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INTERACTION PRINCIPLE OF ROCK-BOLT STRUCTURE AND RIB CONTROL IN LARGE DEFORMATION ROADWAYS

Large deformation in roadways is an inevitable problem faced by many coal mines, and bolt installation is widely adopted to keep roadway stability. To provide a theoretical basis for bolt supporting scheme design in order to eliminate hazards associated with roadway failure, the interaction principle between bolts and the bolted strata should be studied thoroughly. This research attempts to investigate the above principle through theoretical analysis through a group of selected statistics from fifteen different coal mines. At the same time, the thick board support method was proposed and applied for controlling the ribs deformation in a particular coal mine. It is concluded that the interaction of the rock-bolt entity is subjected to the fluctuation balance law. When deformation increases, the bolted structure experiences periodic equilibrium variation. Both the supporting force needed to stabilise the surrounding rocks and the supporting capability of bolted strata show a trend of decrease in this process. The interaction principle of surrounding rocks and bolts is in essence the mechanical phenomenon caused by their mutual load transformation, and the load-carrying capacity varies with the bolted structure's deformation, which is subjected to the following law: elastic roadway>plastic roadway> fractured roadway>broken roadway. The designed bolted thickness of the ribs should be more than 1/5 of roadway height to make full use of the self-stability of surrounding rocks. Finite Difference Method simulation and on-site monitoring data showed that the roof subsidence and ribs convergence of 2201 roadway in Shuguang coal mine was reduced by 83.7% and 88.6% respectively after utilising the proposed support method, indicating that the thick-board method was effective. Results of this research can lay a foundation for support design in large deformation roadways.

Keywords: rock-bolt structure, fluctuation balance law, large deformation roadway, thick-board support

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1. Introduction

Underground coal mine roadway development is a unique process [1]. In the presence of arduous conditions in roadways, adequate stabilisations of the exposed strata boundary are required to ensure safe progress of the excavation, and the installation of bolts is an effective strata control process available to this problem [2]. Nonetheless, the support system is seriously affected by intense dynamic pressures during the service period of coal roadways, leading to problems with large deformation of the roof and ribs, and a high damage rate to the bolts and cables can occur [3]. Numerous coal mines experienced hazards associated with roadway instability despite many advances brought by surrounding rock support, as shown in Table 1.

TABLE 1

Statistics of coal mine accidents and deaths caused by roadway failure in China [4]

Year	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Number of accidents	1,569	1,884	2,132	1,985	1,805	1,633	1,299	1,032	805	702	473
Percentage in total accidents	—	55.0%	55.1%	56.4%	54.6%	55.5%	53.7%	52.8%	49.8%	50.4%	—
Number of deaths	1,807	2,766	2,452	2,209	2,058	1,902	1,518	1,222	939	829	567
Percentage in total deaths	31.4%	39.5%	38.1%	36.7%	34.4%	40.1%	40.1%	38.0%	35.7%	34.1%	—

The risk of fatalities from roadway failure is still prevalent in the coal mining industry [5-6]. Therefore, investigation on the mechanism of bolt support and the interaction between bolts and strata is of practical and economic importance for preventing bolt failure and roadway deformation.

Stability assessment for bolt supporting has been extensively studied. Firstly, Ding et al. [7] explored bolt stress and supporting mechanism during the deformation process of a rock mass, indicating that the bolt stress evolution is closely related to the deformation stages of the rock mass. The drawback is that the deformation stages were not divided in detail from their research. The corresponding relation between axial bolt load variation and roadway surrounding rock deformation and stability was summarised by Zhang et al. [8]. They confirmed that the change of axial bolt load is in accord with the adjustment of surrounding rock stress, which can consequently reflect the deformation and stability state of roadway surrounding rocks. However, they did not point out the deformation law of roadways during their service life. In another research, Šňupárek and Konečný [9] detected that the loading of supports during mining comes from a stress wave in the rock mass in the forefront of coalface. From their perspective, adequate measures could be taken to prevent bolt failure. Utilising a rotatable experimental frame, Yang et al. [10] investigated the behaviours of bolt-supported rock strata and proposed the asymmetrical bolt-mesh-cable supporting system to control rock stability of roadways. However, the interaction mechanism of the structure was not obtained from their research. Apart from this, Zhou et al. [11] pointed out that bolting would alter the natural evolutionary processes and change the multi-field interactions in the rock masses from their initial equilibrium states. This is a novel perspective to investigate the equilibrium variation of the rock-bolt structure. In addition, Kang et al. [12] considered the cable prestress when monitoring the stability of the roadway, and detected that the fully grouted cable with a short length, high strength and high prestress is an effective way to reinforce the roadway suffering from severe mining-induced stresses. This method has been promoted to be applied in many coal mines. From a different aspect, Chang et al. [13] proposed the hydraulic expansion bolts to control floor heave in soft rock roadway. Their research mainly focused on the working mechanism of the hydraulic expansion bolt, but did not explore the load transformation law between bolts and rocks. It is widely known that Armand et al. [14] performed mine-by experiments to measure the hydromechanical response of the rock and the mechanical loading applied to the support system due to the digging and after excavation, and described the convergence of roadway as a function of time. This function can be applied to monitor the stability of roadways. In addition to this, Khalymendyk et al. [15] analysed the effectiveness of roadway reinforcing by means of cable bolts, and revealed that the application of cable bolts allows for a reduction in the vertical convergence of the roadway. This conclusion lays a foundation for the application of cables in preventing roadway deformation. At the same time, Charlie [16] points out that a natural pressure arch is formed in the rock at a certain distance behind the tunnel wall. Rock bolts should be long enough to reach the natural pressure arch when the failure zone is small. When designing bolt support, the bolt length should be calculated based on this assumption.

The aforementioned investigations focus mainly on the working mechanism of bolt support. However, little has been done in investigating the mechanism of load transfer between bolts and surrounding rocks. In this area, Frith et al. [17] tried to study the natural self-supporting ability of roof strata and their interaction with bolts. This is the basis of this research for designing a thick-board support method to utilize this ability. In addition, Wu et al. [18] presented a series of laboratory pull-out tests to explore the effect of bolt rib spacing on a load transfer mechanism. Heritage [19] on the other hand, pointed out that the key roles of bolt support in ribs include controlling kinematic failures and the progression of rib deformation further into the rib, generating confinement and increasing overall rib strength. Their research results can guide rib control in large deformation roadways. Wu et al. [20] investigated the stability of the "rock-coal-bolt (RCB)" composite system to analyze the mechanical mechanism of the bolt under the combined action of tension and shear stress. Under the real condition, the mechanical phenomenon is complicated. Their research is therefore of practice value. During one research, Sjölander et al. [21] presented a numerical model capable of simulating the failure of a bolt-anchored and fibre-reinforced shotcrete lining, considering the interaction between the bolt and strata. However, they did not point out the interaction principle. In addition, Kang et al. [22] performed a series of laboratory tests to study the mechanical behaviours of rebar, thread, plate and domed washer. The characteristics of deformation and damage of each component were presented, but they did not explore the interaction mechanism of the bolted strata as a whole system. Sinha and Chugh [23] utilized the critical strain technique (CST) to research quantifying the rock bolt's composite reinforcement effects. This investigation is a try on exploring the rock-bolt structure's interaction. Singh et al. [24] found that the application of a high density of bolts to arrest the roadway failure would work only if the surrounding natural supports are stable. The stability of natural support is found to be diluted due to side loosening caused by the mining-induced stress. However, they did not explain the self-stabilization of surrounding rocks a step further. During a case study in the Karvina subbasin, Waclawik et al. [25] dealt with the behaviour of roof bolting, including the loading of the bolts, yielding of the rock mass and convergence in the roadways. These three mechanical behaviours conclude the working process of bolt supporting. To analyze the effect of combined loading on rock bolt design for suspension and beam building models, Singh et al. [26] used analytical methods to calculate the required spacing of rock bolt for a given safety factor. They found that the shear displacement between the bolted layers depends on the vertical roof deformation and thickness of beds. This is an important consideration during designing bolt spacing. The results of Pinazzi et al. [27] showed that the rock bolt could resist higher axial loads than shear under pure or combined load conditions, but the bolts are under composite mechanical conditions in practice. According to the research results of Mohamed et al. [28], they developed guidelines for modelling mechanical bolts using the tri-linear load-deformation response. Finally, there is a need to mention the application of numerical methods on exploring the mechanism of the bolt-rock structure. Abousleiman et al. [29] adopted the discrete element method (DEM) to explore the self-supporting capacity of surrounding rocks after mining, considering a range of in-situ stress ratios, material properties and joint networks. Several researchers [30-33] have recommended the use of FDM for analysis of roadway deformation, bolt supporting and the nature of failure detected in both continuum and discontinuum rock masses. Their researches open the mind in the area of bolt supporting.

The literature on the subject reveals the widely applied bolt supports and their working mechanism, and it also shows that there are few in-depth types of research focusing on the principle of interaction between bolt and strata. It is the key to long-term stable roadway support design. Engineering practices indicate that the interaction principle and effect between the bolt support structure and surrounding rocks are still unclear so far. In particular, there is still a lack of comprehensive study on the equilibrium structure and its mechanical properties.

This research presents the results of an attempt to explore the interaction principle between bolts and surrounding rocks in coal mine roadways, by means of theoretical analysis and numerical simulation. Theoretical analysis was performed with the statistics of bolt supporting and roadway deformation in fifteen different coal mines. The adopted research thesis assumed that the bolt-rock entity would be of high stability when anchoring thickness is more than one-fifth of roadway height. Thick board bolt support was thereby proposed with a subsequent case study. Finally, the results of FLAC3D numerical simulation and on-site monitoring data validated the control effectiveness of the proposed support system.

2. Materials and methods

2.1. Collected statistics for theoretical analysis

The study was carried out with roadway support and deformation statistics (Table 2) from fifteen coal mines with different bolt supporting systems and surrounding rock states and loading conditions. The statistics were used for investigating the interaction law between bolts and surrounding rocks.

A coal mine roadway is a typical complex underground engineering with a large degree of uncertainty about the load, the composition of the load-bearing system, the structural characteristics and mechanical properties [34-37]. The load-bearing body and load-giving body may transfer from one to another with different support methods and the change of stress distribution and deformation state in surrounding rocks. In other words, under certain conditions, the carrier body can transform into a loading body, and the loading body can convert into a carrier body as well [38]. In addition, this transformation will bring about differences in structural characteristics, load bearing capacity, deformation and stability of the surrounding rock bearing system in the

TABLE 2

Statistics of bolt supporting and roadway deformation in different coal mines of China

Coal mine	Size of roadway		Mining depth/m	Support methods	Condition of surrounding rocks	Monitoring time
	Width/m	Height/m				
Xieqiao	4.0	3.0	500	H-shape steel shelves; resin bolts	Broken ribs; high ground stress	06,1999~06,2001
Zhaizhen	3.4	2.6	200	Anchor cable; high-strength bolt	Joint fissures; large faults	05,2005~09,2008
Xiandewang	5.0	2.6	240	Full-length resin anchoring; high-strength rebar bolt	Extremely soft and hydro-expansive rocks	04,1998~01,2001
Shuijingtou	2.0	2.0	515	High strength bolt; anchor cable; grouting	Joint fractures; large faults; high tectonic stress	05,2001~06,2006
Xinwen	3.7	2.4	1200	Bolt-mesh grouting; secondary reinforced support	Complex geological structure; large deformation of surrounding rocks and serious floor heave; rock burst	06,2003~10,2007
Dongpang	3.5	3.5	420	Ultra-high-strength rebar bolt; full-length resin anchoring; grouting	Large deformation; high tectonic stress	01,1999~01,2001
Hongmiao	3.8	2.5	350	Prestressed full-length resin anchoring	Low strength; loose, broken and eugeogenous surrounding rocks	10,2009~10,2010
Xingdong	3.8	3.5	800	Anchor cable; lag and side installed bolts	Large deformation; soft and broken rocks; high ground stress	03,2002~06,2005
Changcun	4.0	3.0	365	Rebar anchor; anchor cable	Strata separation and sliding; cracks	10,2004~10,2005
Qishan	3.5	3.5	600	Wire rope mortar anchor and shotcrete support	Soft rocks; large deformation; high tectonic stress	06,1995~06,1997
Yima	4.0	3.0	815	Heat-rolled and heat-treated bolts	Frequent rock burst; broken surrounding rocks	10,2014~10,2015
Zhaogu	3.2	2.8	700	Extendable bolts; rigid long rebar bolt; shotcrete	Fissure development; low strength; large deformation	08,2014~07,2016
Pingdingshan	4.2	3.0	930	Anti-breaking anchor; resin lengthened anchorage	Soft and broken ribs; coal and gas outburst	11~2002~01,2006
Baiji	4.0	3.0	830	Full length resin anchored high-strength bolt; W-shape steel belt and diamond metal mesh	Low strength; roof caving and rib spalling	02,1997~04,1999
Wangzhuang	3.5	3.0	350	High-strength rebar bolts; resin lengthened anchorage	Hard and stable surrounding rocks	10,2003~07,2004

roadway [39]. Consequently, when considering roadway supporting, apart from the factor of bolt supporting capacity, it should be well mentioned that surrounding rock is a natural supporting structure, which will show strong self-bearing capacity under certain conditions [40]. The mechanical status of surrounding rocks is varietal during the whole service period of roadway, therefore different support systems under the same surrounding rocks and load conditions or the same support system under different surrounding rocks and load conditions may experience different deformation and stress process [41]. In-situ stress equilibrium in surrounding rocks is disturbed after excavation, thus the stress will redistribute to achieve new equilibration [42]. During this process, corresponding deformation and displacement will occur. Due to the existence of a supporting structure, the formation process will change in the surrounding rock as a result of a new equilibrium state. Displacement formed in this procedure and pressure caused by support will be different under different support conditions [43-44]. With the data collected, the aforementioned questions about the process of load transformation and the interaction principle of the bolt-rock structure will be analyzed and presented in Section 3.1.

2.2. Numerical method for rib control

Through numerous simulations and in situ experiments [45-49], it is found that the compressive and shear resistance stress of the anchor entity will be relatively high when anchoring thickness is more than one-fifth of roadway height. The method of using thick-board bolt support to control large deformation roadway is then suggested. The vertical load of rib support is calculated through the structural and mechanical characteristics of surrounding rocks, and then the anchorage strength can be determined by limit equilibrium analysis. Parameters of support can be calculated as follows:

Anchorage strength p is calculated by [50]:

$$p = q\frac{1-\sin\phi}{1+\sin\phi} \tag{1}$$

$$q = \frac{B^{'}-B}{2t_3}(\Sigma h + \frac{B^{'}}{2f})\gamma \tag{2}$$

where, q is load density carried by bolt structure in ribs; ϕ is friction angle of rib strata; Σh is thickness of weak strata in roof, m; B is width of roadway, m; $B^{'}$ is equivalent width of roadway, m; f is Protodyakonov coefficient of roof strata; γ is average weight of roof strata, kN/m^3; t_3 is thickness of load-bearing anchor, m.

Distance between bolts b is:

$$b = \sqrt{\frac{p_0}{p}} \tag{3}$$

where, p_0 is the designed tensile failure stress of bolts; p is anchorage strength.

Bolt length t is determined by the support entity's board characteristics and distance between bolts (Fig.1) [50].

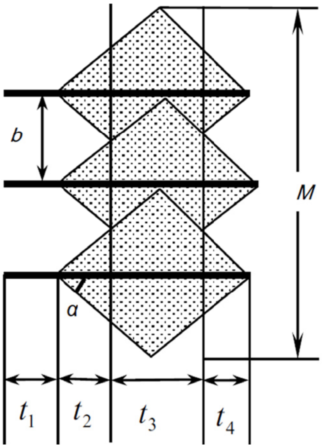


Fig. 1. Bolt support structure for rib control

$$t = t_1 + t_2 + t_3 + t_4 \tag{4}$$

where

$$t_1 = \frac{1}{2}\frac{p_0}{\pi\phi c_0} \tag{5}$$

$$t_2 = \frac{1}{2}b\cot\alpha \tag{6}$$

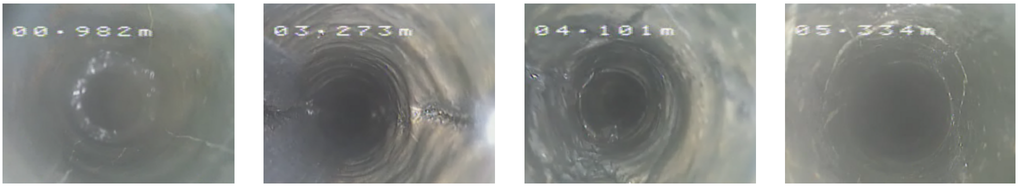
$$t_3 \geq \frac{1}{5}M \tag{7}$$

$$t_4 = \frac{1}{2}(b - 0.1)\cot\alpha \tag{8}$$

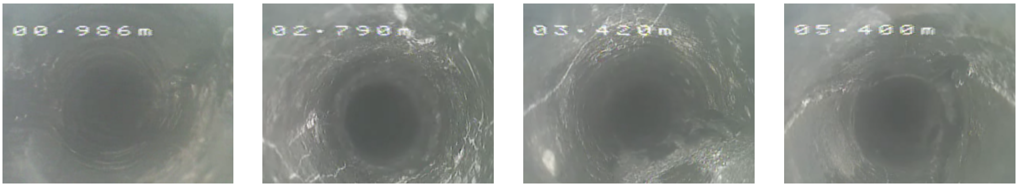
where, t_1 is accumulation length of anchorage adhesive force, m; c_0 is anchorage adhesive force of ribs, MPa; t_2 is thickness of non-overlapped area influenced by bolts at anchorage end, m; t_3 is stable bolt length; M is roadway height, m; t_4 is thickness of non-overlapped area influenced by bolts at anchorage tail, m; α is inclined diffusion angle affected by anchoring force.

2.3. Case study

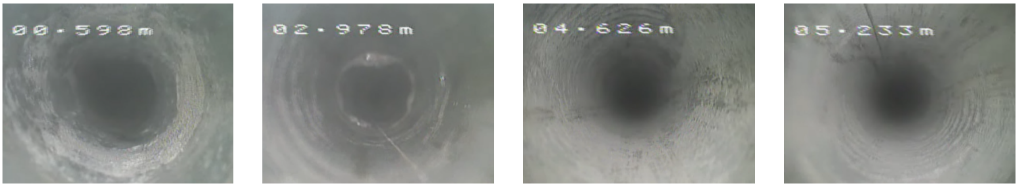
Considerable deformation occurred in 2201 Roadway during the excavation of the Shuguang coal mine in Shanxi, China. How to choose a proper support scheme and support parameters was therefore of urgent need. The width and height of the 2201 Roadway were 5 m and 3 m respectively. The roof of the roadway was stable with high strength while ribs were severely fractured, thus ribs were key consideration during support design. To analyse the strata condition of the roadway, we drilled a series of 6-meter-deep peepholes in the roof and ribs (Fig. 2).



(a) Strata condition of the left rib



(b) Strata condition of the right rib



(c) Strata condition of the roof

Fig. 2. Condition of 2201 Roadway from monitoring peephole

From monitoring peephole results, the fracture characteristics of 2201 Roadway surrounding rocks could be concluded as follows: (1) within two meters, there was no obvious fracture development in the left rib. Vertical and circumferential fractures occurred between two and five meters deep in the left rib. This area was called the fracture coalescence zone. Strata over five meters were intact and no fracture was observed (Fig. 2(a)); (2) fracture development was more severe in the right rib, where fissures frequently occurred along with the peephole. This region could be defined as a fracture developing zone (Fig. 2(b)); (3) the roof could maintain better integrity than ribs after roadway excavation, a small fracture was seen in the peephole. This section could be called a micro-fracture zone (Fig. 2(c)).

The fracture development analysis using on-site peephole monitoring data provided an important basis for roadway support design. Thick board bolt support proposed in Section 2.2 was applied in this project according to the strata distribution characteristics of the roadway. The average weight of roof strata was 25 kN/m^3, and the thickness of weak stratum in the roof was 1 m; *f* of strata above weak seam was 2; the fraction angle of broken ribs was 30°. A round steel anchor with resin roll was used, and the bond strength was 1.5 MPa; the designed tensile failure force was 100 kN. Bolt support parameters were calculated as follows:

Thickness of load-bearing anchor:

$$t_3 = \frac{1}{5} M = 0.6\,\mathrm{m}$$

Equivalent width of roadway:

$$B' = 5 + 2 \times 3 \tan 30° = 8.46\,\mathrm{m}$$

Load density carried by bolt structure in ribs:

$$q = \frac{B' - B}{2t_3}\left(\Sigma h + \frac{B'}{2f}\right)\gamma = \frac{8.46 - 5}{2 \times 0.6}\left(1 + \frac{8.46}{2 \times 2}\right) \times 25 = 224.54\,\mathrm{kN/m^2}$$

Anchorage strength:

$$p = q\frac{1 - \sin\phi}{1 + \sin\phi} = 224.54 \times \frac{1 - \sin 30°}{1 + \sin 30°} = 74.85\,\mathrm{kN/m^2}$$

Distance between bolts:

$$b = \sqrt{\frac{p_0}{p}} = \sqrt{\frac{100}{74.85}} = 1.2\,\mathrm{m}$$

Accumulation length of anchorage adhesive force:

$$t_1 = \frac{1}{2}\frac{p_0}{\pi\phi c_0} = \frac{1}{2} \times \frac{100}{3.14 \times 0.27 \times 150} = 0.4\,\mathrm{m}$$

Thickness of non-overlapped area influenced by bolts at anchorage end:

$$t_2 = \frac{1}{2} b \cot\alpha = \frac{1.2}{2}\cot 45° = 0.6\,\mathrm{m}$$

Thickness of non-overlapped area influenced by bolts at anchorage tail:

$$t_4 = \frac{1}{2}(b - 0.1)\cot\alpha = 0.55\,\mathrm{m}$$

Bolt length:

$$t = t_1 + t_2 + t_3 + t_4 = 2.15\ \mathrm{m}$$

Bolted length $t_0 = 2t_1 = 0.8$ m.

Table 3 shows the final bolting parameters of ribs:

TABLE 3

Bolting parameters of ribs

Anchorage strength ($\mathrm{kN/m^2}$)	**Designed tensile failure force (kN)**	**Distance between bolts (m)**	**Bolted length (m)**
74.85	100	1.2	0.8

In the project, the roof was installed with left-hand threaded steel anchors, whose distance was 1.25 m and row spacing was 1 m with each row having five anchors. Anchor cables were installed every two meters along the excavation direction with a distance of 2 m. Ribs were installed with round steel anchors. The anchor distance was 1.2 m, and row spacing was 1 m, with each row having two anchors (Fig. 3).

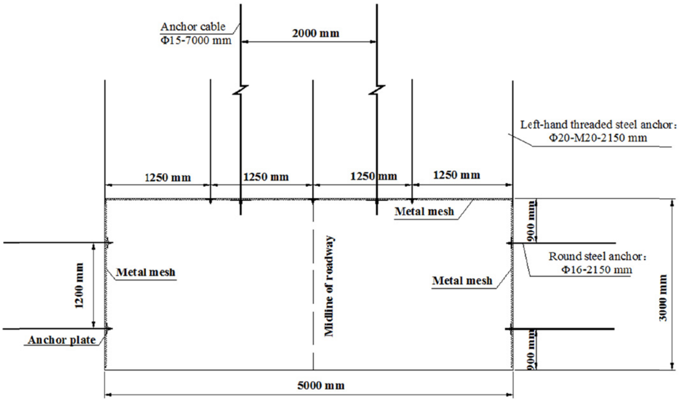


Fig. 3. Support scheme of thick-board bolt

2.4. Numerical simulation model

The effectiveness of the proposed support method on the final reduced roof and ribs displacement in Section 2.3 was evaluated. A Finite Difference Method (FDM) numerical simulation was applied to investigate the deformation behaviour around the tunnel after excavation, under the situation of unsupported and supported conditions respectively.

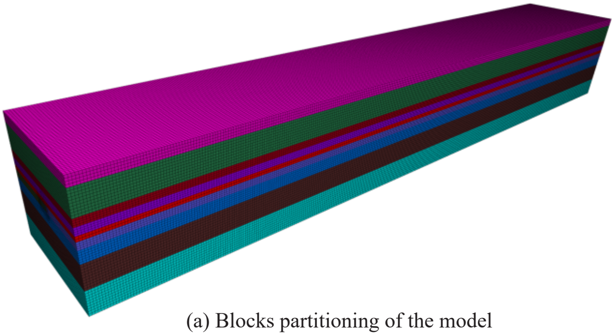
Differing from Finite Element Methods (FEM) [51-52], FDM is the earliest methodology adopted for partial differential equation in numerical simulation, including regional division and replacing the derivative by difference quotient [53]. It is an approximate numerical solution that directly transforms a differential problem into an algebraic problem [54]. The first step is to divide the solution zone into difference grids and replace the continuum zone with finite grid nodes. Then, use the Taylor series expansion method to replace the derivative term in the partial differential equation with the difference quotient of the function on grid nodes for discretisation, thereby establishing a system of algebraic equations whose unknowns are values on grid nodes [55]. The difference scheme is expressed as

$$u_j^{n+1} = u_j^n - a\frac{\Delta t}{\Delta x}\left(u_j^n - u_{j-1}^n\right) \tag{9}$$

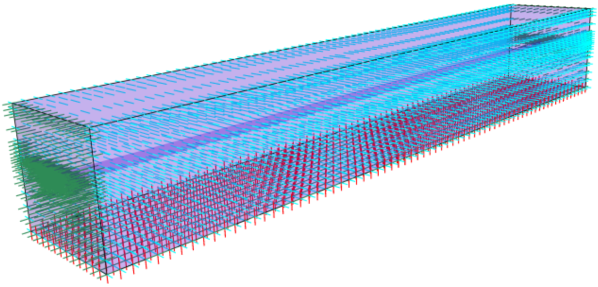
$$u_j^Q = \phi(x_j),\ j = 0, \pm 1, \pm 2, \ldots \tag{10}$$

where, a is movement velocity of the element; Δx is space step; Δt is time step; $(j\Delta x, n\Delta t)$ is grid; u is displacement of element, and $\phi(x)$ is the initial value function. FLAC^{3D} is one of the most well-known and powerful FDM programs being widely used in the field of underground engineering and mining, supporting the behavioral study of underground structures under diverse geological conditions [56]. Thus, the method was used in this simulation.

The geometry of the model (length L = 700 m, width W = 200 m, height H = 200 m) and its boundary conditions are depicted in Fig.4. 1,258,174 blocks with 1,177,541 nodes were created to model the rock mass. To diminish the effect of boundary conditions on the deformation behaviours of the roadway, the translational freedoms of X and Y directions of the model boundaries were constrained, thereby movements of the bottom and sides were restrained. The top boundary was not constrained but applied by a load of 4 MPa to simulate the gravity condition of overlying strata. In this model, general contact was adopted to model the contact property between bolts and surrounding rocks. The length of the excavation step was 50 m, and monitoring was conducted after each excavation. The failure criterion used was the Mohr-Coulomb Failure Criterion, which revealed the deformation law and plastic zone distribution of surrounding rocks.



(a) Blocks partitioning of the model



(b) Boundary conditions of the model

Fig. 4. Numerical simulation model

The criterion is expressed as

$$\frac{1}{2}(\sigma_1 - \sigma_3) = c\cos\phi - \frac{1}{2}(\sigma_1 + \sigma_3)\sin\phi \tag{11}$$

where, σ_1 and σ_3 are the major and minor effective principal stress respectively; c is cohesion of each stratum, and ϕ is the internal friction angle of the stratum. Table 4 shows the strata mechanical parameters used for simulation, provided by the coal mine.

TABLE 4

Mechanical parameters of the model

Stratum	γ (kN/m³)	E (GPa)	v	R_c (MPa)	R_t (MPa)
Medium sandstone	26	76.1	0.24	96.7	4.5
Fine sandstone	26	62.1	0.12	121.1	4.9
Siltstone	25	54.8	0.21	76.8	3.5
Shale	26	35.9	0.19	34.6	2.5
Sandy mudstone	24	41.6	0.16	60.5	3.2
2# coal	14	8.0	0.34	16.7	0.66
Siltstone	25	78.6	0.21	70.6	3.8
Fine sandstone	26	36.7	0.21	38.8	4.4

3. Results

3.1. Results of statistics analysis

According to statistics in Section 2.1 (Table 2), the relationship curve of the roadway deformation and support force could be summarised as Fig. 5 and Fig. 6.

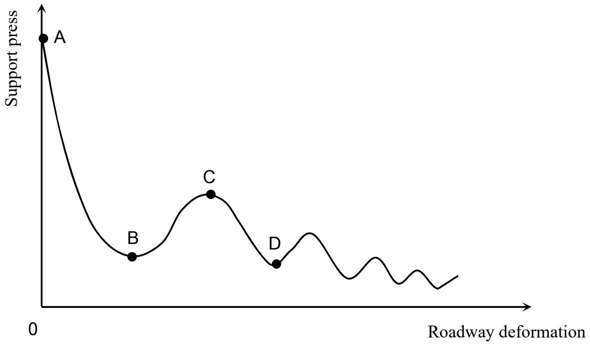


Fig. 5. Relationship curve of support press and roadway deformation

When the interaction of surrounding rocks and support reaches equilibrium, the variation relationship curve of support press and roadway deformation can be divided into the following three characteristic stages according to roadway deformation state (Fig. 5):

(1) Surrounding rocks are within an elastoplastic state completely, i.e., there are only elastic and plastic zones in surrounding rocks. Before strength failure, rock stress varies directly along with roadway deformation. The greater the roadway deformation, the greater the stress acting on the surrounding rocks, thus producing more loads on the strata and fewer loads on the support (section A-B in Fig. 5). Consequently, to control deformation, the load on surrounding rocks must be reduced appropriately. This can be done by providing a certain supporting force on the bolts to reduce stress concentration and roadway

deformation. It can be seen from the deformation property curve that, in order to make full use of its load-bearing capacity, the surrounding rock should be allowed to produce as much deformation as possible under the prerequisite of maintaining continuity.

(2) Surrounding rocks are within the early stage of strength failure, when the surrounding rock is partially in a cracked or loose deformation stage. After partial strength failure, this part of surrounding rocks will lose some or even all of their self-supporting capacity, thus transforming from the load-bearing body into a load-giving body. Once this destruction phenomenon develops to a certain degree, there will be a broken or loose deformation zone in surrounding rocks. During a certain deformation stage, the load born by support will increase, along with the increase of surrounding rock deformation to keep its stability (section B-C in Fig. 5). This is because deformation increase is accompanied by the expansion of rupture and loose deformation zone, thereby increasing the support strength needed to prevent the loss of self-supporting capacity in surrounding rocks. To maintain stability, greater support stress is therefore needed at this stage.

(3) Large area of the loose zone is generated in surrounding rocks. With destruction zone expansion and deformation increase of surrounding rocks, fractured rock masses may form a masonry-beam or a balance-arch bearing structure due to their mutual action of extrusion, meshing and friction. During this time, a turning point appears again in the support-rock interaction curve (point C in Fig. 5). In other words, due to the formation of surrounding rock bearing structure in a loose zone, the support force required to maintain surrounding rock stability would decrease along with the continuous increase of rock displacement. This trend will be maintained until the load-bearing structure of the damage zone fails due to a rather large deformation and rotation (point D in Fig. 5). After that, the stable-unstable-stable characteristic process as shown in section B-C-D of Fig. 5 will cycle periodically. During each cycle, the minimum support force required to maintain surrounding rock balance will reduce to a certain extent (but this trend can be formed only when surrounding rock is effectively controlled).

The analysis above indicates that under a constant boundary stress field, the interaction between bolts and surrounding rocks shows fluctuation balance characteristics [57].

With distortion and failure of surrounding rocks, corresponding changes will happen to the rock-bolt entity. Its mechanical condition will change from elastic state to plastic state and finally to incompact state. The deflection process of the entity can be divided into a small deformation period and a large deformation period based on its displacement. Alternatively, it can be divided into the elastic period, plastic period, fractured period, broken period and loosened period according to the mechanical status of the entity [58]. The entity's load bearing capacity will change along the transformation process of its mechanical state correspondingly (Fig. 6).

When the roadway deforms from elastic status to a plastic state, the interaction force-deformation curve of the entity belongs to the reinforcement section. The load carried by the entity increases along with the increase of deformation (a-b section of curve 5). During the fractured period, as fracture occurs and develops, the rock within bolted area changes into blocks. The entity's variation curve steps to softening section. The load carried by the entity decreases while deformation increases (b-c section of curve 5). After the fractured period, rock blocks will move, rotate, and squeeze until forming an articulated structure ultimately. The load carried by the entity increases again along with the increase of deformation (c-d section of curve 5). When equalisation between load and load bearing integration is disturbed, the articulated structure will fail gradually and load carried by the entity decreases while deformation increases (d-e section of curve 5). As deformation increases and load removes to the outer rock partially, a new articulated structure will be formed. At this time, the load carried by the entity will fluctuate along with the increase of roadway deformation (e-f section of curve 5). After that, the curve of interaction between the entity and outer rock will vary cyclically, which observes the fluctuation balance law.

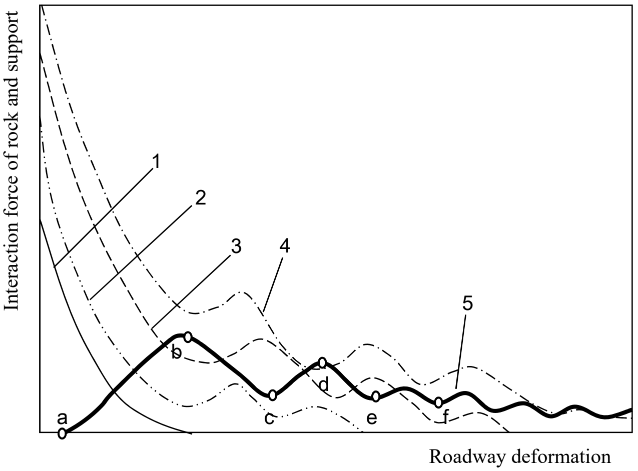


Fig. 6. Relationship curve of roadway deformation and interaction force of the support entity: 1 – Elastic roadway: surrounding rocks can maintain self-stable state. 2 – Plastic roadway: surrounding rocks can form self-stable state after small reasonable deformation under support control. 3 – Fractured roadway: surrounding rocks can form self-stable state after large reasonable deformation under support control. 4 – Broken roadway: surrounding rocks cannot form self-stable state anymore. 5 – Relationship between rock-bolt entity load and surrounding rocks

In summary, the integral rock-bolt structure is adaptable to large deformation, and the load-carrying capacity varies with the structure's deformation. The rock-bolt structure is a special support combined with bolt, rock surface retaining and protecting devices and bolted rocks themselves [59]. The deformation and failure of the rock-anchoring entity and surrounding rocks show periodic features, and the stability of surrounding rocks under this retaining system shows dynamic features. Therefore, the interaction state between the rock-bolt entity and surrounding rocks is changeable and corresponding to load conditions. According to a comprehensive analysis of stress, displacement and failure of the entity and outer surrounding rocks, the interacting force and equilibrium state of the entity and outer rocks are different in different periods of deformation. When stress is small, the system can be maintained in elastic and plastic stable status.

A reasonable squeeze stress field is the prerequisite of forming the rock-bolt entity, especially under the condition of broken surrounding rocks [60]. Generally speaking, there are reasonable extrusion force fields in the inner surrounding rocks of most roadways. The extruding pressure can be supplied by rock surfaces protection devices such as articulated bottom plates and wire meshes [61]. Otherwise, the rock-bolt entity is difficult to be built, and will fail when the squeeze condition disappears. For example, the extrusion stress near the end of the long-wall face is not strong enough, so the load-bearing capacity is strongly reduced. Under such conditions, it cannot be used independently as reasonable support of the roadway [62].

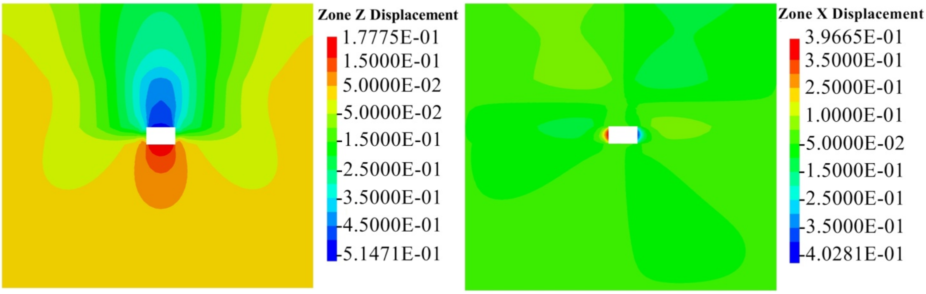
There are two basic types of roadway instability: (1) sudden destabilisation, i.e., roadway failure takes place in a short time with some dynamic phenomenon, such as roof fall and rib spalling; (2) deformed destabilisation, i.e., roadway failure occurs after large deformation without any dynamic phenomenon. The rock-bolt entity is adaptable to large deformation, and it can keep controlling surrounding rocks. Sudden instability will not happen under adequate support of the rock-bolt entity.

It can be seen from the functional mechanism of the rock-bolt entity that the natural self-load-bearing capacity of surrounding rocks needs to be fully utilised in roadway support. Deformation of surrounding rocks should be allowed to occur as much as possible while maintaining continuity, thus improving the rock-bolt entity's compressive strength to achieve the purpose of controlling the roadway.

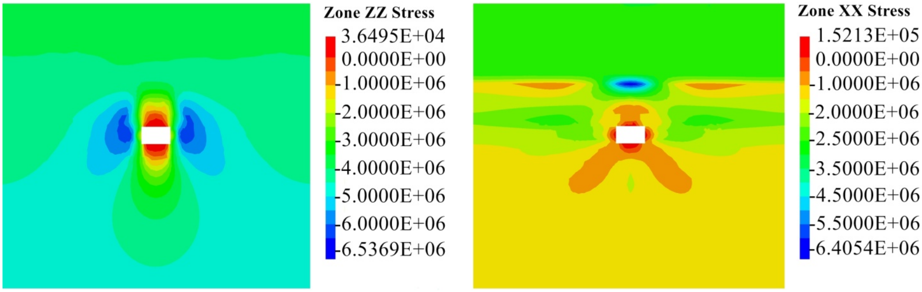
3.2. Results of numerical simulation

(1) Simulation of roadway development without bolt support

From Fig. 7, we can see that after excavation the in-situ stress of roadway surrounding rocks was disturbed and redistributed. The redistribution of stress caused deformation and displacement in the roadway surrounding rocks. Without support, the maximum displacement of the roof and ribs reached 514.7 mm and 402.8 mm, respectively.



(a) Vertical displacement (b) Horizontal displacement



(c) Vertical stress contour (d) Horizontal stress contour

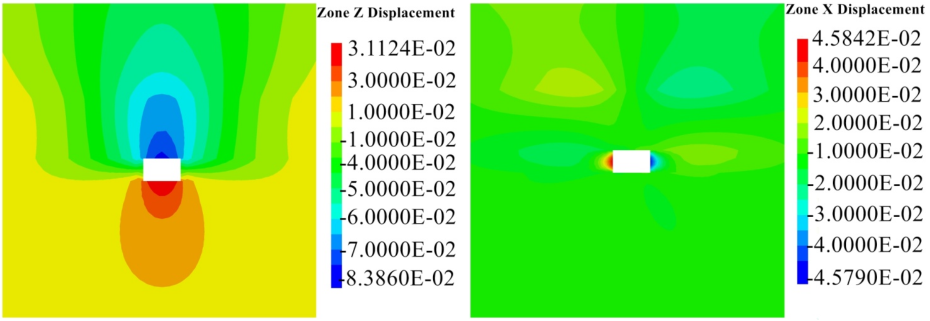
Fig. 7. Simulation results without support

(2) Simulation of roadway development with proposed bolt support

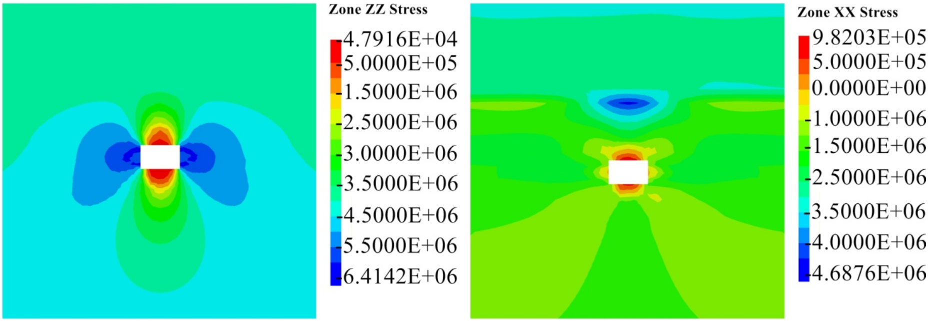
The bolt installation parameters in Section 2.3 were proposed in the simulation model. Stress contours in Fig. 8 show that the strength and bearing ability of the roadway improved after utilising thick-board support. The maximum of the final roof subsidence was 83.86 mm, and the maximum rib displacement was 45.79 mm, reducing 83.7% and 88.6%, respectively. This indicates that the proposed support method reduces the development of failure and plastic zone in roadways effectively. Numerical simulation results coincide well with on-site monitoring data, showing that subsidence of roof and convergence of ribs were all within reasonable values under the thick-board bolt supporting.

The formation of bolted strata, especially bolted broken strata, depends on the existence of compressive force rather than the quality of surrounding rocks. For broken ribs, bolt support should be conducted based on the theory of squeezing reinforcement and integral bolting. The bolt-strata entity will be of strong load-bearing capacity when anchorage thickness is more than one-fifth of roadway height, and tick-board bolt support is used to form a reinforced wall in ribs.

The results from the simulation model and the field monitoring demonstrate that the thick-board bolt support methodology could improve the surrounding rock strength and load-bearing capacity of the support structure, thus controlling large deformation failure in rock roadways. As a result, the long-term stability and safety of roadway are guaranteed.



(a) Vertical displacement (b) Horizontal displacement



(c) Vertical stress contour (d) Horizontal stress contour

Fig. 8. Simulation results with bolt support

The practice of thick-board bolt support in Shuguang coal mine indicated that surrounding rocks of roadway are of a particular self-load-bearing capacity after excavation, and bolt support reinforces this capacity significantly. Therefore, deformation of surrounding rocks should be allowed to occur as much as possible to improve the rock-bolt entity's compressive strength. From Section 3.1, we can conclude that the relationship between support and surrounding rocks follows the fluctuant equilibrium principle. While the boundary stress field keeps constant, the load on support decreases gradually. As deformation increases, the rock-bolt entity's stress condition varies from equilibrium to disequilibrium and then to equilibrium state. In this process, the entity's load-carrying capacity shows fluctuating feature and decreases gradually.

4. Discussion

The focus of this investigation is primarily on the interaction principle of rock-bolt structure. One intriguing result revealed by this study is that this interaction observes fluctuation balance law, as shown in Fig. 5. Bolted strata are not a static structure but under a dynamic equilibrium during their service life. The load born by support varies accordingly along the deformation stages of surrounding rocks, and the load-giving body may transfer into a load-bearing body in this procedure (Fig. 6). Certain deformation of surrounding rocks should therefore be allowed to occur to utilise their self-stability. The interaction principle of rock-bolt structure is the mechanical phenomenon caused by the load transformation between surrounding rocks and supporting bolts. In engineering practice, bolt installing may not consider the functional mechanism of the bolts on rocks in detail. However, one principle that should be prioritised is to form a thick-board to maximise the natural self-supporting stability of surrounding rocks. This method can be promoted to control ribs in large deformation roadways or prevent deformation of roadways from the very origin during excavation.

In the application of thick-board support, Singh et al. [63] proposed using a grouted steel rope method under tension to improve the safe span of overhanging strata near the goaf edge. This resulted in stress redistribution around the bolted strata, which, as this research has shown, transfers the roof strata from load-giving body to load-bearing body. In addition, the beneficial effect of thick-board bolt support on the improvement of coal mine roadway stability has been demonstrated by Rakesh et al. [64]. Subsequent studies of rock-bolt interaction have shown that, the neutral point is determined by bolt length, the size of the roadway, and the mechanical properties of surrounding rocks [65-66]. This is consistent with the result of this investigation. During the dynamic interaction process between rock and bolts, the position of the neutral point is changeable and under a fluctuant balance state. Whether the diameters of bolt and borehole match or not will determine the supporting effect [67]. This will also affect the interaction between bolt and rock mass. Kumar et al. [68] proposed a novel coupler of dual height rock bolts to avoid bolts connection breaking. They discovered that under applied axial loads, the load transfers from inner bolt to outer bolt. However, they did not investigate the opposite load transformation mechanism. In addition, many mechanical experiments have been conducted by researchers to investigate the rock/bolt interaction behaviour, which can be seen as a supplement to the theoretical analysis of this research. For example, Che et al. [69] performed pull-out tests to study the mechanical behaviour of the bolted entity from micro-scale to macro-scale. Numerical modelling is an effective methodology to reveal the complex mechanical behaviour between bolt and rock. Cui et al. [70] used FLAC3D to model the rock-bolt interaction, considering elastic-brittle-plastic and elastic-perfectly-plastic strata behaviours respectively; Wu et al. [71] deduced the equilibrium and compatibility equations of the energy-absorbing bolted structure based on the plane-strain axial symmetry assumption and the incremental theory of plasticity, and programmed the model via VB. The energy-absorbing model is similar to the load transformation process described in this investigation. The numerical modelling used in this research is to validate the effectiveness of the proposed supporting method in a coal mine. The interaction between rock and bolt was described generally in this paper, which is derived from statistical analysis. In contrast, Cai et al. [72] considered the coupling and decoupling behaviours of the interface between rocks and bolts as well as axial force distribution along the bolt to investigate the mechanical behaviour of the bolted structure.

It is also worth adding that the fluctuation balance law of bolt supporting is only applicable to coal mine roadways, and this is where our investigation derived from. In railway or road tunnels adopting bolts for support, there is lining below the bolts, thus the structure is more stable than that of coal mine roadway where the end of the bolt is exposed to the air and without additional support. Deformation of the bolted entity in this situation is marginal, and its mechanism is worth exploring further.

Nevertheless, it turns out that the conclusions above may state the considerations discussed in the introduction to this paper. The fluctuation balance law of the rock-bolt entity lays a foundation for bolt supporting scheme design to eliminate hazards associated with roadway instability. Furthermore, the thick-board support can be an effective and secure method to reduce roadway failure.

Despite important discoveries revealed by our study, there are also limitations. The investigation is derived from limited statistics from coal mines in China. There may be insufficient data or a bias in the data collection locations, which results in data that is not fully representative of all coal mines. Successful application of bolt support depends not only on bolt categories and support methods, but also on geological and mining conditions. This potential variability between mines makes it difficult to have a ‘‘one size fits all” approach. Therefore, the applicability and generalisation of the fluctuation balance law and thick-board bolt support method in other countries is yet to be validated. A much larger set of statistics spanning multiple mines are needed to make any definitive conclusions. In addition, there are no additional research methods such as modelling experiment or numerical simulation to verify the conclusions in Section 3.1, thus lacking strong reliability. Furthermore, the definition of “thick-board” is still to be discussed. The bolted thickness “one-fifth of roadway height” is an empirical value. Currently, it is unknown if there is a way to optimise thickness for certain coal mines to form a thick-board. Overall, there is still much work that should be conducted in the future.

5. Conclusions

The statistics from different coal mines were analysed to reveal the interaction principle of rock-bolt structure in large deformation roadways to derive an effective support scheme. The theoretical analysis provided a significant basis for roadway support design, and the thick-board bolt method was employed for rib control in the Shuguang coal mine. Ultimately, a numerical simulation was carried out for verification. The detailed analysis and discussion of the results in this investigation lead to the following conclusions:

(1) The interaction between bolts and rocks observes fluctuation balance law. When deformation increases, the bolted structure experiences periodic conditions. The supporting

force needed to stabilise surrounding rocks shows a decreasing trend in this process, while the supporting capability of bolted strata fluctuates and decreases gradually.

(2) When the roadway deforms from elastic condition to broken status under the load imposed by upper strata, the load-bearing capacity of the bolted strata subjects to the following law: elastic roadway>plastic roadway> fractured roadway>broken roadway.

(3) To utilise the self-load-bearing capacity of surrounding rocks, deformation space needs to be accounted for during bolt installation. The thick-board support was proposed under this basis. Bolted thickness was designed more than one-fifth of roadway height to improve the compressive and shear resistance stress of the bolted entity.

(4) The proposed thick-board support method was adopted to control roadway deformation in the Shuguang coal mine. Numerical simulation and on-site monitoring results showed that, the roof and rib convergence of the 2201 roadway reduced 83.7% and 88.6%, respectively.

Although the proposed thick-board method could be used to control roadway deformation, it does not currently consider the condition in different mines and give a universal definition. In addition, the statistics are insufficient to cover coal mines in other countries, and additional research methods should be conducted to validate the research conclusions. It is expected that more accurate and reliable data will be employed in the future, to replenish the interaction law of rock-bolt structure. By means of on-site monitoring, simulation experiment, numerical simulation and analytical and reverse analysis methods, the research results should be made more convincing. The theory of thick-board bolt support should also be completed in future research.

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