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Numerical analysis of the influence of coal pillar size on auxiliary tunnel stability

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ABSTRACT

It is very important to study the stability of the tunnel in the area affected by mining activities. In particular, the choice of coal pillar size has a direct influence on the stability of these tunnels. The authors of this study used the Flac^{3D} program to model a mining face LC1 with various coal pillar sizes. The 220 m-long mining face known as LC1 has 20 degrees rock mass layers. The studied coal pillars are various widths at 5 m, 8 m, 10 m, 15 m, 20 m, and 30 m. The highest vertical stress and maximum horizontal stress are placed at different locations along the lower mining face (LC2), as shown by the results of the numerical simulation. The pressure distribution of the rock mass on the tunnel's top and the level of stress concentration on its two sides are asymmetrical for inclined seam conditions. The position of the maximum vertical tension is expected to change from the left hip to the side of the coal pillar as the coal pillar widens. This change essentially marks the system's transition from one stable state to another. Due to the rock mass's weak stability during this transition, the support must be strengthened in order to improve the rock stability.

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1. Introduction

Up to now, the choice and calculation of coal pillar width in the design of auxiliary tunnel systems have been made empirically, or through the use of empirical formulas or modeling techniques. In recent years, many experts and scholars like Bai and Hou, 2006, Ma and Wang, 2009, Zhang, 2011, Jiang et al., 2015, Men, 2000 have managed to successfully apply the use of coal pillars to ensure stability for mining auxiliary tunnels.

In most coal mines in Vietnam, especially in Quang Ninh, the design and calculation of coal pillar width have not been paid too much attention. In some cases, the calculations were performed according to the empirical formulas. However, the selected size is often larger than the calculation results would suggest to simply ensure safety conditions. The coal pillar size based on designer experience normally ranges from 10÷25 m. The coal pillar is either dumped or used to recover some of the mineral resources when the face mining is finished. The exploitation of an inclined coal seam presents another obstacle. Here, underground mining techniques are employed, posing a number of geotechnical and practical problems. The underground mining industry faces a significant issue with the mechanized extraction of an inclined coal seam (Das et al., 2017; Sun et al., 2020).

In the past, published documentation in Vietnam was all concerned with evaluating the size of coal pillars (Pham et al., 2018; Dao, 2016). Dao (2016) calculated a needed coal pillar size of 6m based on the mechanical characteristics of the Khe Cham coal mine but did not account for the impact of the actual coal seam inclination angle. Pham and Tran (2018) neglected the impacts of the mining face and the size of the coal pillar on the mechanical behaviour of the auxiliary tunnel in their study which only took into consideration the tunnel location's influence on the auxiliary tunnel stability.

The authors of the current work concentrated on the impact of the coal pillar size on the auxiliary tunnel stability for inclined seam coals settings, taking into account the difficulties that have not been examined by local researchers. Flac3d modelling provided help for the analysis. The study's findings can be used as a guide to select the ideal coal pillar size for the actual processing.

2. Input parameters and modelling

2.1. Input parameters

The created simulation model has a length × width × height of 220 × 120 × 150 m, rock layers, and coal seams inclined at an angle of 20 degrees. The model includes 14 different rock layers, as listed in Table 1. On the top of the model, a uniformly distributed force is applied, which represents the pressure created by the weight of the above rock mass. The Layout diagram of the tunnel system for the exploitation of two mining faces of LC1 and LC2 is presented in Figure 1a.

The model is composed of gritstone, sandstone, siltstone, and coal as shown in Table 1 (Vu, 2015).

Table 1. Mechanical properties of rock layers.

TT	Layer	Compressive Strength σ_c, (MPa)	Tensile Strength σ_t, (MPa)	Unit weight γ, (N/m^3)	φ (degrees)	C, (MPa)	E (GPa)	Poisson's ratio, υ
1	Sandstone (f =6-8)	96.64	8.5	2.67	34	33.6	20	0.26
2	Siltstone (f=4-6)	47.79	5.2	2.73	32	14.6	18	0.28
3	Gritstone (f =8-10)	138.13	11.9	2.59	34	47.2	22	0.24
4	Coal (f =1-2)	15	2.5	1.50	20	2.2	5	0.35

The coal seam inclination angle is 20⁰, the depth of the tunnel's floor is 300 m, the supporting structure consists of CBII-27 steel ribs with distance support of 0.7 m/set, and the coal seam thickness is 3.5 m.

The tunnel has the shape of a straight-leg semicircle arch, with a width of 5.0 m and a height of 3.5 m. The model of the tunnel system includes Two mining faces of LC1 and LC2, the vented tunnel 01, the transport tunnel 02, and the vented tunnel 03 as shown in Figure 1b.

The coordinate center of the model is located at the center bottom tunnel. The grid line is more densely divided near the tunnel area but more sparsely divided further away from the tunnel.

2.2. Numerical model building process

Based on the actual tunnel excavation data and the processing phases in the simulation, the modeling computation phases are simplified to the following steps:

Step 1: Post modeling, stress application, then running the model until reaching equilibrium state;

Step 2: Excavating tunnels No. 1 and No. 2 to the mining boundary line, running the model until reaching equilibrium state;

Step 3: Exploitation of LC1 mining face, running the model to reach equilibrium;

Step 4: Excavating tunnels No.3 to the mining boundary line, running the model until reaching equilibrium state;

Step 5: Extracting the values of stresses, displacements, and plastic area of each survey factor to analyze and determine the stability of the tunnel.

In the present paper, The impact of six various coal pillar sizes -5 m, 8 m, 10 m, 15 meters, 20 m, and 30 m on the stability of tunnel No. 3 is discussed.

3. Numerical analyses

3.1. The behaviour of stress variation of the lower surrounding rock mass during the upper mining faces LC1 exploitation

Figure 2a depicts the vertical stress distribution on the lower neighboring rock mass during the exploitation of LC1 mining face. The coal pillar size range is 5÷10 m, while the LC2

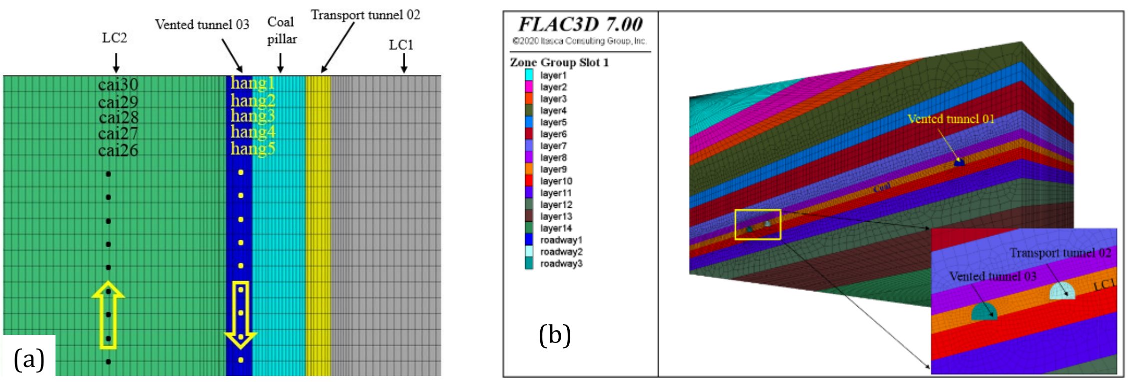


Figure 1. (a) The layout diagram of tunnels system; (b) Model on Flac3D.

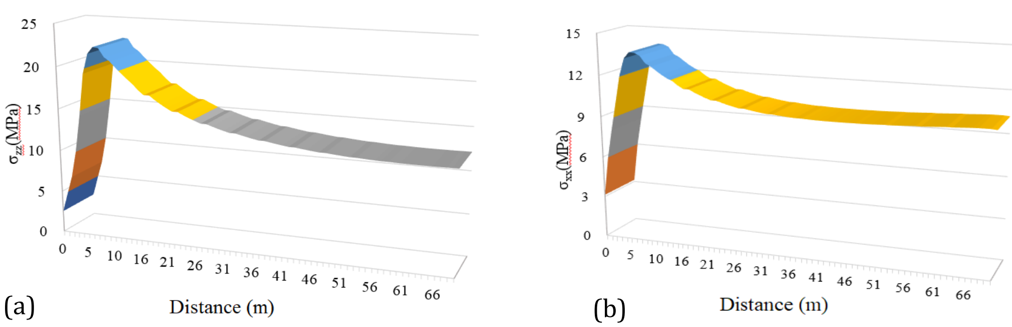


Figure 2. Stress distribution of the rock mass in the lower mining face LC2. a) vertical stress; b) horizontal stress.

mining face's range is x > 10 m. At the edge of the LC1 mining face, the coordinate x is 0 m.

Figure 2 shows that the vertical stress distribution of the LC2 mining face surrounding rock is strongly influenced by the LC1 mining operation. The stress concentration was formed mainly in the coal seam within the mining face LC2. The maximum concentrated stress value is about 25 MPa which is about 2.0 times higher than the initial primary stress value. The zone of maximum support pressure in the mining face LC2 area is about 7.5 m away from the side of the coal pillar.

3.2. Effect of coal pillar size on the vented tunnel N03 stability

3.2.1 The law of stress distribution on the right side of the tunnel (range of coal pillar)

Figure 3 depicts the vertical stress in the coal pillar according to each size of the various ones.

When can be seen from the image, the vertical stress value in the coal pillar's curve transforms according to the following rule: as the coal pillar's size expands, the vertical stress will change according to the law of increasing first, then reducing, and finally entering a steady state. The peak vertical stress in the coal pillar is less than 12 MPa when the width of the coal pillar is 5 m. This happens because the coal pillar's size is insufficient to support the weight above it, leading to instability and a reduction in bearing capability. The peak stress in the coal pillar grows noticeably when the width of the coal pillar climbs to 10 m, indicating that the breadth expansion can greatly boost the strength of the coal pillar. A 10 m coal pillar's size can meet the strength requirements of the underlying strata load since the growth of stress concentration factor somewhat lowers as the coal pillar's breadth increases.

3.2.2. Vertical stress distribution of the top rock of the auxiliary tunnel No. 3

Figure 4 shows the maximum vertical stress of the tunnel top rock corresponding to different sizes of coal pillar width.

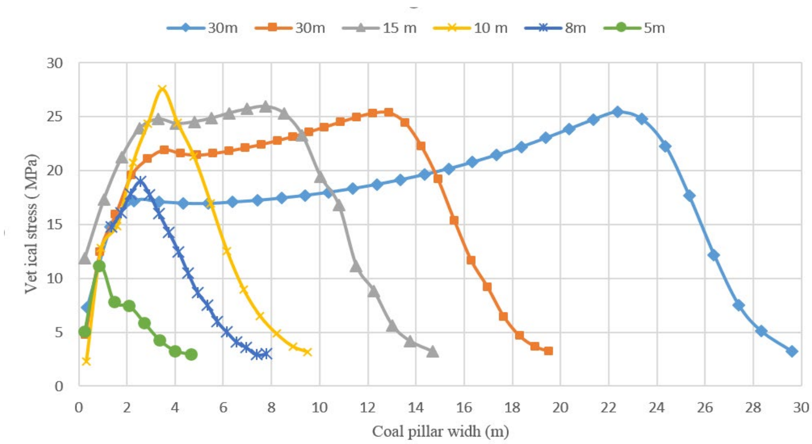
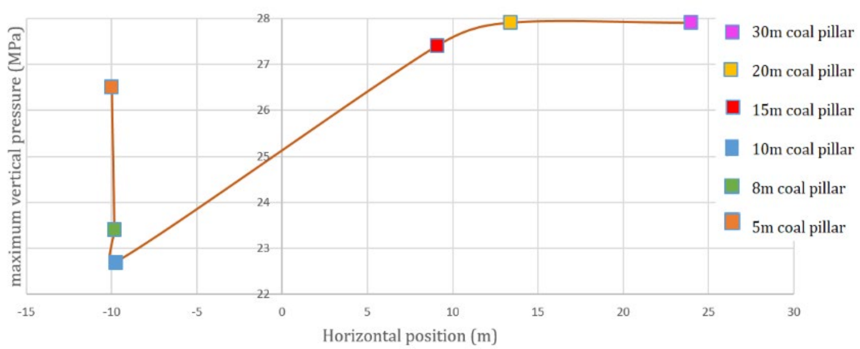


Figure 3. Vertical stress in the coal pillar.



x= 0m : Center of tunnel; x > 5m : range of coal pillar; x < -5m : The left side of tunnel

Figure 4. The maximum vertical stress on the top rock of vented tunnel No. 3.

As a result, when the coal pillar width changes from 8÷15 m, the position of the tunnel top rock's maximum vertical compressive stress will vary, gradually shifting from the left to the right side of the tunnel (inside of the coal pillar near the empty mining space of the mining face LC1).

In general, when the width of the coal pillar increases, the trend of the maximum vertical compressive stress value can be simply described as starting from the coal mass on the left side of the tunnel, the maximum vertical compressive stress tends to move toward the empty mining area of LC1. Then it skips the top of the tunnel to the right side and then in the original direction, it keeps moving towards the empty mining space.

From the viewpoint of the stability of the rock mass, it can be seen that the adjustment process to reach a new equilibrium condition may be thought of as the change and displacement of the top rock's maximum compressive stress.

From the viewpoint of the stability of the rock mass, it can be seen that the adjustment process to reach a new equilibrium condition may be thought of as the change and displacement of the top rock's maximum compressive stress. The place of greatest stress will be inside the coal pillar as coal pillar size increases because larger coal pillars have better- supporting capacities. The highest vertical compressive stress gradually shifts towards the lower mining face LC2 area as the coal pillar's supporting capacity steadily deteriorates with decreasing width. This shows the rock mass adjusting on its own to keep itself stable.

The system is transitioning from one stable condition to another with this change in the maximum vertical compressive stress location. The rock mass's stability is still insufficient throughout this transition, thus it's important to focus on the supporting structure in order to increase the rock mass's stability. If the width of the coal pillar keeps shrinking after the rock mass transitions to the following stable condition, the stability of the system will start to deteriorate once more. The coal pillar's capacity to self-regulate inside the rock mass is constrained when its width is too small.

3.2.3. The distribution of plastic destruction zone of the rock mass around the auxiliary tunnel No.3

Figure 5 shows the distribution of the plastic destruction zone of the rock mass around the auxiliary tunnel No.3. The distribution corresponds to different sizes of coal pillars. The interpretation of the figure is as follows:

The rock mass surrounding tunnel No. 2 was destructured as a result of mining operations after the mining face LC1 was dug. The area of plastic deformation was considerable, measuring around 7 m.

The coal pillar's continuous plastic deformation area becomes discontinuous as the coal pillar's breadth steadily increases from small to large (Figures 5a÷5g).

The coal pillar's plastic destruction zone is not breached when the breadth of the coal pillar is less than 10 m (Figures 5a÷5c). The plastic destruction zone is penetrated, and elastic cores with thicknesses of around 4 m, 9 m, and 20 m appear within coal pillars when the breadth of the pillar changing between 15m and 30 m (Figures 5e÷5g).

The area of the plastic degradation zone on the left side of tunnel No. 3 is approximately 5 m^2 when the width of the coal pillar is between 5m and 10 m. The size of the plastic destruction zone eventually shrinks to only around 3÷4 m when the coal pillar's width is between 15m and 30 m.

Deformation and destruction in the coal pillar are mainly caused by shearing combined with sliding. While the destruction of the coal pillar on the left side of tunnel No.3 is mainly caused by shearing, the destruction of the tunnel surface is mostly due to both forces, shearing and sliding.

3.2.4. The deformation behaviour of the rock mass around tunnel No. 3

Figure 6 presents the deformation and displacement vector on the surface of tunnel No.3. It is clear that the deformation of the coal on the left side of the tunnel is often greater than that on the right side due to the geological structure of the coal seam in inclined settings.

The rock deformation around the tunnel grows as the coal pillar's breadth steadily increases from 5÷10 m, and the damage worsens.

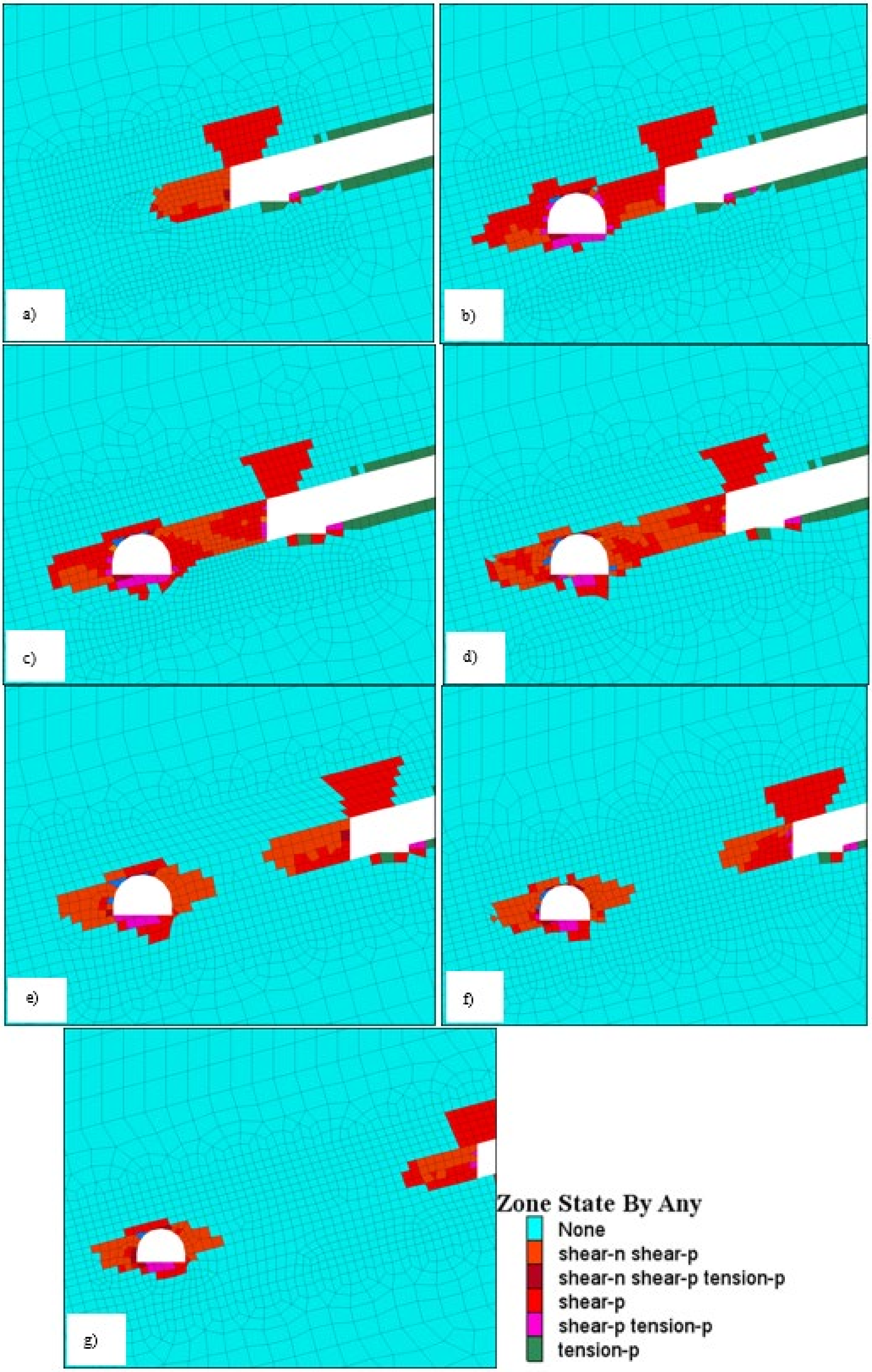


Figure5. Distribution of the plastic destruction zone of the rock mass when the size of coal pillar changes: a - 0 m, b - 5 m, c - 8 m, d - 10 m, e - 15 m, f - 20 m, g - 20 m, h - 30 m.

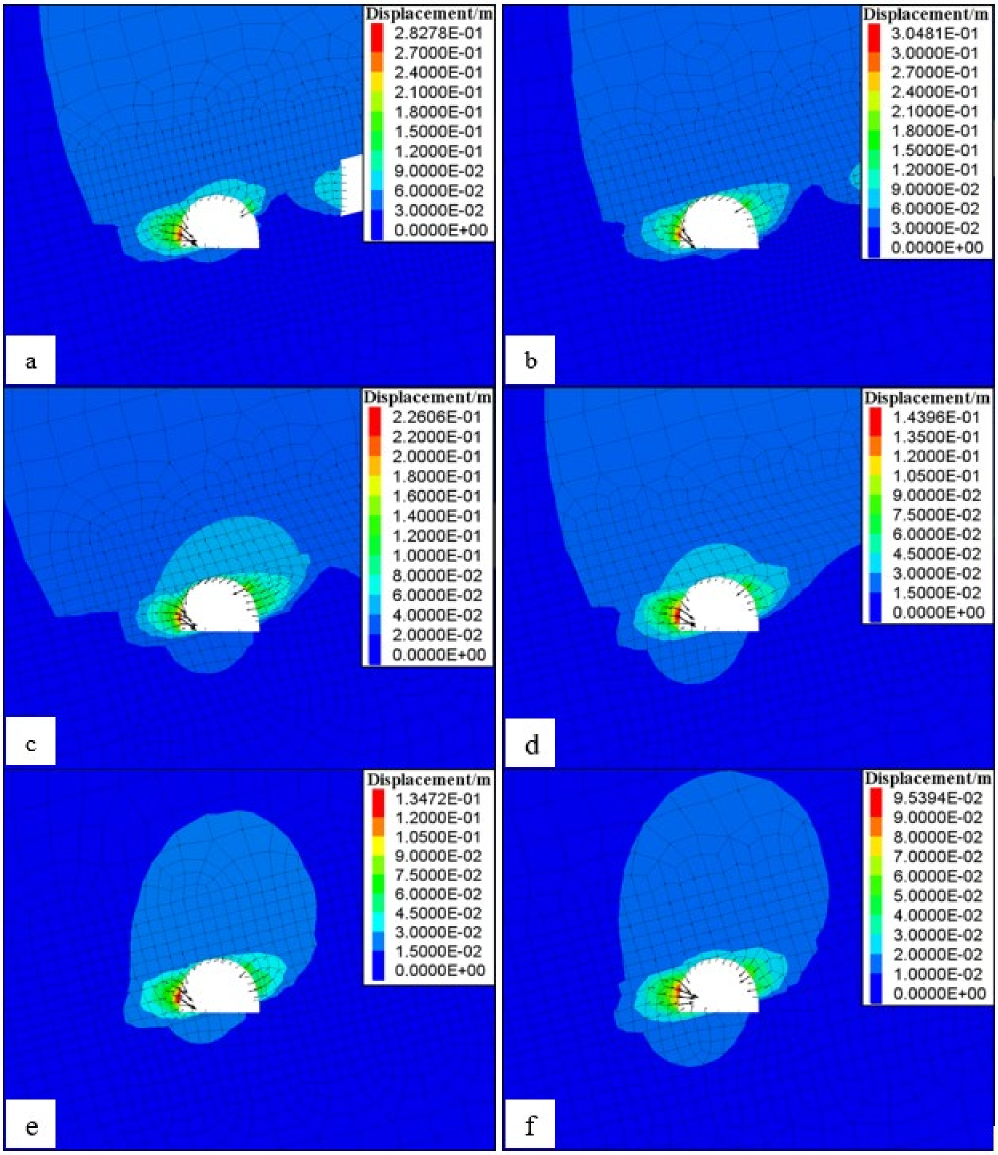


Figure 6. Rock mass displacement characteristics around the auxiliary tunnel No. 3 when the size of coal pillar changes: a - 5 m, b - 8 m, c - 10 m, d - 15 m, e - 20 m, f - 20 m, g - 30 m.

After that, the deformation of the rock surrounding the tunnel will be decreased as the coal pillar's breadth reaches more than 10 m. This indicates that the coal pillar of around 10 m in width is an important parameter when surveying and evaluating the stability of tunnel No.3.

In general, the factors that should be considered when determining the optimum size of the coal pillar, are as follows (Zhang et al., 2015; Xie et al., 2007; Yao and Kang, 2002).

When the auxiliary tunnel is supported by the anchor, the size of the coal pillar must be enough to install the anchor, long enough for the anchor section to be reinforced within the rock/coal mass. In the case of heavy exploitation works, the size of the coal pillar must be guaranteed not to be less than 2.5 m.

Assuming favorable stress conditions, after the mining face LC1 has been excavated, the two sides of the mining face form a supporting stress area. This zone is subdivided into a decreasing stress zone, an increasing stress zone and an original stress zone. If the auxiliary tunnel is placed in the decreasing stress zone, the stability of the tunnel and coal pillar will be ensured.

If the tunnel is supported by anchors the geomechanical parameters of the coal pillar must offer sufficient strength for the installation of reinforcement structures. The stability and bearing capacity will be insufficient if the coal pillar mechanical conditions are too poor, deposits are cracked, and deposits are fragmented. An anchor's pullout strength will be insufficient in this situation. Therefore, the anchors must be arranged outside the destruction area potentially caused by the influence of mining face LC1.

In terms of the expected deformation of the rock mass around the auxiliary tunnel deformation in the mining face area is usually quite large. Accordingly, the decision to choose the coal pillar width should not only ensure the stability of the tunnel but also ensure efficient exploitation, avoiding overrising of supporting structures.

4. Conclusions

In the present study, a numerical analysis using finite element software has been conducted to investigate the effect of the size of coal pillars on the displacement convergence of the auxiliary tunnel surrounding rock mass. The main conclusions arising from conducted numerical simulations are given in the following points:

Maximum vertical and horizontal stresses are located in different locations at the base of the lower mining face (Mining face LC2).

The pressure distribution of the rock mass on the tunnel's top and the level of stress concentration on its two sides are asymmetrical for inclined seams conditions. Additionally, the rock mass around the tunnel tends to distort more on the left side of the tunnel than on the right.

The position of greatest stress will be within the coal pillar as its breadth increases, increasing the coal pillar's capacity to support the weight. When the width of the coal pillar is smaller, the supporting capacity of the coal pillar gradually weakens, so the maximum vertical compressive stress begins to move towards LC2 of the lower mining face area. This represents self-adjustment of the rock mass to maintain its stability.

When the width of the coal pillar changes gradually from 5÷30 m, the plastic deformation shape changes from continuous, to discontinuous.

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Contribution of authors

Nhan Thi Pham - conceived the idea, performed the analytic calculations, wrote the manuscript, collected documents and edited the manuscript; Cuc Thi Nguyen - edited the manuscript.

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