080–1087.
3. Liu, C.Y.; Yang, J.X.; Liu, J.R. Mechanism of strong pressure reveal under the influence of mining dual system of coal pillar in Datong mining area. *J. China Coal Society*. **2014**, *39(1),* 40–46.
4. Lei, X.U.; Hailiang, Z.; Dongkun, G.; Bo, L.I. Principal stress difference evolution in floor under pillar and roadway layout. *J. Min. Saf. Eng*. **2015**, *32(3),* 478.
5. He, Y.; Huang, Q.; Ma, L.; Wang, Q.; Fan, D. Research on roof weighting mechanism of coal pillar mining in shallow buried closely spaced multi-seams. 2023.
6. Xia, B.; Jia, J.; Yu, B.; Zhang, X.; Li, X. Coupling effects of coal pillars of thick coal seams in large-space stopes and hard stratum on mine pressure. *Int. J. Min. Sci. Technol*. **2017**, *27(6),* 965–972.
7. Huang, Q.; Du, J.; Chen, J.; He, Y. Coupling control on pillar stress concentration and surface cracks in shallow multi-seam mining. *Int. J. Min. Sci. Technol*. **2021**, *31(1),* 95–101.
8. Cheng, W.; Nong, Z.; Guichen, L.; Nianchao, Z. De-stressed mining of multi-seams: Surrounding rock control during the mining of a roadway in the overlying protected seam. *Min. Sci. Technol*. **2011**, *21(2),* 159–164.
9. Mu, H.; Bao, Y.; Song, D.; Su, D. Investigation of strong strata behaviors in the close-distance multiseam coal pillar mining. *Shock Vib*. **2021**, 1–14.
10. Huang, Q.; Du, J.; Chen, J.; He, Y. Coupling control on pillar stress concentration and surface cracks in shallow multi-seam mining. *Int. J. Min. Sci. Technol*. **2021**, *31(1),* 95–101.
11. Yuan, L. Technique of coal mining and gas extraction without coal pillar in multi-seam with low permeability. *J. Coal Sci. Eng.* **2009**, *15(2),* 120–128.
12. Mu, H.; Wang, A.; Song, D.; Su, D.; Li, D. Failure mechanism of gob-side roadway under overlying coal pillar multiseam mining. *Shock Vib*. **2021**, 1–13.
13. Tati, B. Multi-seam coal mining. *J. South. Afr. Inst. Min. Metall*. **2011**, *111(4),* 231–242.
14. Huang, Q.; Cao, J. Research on coal pillar malposition distance based on coupling control of three-field in shallow buried closely spaced multi-seam mining, China. *Energies* **2019**, *12(3),* 462.
15. Ghosh, N.; Agrawal, H.; Singh, S.K.; Banerjee, G. Optimum chain pillar design at the deepest multi-seam longwall workings in India. *Min. Metall. Explor*. **2020**, *37*, 651–664.
16. Tian, C.; Yang, X.; Sun, H.; Liu, Y.; Hu, Q. Experimental study on the overburden movement and stress evolution in multi-seam mining with residual pillars. *Energy Sci. Eng*. **2019**, *7(6),* 3095–3110.
17. Zhu, Z.; et al. Overburden movement characteristics of top-coal caving mining in multi-seam areas. *Q. J. Eng. Geol. Hydrogeol*. **2018**, *51(2),* 276–286.
18. He, Y.; et al. Research on roof weighting mechanism of coal pillar mining in shallow buried closely spaced multi-seams, 2023.
19. ITASCA. Fast Lagrangian Analysis of Continua User's Guide; Itasca Consulting Group Inc.: Minneapolis, MN55401, USA. 2019. https://www.itascacg.com/search.
20. Phuc, L.Q. Cause and solution to roadway deformation in Vietnam underground coal mines. *Inżynieria Mineralna* **2021**, *2(1),* 381–390.