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Cause and Solution to Roadway Deformation in Vietnam Underground Coal Mines

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Abstract. The deformation and support method of roadways have always been important issues in safe mining and production. Vinacomin's statistics show that, by 2021, there will be 64.19 km of roadways that need to be repaired (accounting for 25% of the total new roadways). Thus, the problem of maintaining roadway stability is facing difficulties in underground coal mines in Vietnam. To find out the causes of roadway failures, a case study at roadways of the Khe Cham I and Khe Cham III coal mines, Vietnam, is presented in this paper. Based on the results of a detailed field survey, the deformation characteristics of roadways and the failure mode of support structures were investigated. The results show that the roadway deformation is severe and the main support cannot control surrounding rock mass. Also, the destruction of support structure is frequent on reused roadways, affecting production efficiency and work safety. Therefore, to reduce deformation and increase roadway stability, a new support method called "multi-stage anchor of rock bolt + cable bolt" has been developed and a new longwall mining system with critical coal pillar width has been proposed. The new findings of the research can provide references for scientific studies, and apply them in Vietnam's underground coal mine practices.

Keywords: Roadway deformation, Coal pillar, Longwall mining system, Underground coal mine

1. Introduction

In coal production by underground mining method, controlling and maintaining roadway stability is an important task and has a positive influence on safety and high-efficiency production. Controlling roadway deformation using appropriate support and retention measures has become an extremely important area of focus in the study of rock mechanics and mining [1]. The deformation characteristic of roadways have been one of the hot research topics and have received considerable attention from researchers around the world. Coggan et al. [2] or Huang et al. [3] investigated the effect of an intercalated rock layer in the coal seam on roadway deformation. They found that the weak interstitial rock layer had a significant effect on the degree of roadway failure, causing asymmetric stress around the roadway. Tu et al [4] presented a mechanical model based on theoretical analysis and a prediction of the stress distribution around the roadway. Yan et al. [5] explored the influence of faults on the deformation mechanism of roadways and found that roadway strain increased when they were located near faults. Yu et al. [6] studied the deformation law of the roadway next to gob based on numerical simulation and field survey method. Chang et al. [7] or Gao et al. [8] discussed the characteristics of roadway deformation. They show that the high stress in rock mass, the stress caused by exploitation of adjacent panels, and the low strength of rock mass cause deformation of the roadway. Chen et al. [9], Kang et al. [10] or Yang et al. [11] used numerical simulations such as UDEC and FLAC3D to investigate the damage characteristics due to deformation of deep roadway.

For the conditions of Vietnam's underground coal mines, the deformation and failure mechanism of roadways in the area impacted by longwall faces have not been studied specifically and in detail. The width of protective coal pillar and the roadway support solution are usually taken from the experience of other regions. This implementation causes unsafe and roadway stability problems, which incurs a lot of repair costs. The roadway often suffers large deformations, the supports are destroyed, and the roadway stability cannot be guaranteed. The main remedial solution used was the repair and replace new support. This increases production cost and reduces economic efficiency and labor safety. Vinacomin's statistics show that, by 2021, there will be 64.19 km of roadways that need to be repaired (accounting for 25% of the total new roadways). Thus, the problem of maintaining roadway stability is facing difficulties in underground coal mines in Vietnam.

With these existences, performing field investigations and a detailed assessment of the status of roadways support in Vietnam's underground coal mines in the current period is of high urgency. The research results are practical scientific evidence to develop and apply solutions suitable to specific conditions, ensuring safety and economic efficiency.

2. Study areas and Methods

The study area was carried out at Khe Cham I and Khe Cham III coal mines in the Quang Ninh coal basin. The Field research method was carried out with the help of colleagues and mine engineers. After that, a numerical model is developed for preliminary evaluation of the proposed solution.

3. Results and discussions

3.1 Field research results

Conducting field investigations is a suitable way to understand roadway deformation in detail and visually. In this study, it was carried out on ventilation roadways No. 11.1.3 & No.11.1.4 on coal seam 11 of Khe Cham I coal mine, ventilation roadway No. 14.5.2A on coal seam 14.5 Khe Cham III coal mine. The roadways are located 300 m below the terrain surface. The cross-sectional area of the roadways when designed is about 8.4-9.5 m^2. The width of the protective coal pillars is 18-20 m. Steel supports "SVP" or anchors are used in the roadways. [12, 13].

Roadways No.11.1.4 & No. 14.5.2A used steel support "SVP". Support structures include two support columns linked to beams by sliding connection. The distance between support is 0.7 m and Φ90mm wood is used to make wall and roadway roof inserts.

Roadway No. 11.1.3 using anchor support - rock bolt of type Φ22.0 mm and length of 2.4 m is used; internal length of rock bolts to roof and roadway wall is 2.3 m, the exposed length is 0.1 m, the tensile strength of rock bolt is 260 KN, the layout space is 900 mm x 900 mm.

To provide visual data for the application of appropriate support measures, the survey includes - a survey of rock mass structure, support structure, roadway deformation, construction method, and other factors that affect roadway stability. The visual research results are shown in Figures 1, 2, and 3.

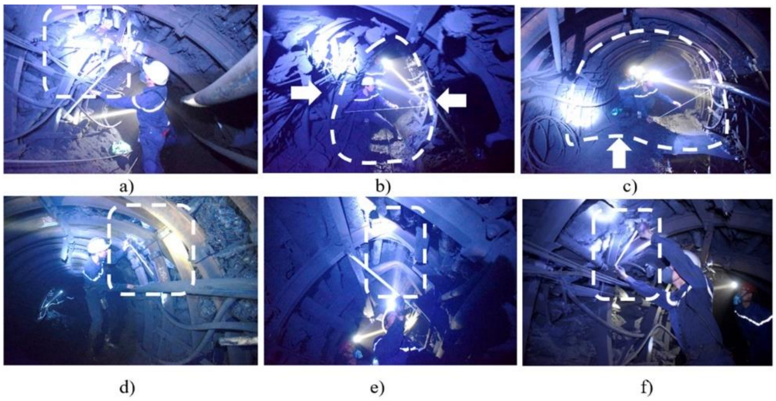

Fig. 1. Visual study results at roadway No.11.1.4, where "SVP" steel support is used.

a - Break of supports; b - Rib bulge; c – Floor heave; d - Break of sliding connection; e - Break beam; f - Steel column tearing.

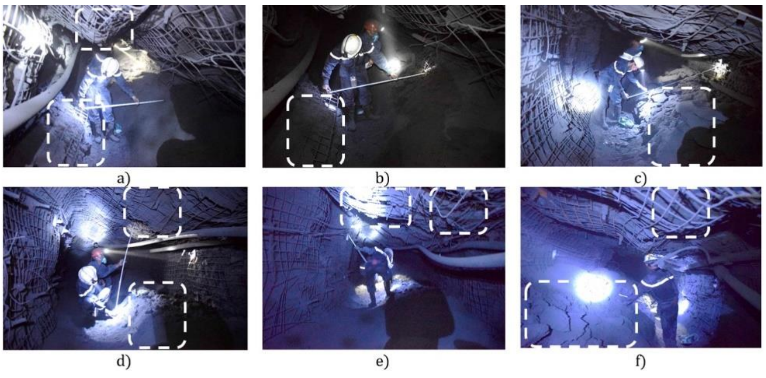

Fig. 2. Visual study results at roadway No.11.1.3, where rock bolt is used.

a - Roof sag and rib bulge; b - Rib bulge; c - Rib bulge and floor heave; d - Roof sag and floor heave; e - Roof sag; f - Floor heave and rib bulge.

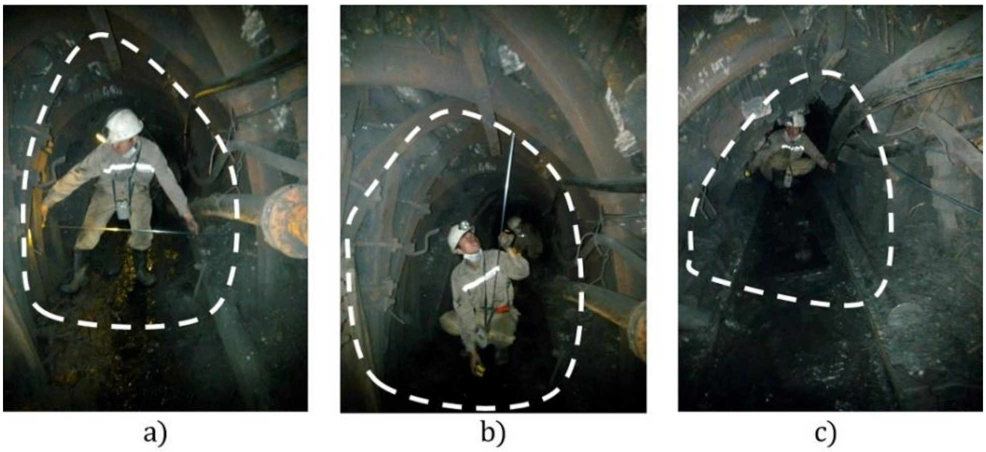

Fig. 3. Visual study results at roadway No.15.5.2A, where "SVP" steel support is used.

Figures 1-3 show the roadway deformation patterns in this area can be arranged as follows: unsymmetrical pressure, rib bulge, floor heaving, broken sliding connection, broken support beam "SVP" or sag roof (rock bolt), the support frame is destroyed.

In addition, monitoring of roadway convergence is carried out with two measuring stations located on the headgates No.11.1.3 and No.11.1.4 (corresponding to two types of supports). At the time of measurement, the upper mining panels have been fully mined. Figure 4a shows the location of this measuring station in the typical area of headgate No.11.1.3. A detailed description of the measurements, including equipment, station installation, and data collection is as follows: For each measuring station, permanent paint marks (solid red circles in Figs. 4c, 4d) are marked respectively on the roof, and the two ribs of the road, and on the floor is fixed with pegs of 50 cm long. The roof and floor are installed in the middle of them, and the ribs are marked on support columns or anchor locks.

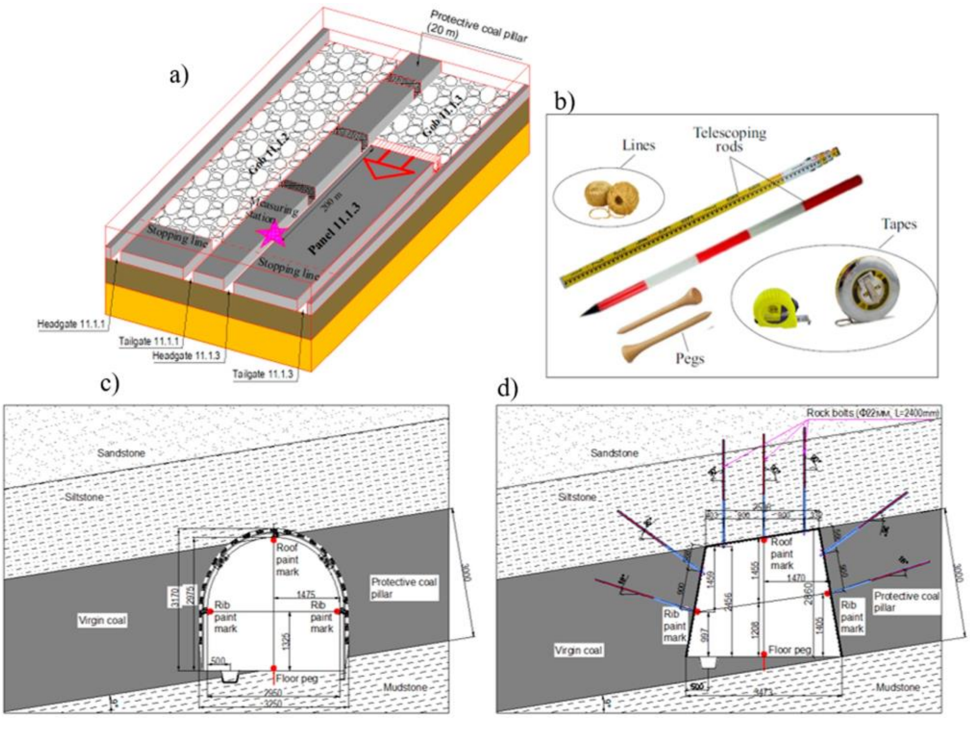

Fig. 4. The layout of roadway and roadway convergence measurement in the field.

a – The layout of roadways, typically at panel 11.1.3; b – Measurement devices; c, d – The layout of the measurement station of roadways No.11.1.4 & No.11.1.3.

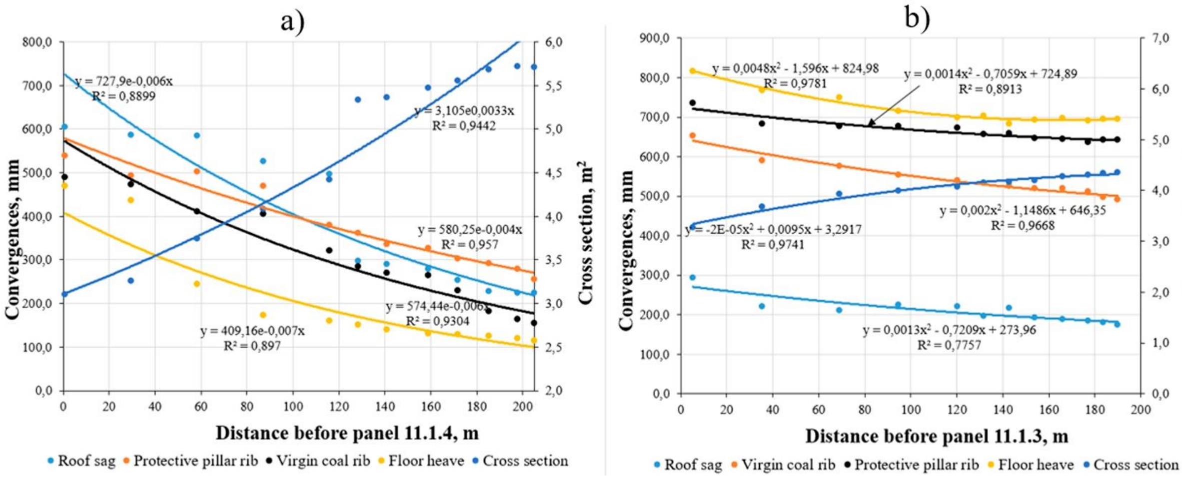

Fig. 5. Measured convergences in headgate during panels retreat.

a - convergences of headgate No.11.1.4; b - convergences of headgate No.11.1.3.

Figure 5 shows the result of the convergence of roadways No.11.1.3 & No.11.1.4 during the reuse period for the lower panel. It should be noted that, at the time of measurement, the roadway had a significant convergence due to the influence of the previous mining panel. The results have shown that about 200 m ahead of the 2nd longwall face, the deformation of the headgate with SVP support is much more intense than that of the headgate with anchor support. For example, at headgate No.11.1.4, the increasing amplitude of roof convergence is from 220 mm to 730 mm, of coal pillar rib is 265-578 mm, of virgin coal rib is 185-575 mm, and of floor heave is 100-405 mm. This shows that the SVP steel support has a good stability during the first panel's exploitation period, but cannot guarantee its integrity when it is in the abutment pressure zone of the second longwall face. A Typical example is the breakdown of the support structure and roadway deformation, as shown in Figs. 1 and 3. Meanwhile, for headgate? No.11.1.3, where anchor support is used, the opposite is true. Most of the deformation occurs during the exploitation of the first panel, and when it is in the bearing pressure area of the second working surface, the amplitude of convergence is not large with roof convergence in the range of 190-275 mm, coal pillar rib 650-735 mm, virgin coal rib 500-640 mm and floor heave 700-810 mm. In actual monitoring at the field, the convergence amplitude of headgate No.11.1.3 is not as high as that of headgate No.11.1.4 due to the addition of two rows of reinforced hydraulic columns at a distance of 25 m in front of the second longwall face. However, in general, both types of supporting structures do not meet the technical and safety requirements. The SVP steel support is easily broken, and the 2.4 m rock bolts are too short and not long enough to penetrate the plastic deformation zone of the surrounding rock mass. The final used cross-section of the roadway is only 2-3 m^2.

3.2 Discussions the results

Based on the above data, we have carried out a comprehensive analysis of the field survey results, and can reveal several causes of roadway deformation with the following characteristics:

3.2.1. Roadway deformation is influenced by the main stress

In the distribution area of the roadways of the longwall mining system, the vertical stress from the main roof is very high, leading to a large horizontal stress growth at the ribs and floor. Fieldwork results have shown that rib bulge, floor heaving, broken sliding connection, broken support beam "SVP", all related to lateral stresses, account for about 70% of the total deformation locations of the roadway. When the roadway is under a lateral force, the weak structural surfaces in the coal pillar and coal massive move towards the free surface, and support structure failures occur if this force exceeds its limiting resistance. In particular, the roadways are within the influence area of the longwall face from the adjacent panel, the deformation of the roadway becomes more severe. Furthermore, we can see from Fig. 1b that the direction of the asymmetric pressure is roughly consistent with the direction of action of the primary stress that thrives from the (almost horizontal) side of the coal pillar.

3.2.2. The influence of the time factor

The effects on the deformation of the roadway from the time factor include two aspects: the deformation rate and the deformation time. In the longwall mining system with the protection of coal pillars, after the first longwall face passes, the unloading and collapse of the surrounding rock mass are very severe because of the stress change in the roof rock layer, which is adjacent to the gob. Depends on the type of support, roadway deformation occurring during this period can account for more than 40% of the total deformation of the surrounding rock (example headgate 11.1.3). After the stress state is redistributed to a new equilibrium, the strain rate slows down and has a linear direction with time until it is in the stress region of the second longwall face. Rock mass deformations accelerate in magnitude under the abutment pressure of the longwall face. Here, the deformation is accelerated strongly with the average speed according to the measurement and statistical results in the study area: the roof convergence is 1.3 mm/day, left rib bulges 4.7 mm/day, right rib bulges 0.6 mm/day and floor heaving 4.1 mm/day. According to the monitoring results, the roadway does not achieve stability when lying in this area, the entire supporting structure is almost destroyed, so it has to be repaired locally to ensure production safety.

3.2.3. The influence of spatial factors

Similar to the time factor, the roadway deformation is greatly influenced by their distribution in relation to the surrounding structures. Previous studies have shown that, in the longwall mining system, the deformation process of the reusable roadway takes place in three main stages:

- During the panel preparation stage - the deformation is very small, the roadway is stable;

- In the second stage when the roadway is in the area of influence of the abutment pressure from the first longwall face, and then the pressure disturbance area from the gob next to the coal pillar - the roadway is deformed strongly and quickly;

- In the third stage, the roadway deformation is slow and linear because the rock layers and coal pillar are in a new equilibrium, and until it is in the abutment pressure area of the second longwall face, its deformation is increasing rapidly and strongly.

Thus, roadway deformation mainly occurs at the 2nd stage and at the end of stage 3. If the roadway support structure is not good, it will lead to deformation and collapse. In the results of the field study, at the end of stage 3, the roadways were greatly deformed and had to be repaired locally.

3.2.4. Influence from the width parameter of the protective coal pillar

In the longwall mining system, besides the role of the supporting structures, the protective coal pillar is a very important factor for the roadway to be reused next to it. The width of coal pillar and its load capacity have been studied in many workings. Many mechanical models have been proposed to analyze the stability of coal pillars such as the nonlinear rheological model of Wang et al. [14], simulating the simple spring model and the curved roof model of Mroz et al. [15]. In addition to mechanical models, mathematical models have also been introduced, for example, logistic regression and symmetry matrices in the study of Salamon [16] or Wattimena et al. [17]. In addition, the studies of Li et al., Wang et al., Mao et al. and Zubov et al. [18, 19, 20, 21, 22, 23, 24, 25] based on the limit equilibrium rule, numerical simulation and experimental research to evaluate the load capacity of coal pillars and the stability of the roadway. These studies all reveal that the coal pillar is stable only when there is an elastic region in the center of the coal pillar. A simulation of this state is shown in Fig. 6.

Fig. 6a shows that the plastic deformation region running through the coal pillar makes it weak and unstable. The coal pillar pushed into the roadway space by the strong development of cracks across its entire width. This causes the roadway to be strongly compressed and asymmetrical between the two sides, the steel support is easily destroyed.

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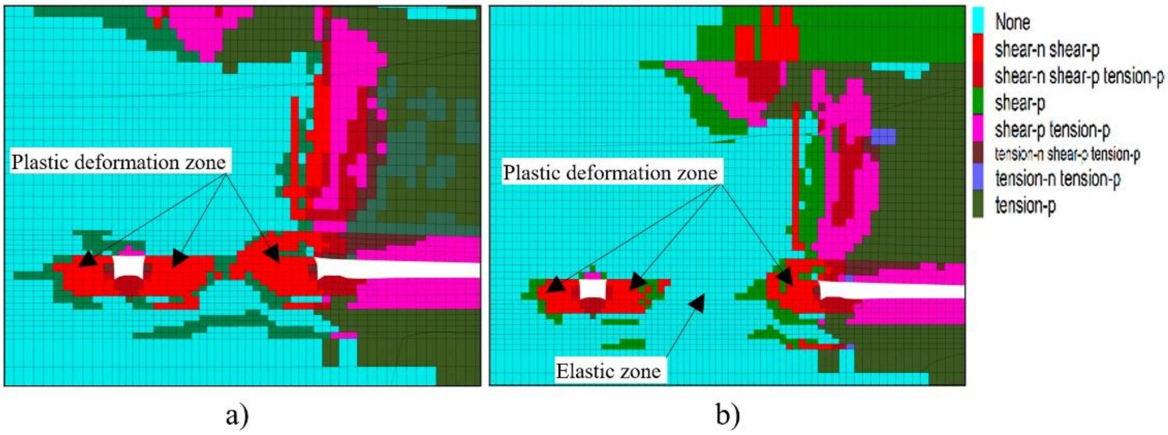

Fig. 6. The distribution of deformation and elastic regions of coal pillars in the longwall mining system, a – Coal pillar 20 m width according to reality; b – 30 m width coal pillar.

Fig. 6b shows that, when the coal pillar width is large enough, an elastic region appears in its center. This is the main bearing area and maintains stability of the coal pillar. The plastic deformation areas only grow to a certain limit. Therefore, if a reasonable supporting structure is used, the roadway will completely ensure the stability and safety of production, reducing the repair costs incurred.

3.1.5. Recommendation of applicable solutions

According to the above analysis, the disadvantages leading to the failure of roadway stability control at underground coal mines in Quang Ninh coal basin of Vietnam are:

(1) Load bearing capacity of the steel support "SVP" according to the current passport is not enough to ensure the stability of the reuse roadway in the area affected by longwall face, the steel support is prone to bending and breaking.

(2) Due to the influence of loads and displacements of the upper rock strata, the coal pillar and surrounding rocks tend to move into the reuse roadway space, and form cracks and plastic deformation in the coal pillar. When the coal pillar is not wide enough, this plastic deformation area will run through and occupy its entire area. The growth of this fissure zone is responsible for the weakening, deformation and even collapse of the coal pillar. This is a dangerous threat to occupational safety and the instability of the reused roadway.

(3) The short rock bolts are not capable of anchoring the rock mass around the roadway with the stable rock deep within. Because their length (2.4 m) is not enough to overcome the plastic deformation area to anchor the surrounding weak rock mass to the more stable rock mass. Therefore, the sole use of these rock bolts in the support structure will not guarantee the effect of roadway stability and safety of production

Thus, from the existing situation of the stability control of the reuse roadway in the longwall mining system, the first problem that needs to be overcome is to determine the critical width of the coal pillar, which capable of guaranteeing its own stability. This means that the coal pillar must be wide enough to ensure its stability, which in turn leads to the stability of the roadway being protected. In addition, the loss of coal in these coal pillars also needs to be studied. Therefore, to compensate for the shortcomings of the current mining system, a scheme is recommended to be applied as shown in Figure 7b [21, 22].

In the recommended diagram, a coal pillar of sufficient width will improve the protection and stability of the reuse roadway. After the function expires, coal pillars will be extracted along with the next longwall face to reduce coal resource loss.

In addition, the support structure of the roadway also needs to change. Steel support with current passport is no longer suitable under high mine pressure conditions. Especially, large rib pressure will easily destroy it. Moreover, the heavy weight of the steel support will be an important drawback when using it for deep roadways [26].

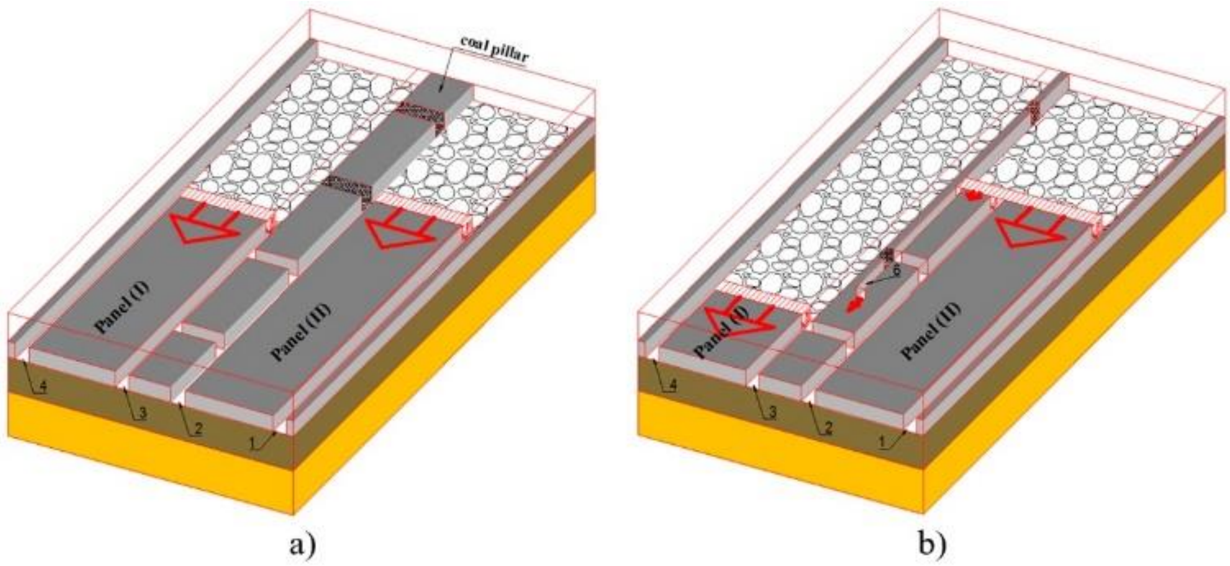

Fig. 7. Diagram of longwall mining system,

a – Current applicable diagram; b – Recommended application diagram.

At present, most of the underground coal mines in the world prefer to use the self-loading support method of the rock mass - the anchor support method. However, in order to improve the efficiency of use, the anchor length must overcome the plastic deformation around the roadway to anchor them to the hard rock mass. On that basis, the article recommends using a multi-stage anchor system combining rock bolts and cable bolts for roadways. The structure of the proposed multi-level anchoring system is as follows:

- Rock bolts: 2.4 m long, with a spacing of 0.9 m × 0.9 m, applied immediately after roadway excavation. The rock bolts pass through the plastic deformation zone around the roadway, securing them to prevent the falling rock into the roadway and collapsing during construction. This kind of flexible support can also release the initial rock stress to some extent, relieving the stress on the cable bolt.

- Cable bolts: 5 m (or 7 m) long, installed on locations where great convergence and deformation often occur, to fully correct the horizontal deformation of the road. Furthermore, cable bolts combine with rock bolts to connect the surrounding rock mass and to form a support system with strong resistance to deformation. This will greatly improve the stability and integrity of the surrounding rock.

The shallow area of broken rock around the roadway has poor stress transfer capacity. Through the multistage anchoring system, an effective superposition of the surrounding rock stress has been achieved, and its combined effect is capable of maintaining good roadway stability. It also fully mobilizes the capacity of the deep rocks, stabilizing the surrounding and inhibiting the development of deformation.

To evaluate the results of the proposed solution, the numerical modeling method with FLAC3D software was used. The input parameters of the model are made similar to roadway No.11.1.3 (in depth H =300 m) on the seam 11 of Khe Cham I coal mine. In the proposed solution, the coal pillar is designed with a width of 30 m, the roadway is supported with the system multi-level anchor system (Fig. 8). The parameters of rock bolts and cable bolts are taken according to its manufacturing specifications. The dimensions of the model are 260 m × 210 m × 150 m. Panels 11.1.1 & 11.1.3 and the gate roads system have been included in the model. A vertical stress of 6.5 MPa was applied at the top model boundary to simulate an overburden pressure by assuming the overburden unit weight is 0.025 MN/m^3, and gravity force was applied. The horizontal displacements of the four vertical planes of the model were restricted in the normal direction, and the vertical displacement at the base of the model was set to zero. Mohr - Coulomb deformation model is used in the research process [27].

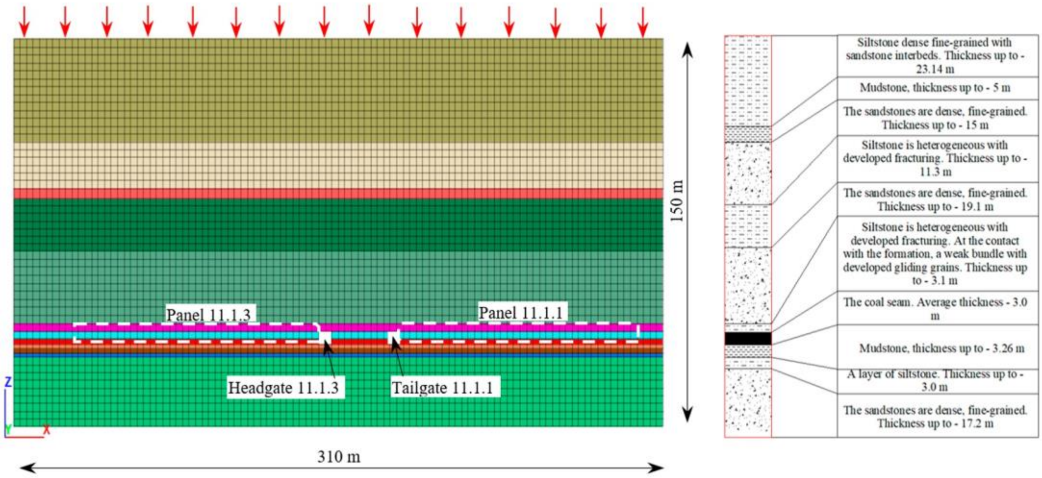

Fig. 8. Configuration of the model performed using FLAC3D and lithological profile.

Tab. 1. Mechanical properties of the rock strata used in numerical modeling.

Strata	Tensile strength (MPa)	Bulk modulus (GPa)	Shear modulus (GPa)	Poisson ratio	Cohesion (MPa)	Friction angle (deg)	Density (kg/m^3)
Sandstone	1.6	7.456	3.244	0.31	3.2	34	2780
Siltstone	0.9	2.333	0.955	0.32	2.1	30	2550
Mudstone	1.2	1.822	0.607	0.35	1.8	26	2250
Coal	0.4	0.748	0.484	0.26	1.5	19	1450

The simulation results of the plastic deformation regions around the roadway and the stress state on the coal pier are presented in Figure 9.

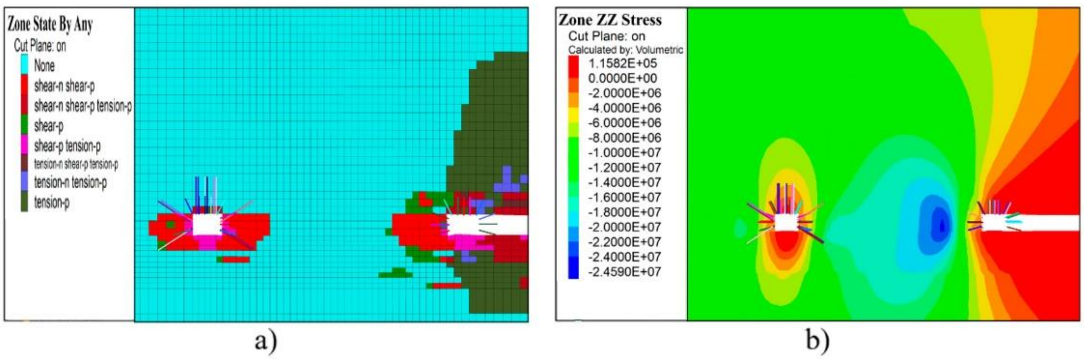

Fig. 9. Numerical simulation with the proposed solution, a – The state where the plastic deformation area appears; b – Vertical stress distribution on the coal pillar and around the roadway.

The simulation results show that the size of the elastic zone in the coal pillar is quite sufficient to ensure the stability of the pillar. With this solution, two vertical stress peaks are formed in the coal pillar, so the roadway is safe from the influence of gobs. The multi-level anchoring system has linked the plastic deformation around the roadway with the hard rock to form a stable and stable block. Therefore, the effect of roadway deformation control effect with the proposed solution is completely feasible.

4. Conclusions

This article has discussed the deformation breakdown and stability control results of reused roadways in the longwall mining system at underground mines of the Quang Ninh coal basin. Characteristic data are obtained through the results of fieldwork at Khe Cham I and Khe Cham III mines. On the basis of detailed field investigation, the types and deformation characteristics of the roadway have been identified. Some proposed solutions to minimise? roadway deformation have also been implemented. The main conclusions of the study are as follows:

(1) The types of roadway deformation failures can be classified into unsymmetrical pressure, rib bulge, floor heaving, broken sliding connection, broken support beam "SVP" or sag roof (rock bolt). Moreover, the main causes affecting the reuse roadway deformation include roadway lifetime effect, spatial effect, effect of main stress and width of the protective coal pillar.

(2) Investigation and measurement results have shown that the roadway deformation occurs very strongly when it is in the abutment pressure area of the longwall faces. Most roadways require local repairs to ensure ventilation and production safety. These roadways have demonstrated that the correlation between the width of the protective coal pillar and the existing roadway support structure does not meet the safety and efficiency requirements.

(3) A new scheme of the proposed longwall mining system and a multi-level anchorage structure has been developed. The elastic zone at the center of the coal pillar completely guarantees the stability of itself and the roadway. In addition, support with multi-tiered anchors and surrounding rock mass forms a hierarchical support system that can cooperate and work together. The evaluation results show that the effectiveness of the proposed solution is completely feasible for the reusable roadway in the longwall mining system.

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