

# Study on the Stability and Deformation of the Roadway Subjected to High In-Situ Stresses

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Received: 6 June 2016 / Accepted: 24 February 2017 / Published online: 27 February 2017  
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**Abstract** To investigate the deformation and failure mechanism of the roadway under high in situ stresses at the 958 section in 2# mine in Jin Chuan, China, field and numerical investigations were conducted. Field investigations on the loosen ring of the roadway show that great roadway deformations and failure in surrounding rocks may result from poorly functioned bolts. Based on the old supporting system, a new supporting system characterized by the installation of steel pipe beams and the elongated bolts was proposed and applied in field. Field data indicate that the roof sag, rib convergence and floor heave significantly decrease. The numerical study illustrates that the properly functioned bolts and steel pipe beams are

responsible for the decrease of roadway deformation. To further control the roadway deformation, two additional supporting systems were proposed and simulated. The increase of the bolt density contributes to reinforcement of the surrounding rocks and the floor heave in the first support system is under controlled. In the second support system, the installation of bolt on floor successfully restrains floor heaves accordingly.

**Keywords** Roadway deformation · High in situ stress · Field investigation · Numerical investigation

## 1 Introduction

Large deformations of surrounding rocks have been encountered in many underground constructions (Barla 1995). These large roadway deformations with instabilities, which may endanger working staff and the construction sequence, have been major concerns in underground constructions in deep and soft rocks. According to the roadway-deformation characteristics, Lu (1984) proposed that the deformation of a roadway consists of the initial deformation, rheological deformation and disturbance deformation. As the deformation accumulates, failures at various roadway sections occur. As the failure pattern varies, Shen (2014) proposed that roadway failures include beam failures, joint controlled rock falls, roof sags, the guttering and shearing failures, skin failures and rib failures.

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Previous studies with various focuses implied that two groups of factors are responsible for the large deformations and instabilities (Liu et al. 2004; Gale et al. 1992; Kang et al. 2012). The first group of factors is the original geological factors, such as mechanical parameters of rock masses, the tectonic stress field and water contents et al. The second group of factors is the human-induced factors that include support methods, mining-induced stresses and the underground constructions layout, et al.

To diminish adverse impacts of aforementioned factors on the roadway stability, extensive studies have been conducted to investigate the roadway failure mechanism. These studies significantly contribute to restrain the roadway deformation in coal mines. For instance, based on the principles for the underground roadway support, Wang et al. (2015) proposed a multiple support system with joints in soft rocks, and this system was proven to be effective and economic by the field investigation. Improved U-shaped steel sets, which can restrain large deformations in roadways, were proposed by Jiao et al. (2013), and Jiao pointed out that back fillings, which were located between U shaped steel sets and surrounding rocks, can significantly reinforce the coupling effect of surrounding rocks and balance the forces on the steel sets. Chen and Li (2015a, b) and Chen (2014) studied the pull-and-shear performance of rock bolts and indicated that the capacity of deformed bolt in hard rock and soft rock conditions. Combining the numerical study with the field investigation, a support system by Kang et al. (2014), where hollow grouting cables with high strengths were introduced, satisfied the requirements of large-deformation controlling in a winch room. Numerical investigations by Gao et al. (2015) successfully illustrated the characteristics of roadway deformations because of mining-induced stresses. Ghabraie et al. (2013) reported that a wider span truss with sharper angle of incline bolt contribute to restraining horizontal movement of the immediate layer in high horizontal in situ stress. An analysis by Zhang et al. (2015) on the stress evolution of bolts and cables shed lights on effectively using these devices in roadways. Some other studies that focused on civil tunnels (Aksoy et al. 2012; Yassaghi and Salari-Rad 2005) have been conducted. However, limited investigations have been conducted on the roadway deformation in Metal and non-metallic mines, especially

those in depths characterized by high tectonic stresses and low rock strengths.

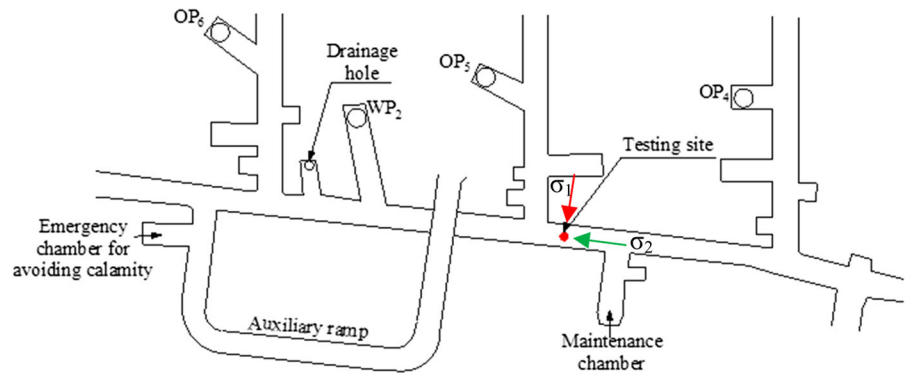
In the present paper, a field study was conducted to investigate the roadway deformation and failure mechanism in Jin Chuan mine, China. In addition, to further study the deformation mechanism and improvement of support, the numerical simulations based on FLAC 3D code was performed. The analysis of numerical tests was conducted.

## 2 Geological and Engineering Features

The problematic roadway was the haulage roadway located at the 958 section in 2# mine in Jin Chuan, China. A partial layout of the 958 section is shown in Fig. 1. Most roadways were excavated in thick marbles with the uniaxial compressive and tensile strength of 130.4 and 9.1 MPa respectively. Since these marble rocks at this section were characterized by few discontinuities and no water inflow, the geological condition was good enough for mining engineering. However, Fig. 2 indicates that intensive floor heaves and rib convergences were observed in the roadway where a multiple support system was applied. Based on the original support principles, the multi-support system consisted of the soft support at an early excavation stage and the rigid support after the sufficient stress release. The soft supports mainly consisted of spraying concretes and the bolt-mesh, the rigid support elements included U-shaped steel sets and the secondary concrete lining. Despite large floor heaves were encountered, no support was installed on the roadway floor. To avoid the disturbance on transportations, great costs and lots of times were consumed to remove the wreckages that were caused by floor heaves.

The vertical stress of the testing section was 22.2 MPa, as shown in Fig. 1. The maximum horizontal principle stress ( $\sigma_1$ ) denoted by a red arrow was perpendicular to the target roadway and its value is 44.5 MPa. The other horizontal principle stress ( $\sigma_2$ ) denoted by a green arrow was parallel to this roadway and the relevant magnitude is 32.9 MPa. These high in situ stresses may induce great roadway deformations, such as large floor heaves and rib convergences. According to a similar study, the high compressions caused the high vertical and horizontal stresses may be responsible for rib and floor failures (Shen 2014).

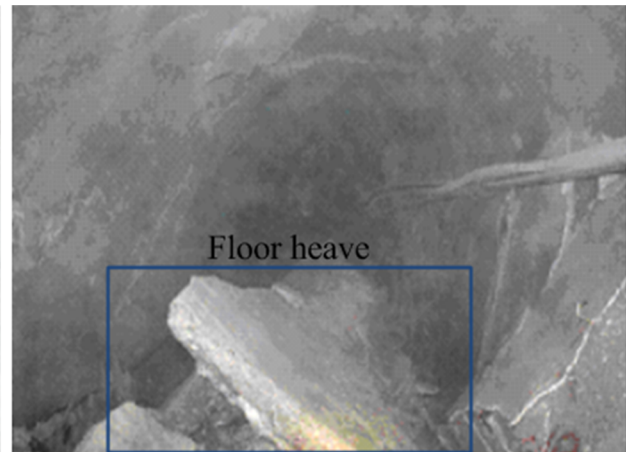
**Fig. 1** A partial layout of the 958 section



(a)



(b)



**Fig. 2** Typical roadway failures

Another factor, which may be responsible for the intensive roadway failure, is the insufficient support. Bolting, which is an important support method in the original system, significantly affects the roadway stability. A previous investigation proposed that the bolting length and density are two important factors affecting the bolting function (Zhang et al. 2015). If bolts are too short, the bolts installed in the plastic or failure zones cannot function effectively. Thus, the characterization of the plastic or failure zone is a fundamental index for the selection of bolts. On the 958 segment, RSM-SY7 data collector in Fig. 3a was applied to measure the loosen ring of the roadway with the affiliated detectors in Fig. 3b. The maximum length of the loosen ring is 2.3 m. However, the length of the installed bolts was only 2.25 m. Therefore, partial deformations in ribs were not effectively restrained and the forces in bolts increase with the increasing bolting spacing. The loosen ring in Fig. 3b and the bolt length indicate that only parts of the

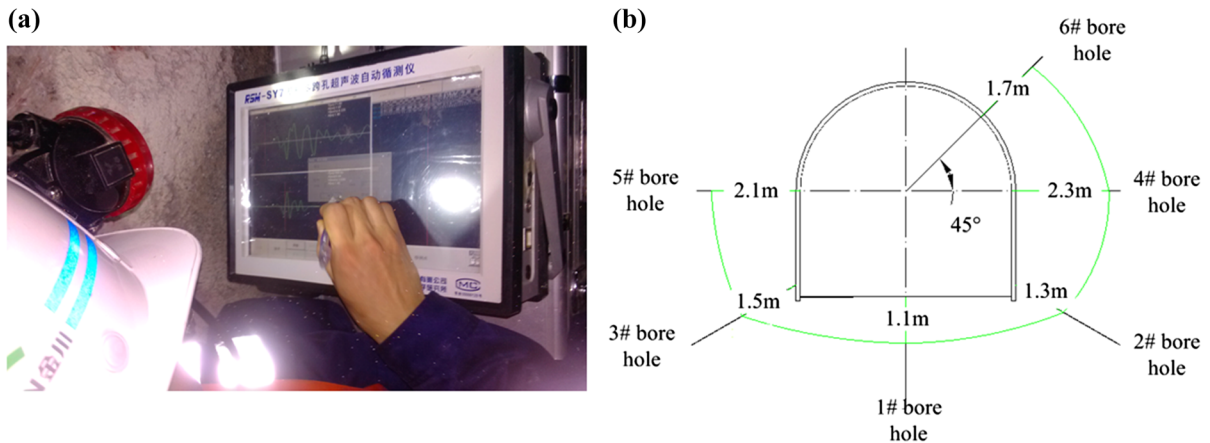
bolts can function properly. Thus the loading plates, bolts and screws failures resulted from high axial forces were frequently encountered (Fig. 4). These failures may also result from the large spacing of 0.8 m between bolts and the failures in rib may aggravate floor heaves accordingly (He et al. 2009).

### 3 New Supporting Strategies and Field Investigations

#### 3.1 Proposed Supporting Strategies

To restrain roadway deformations in Jin Chuan Mine, the following effects should be achieved in the new support system:

1. Improvements of the intrinsic rock strength by installing increased fully anchored bolts in the



**Fig. 3** The equipment and results for the loosen ring of the roadway: **a** RSM-SY7 data collector; **b** obtained schematic of the loosen ring

loosen ring; installation of longer bolts to connect the reinforced loosen ring with the relatively deeper-intact rock.

- To restrain floor heaves, reinforcement of the rock mass and the ground stress unloading, especially the former one, can be conducted (Dong et al. 1994; Feng and Kang 2009). Reinforcements of the rock mass can be achieved by bolting, grouting and installing inverted-steel arches. By considering the difficulties of roadway repairs, which may be met when bolting or grouting are finished on the floor, steel-pipe beams on the shallow floor may be installed feasibly. Furthermore, these installed beams may contribute to the deformation control of ribs.

### 3.2 Construction Procedures of the New Support System

Based on aforementioned strategies, a combined supporting system in Fig. 5 was proposed. This system includes the short bolting, long bolting, concrete lining and steel pipe beams. Corresponding field experiments were conducted at a testing site which is shown in Fig. 1. Specifications of this supporting system are listed in Table 1.

Detailed construction procedures are as follows:

- After the excavation of deformed surrounding rocks, a concrete lining, which was 50 mm in thickness, was immediately sprayed on the arch-shaped roof. Figure 6a shows that steel nets and

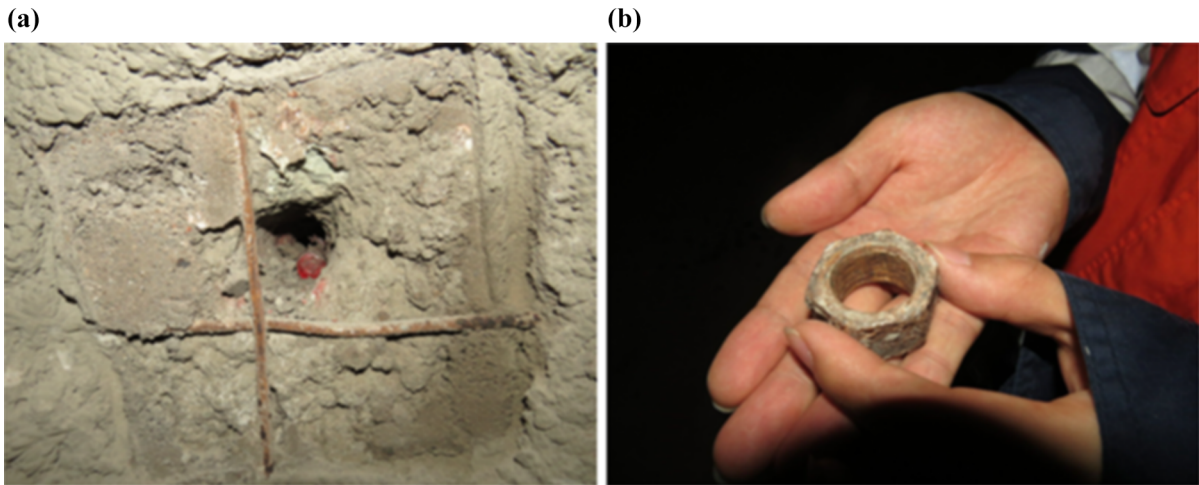
the fully grouted bolts were installed. Afterwards, the spray the concrete lining with 150 mm in thickness was applied on the roof again.

- Repeat Step (1) at ribs of the roadway.
- Install steel pipe beams which spacing was 1 m on the floor.
- To efficiently and economically monitor roadway deformations, Fig. 6c shows totally 10 measuring points at the left and right sides of the roadway were installed respectively on the sections, which distance was 1.6 m along the experimental roadway. The characteristics of the roadway deformation were obtained and analyzed according to MATLAB finally.

### 3.3 Monitoring Results and Discussion

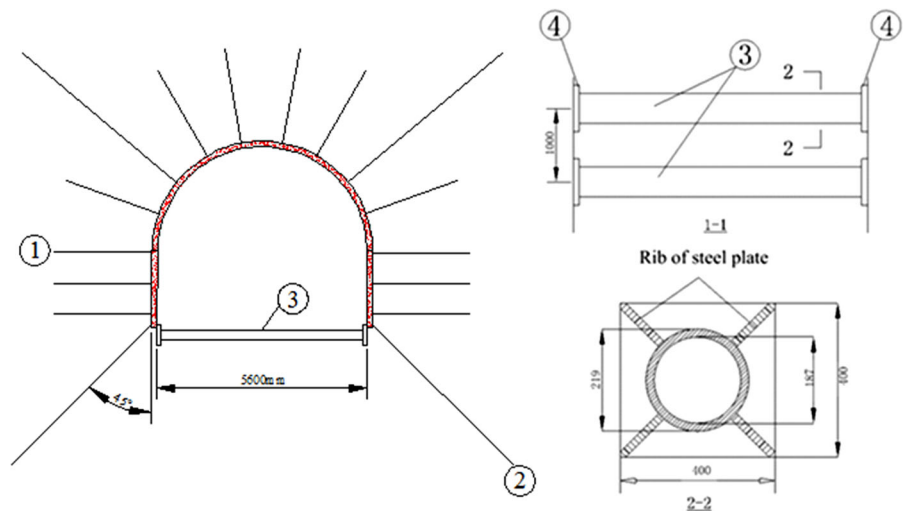
#### 3.3.1 Rib Convergences and Roof Sags

The typical displacement curves of the middle section are drawn in Fig. 7. Similar to the results reported in Wang et al. (2015), Kang et al. (2014) and Jiao et al. (2013) studies, two displacement stages are observed. The first stage which is named initial stage of rib convergences, Stage A, lasts for nearly 40 days after the support installation. In this stage, because of the high ground stresses at this experimental site, the release of ground stresses result in a high convergence rate in ribs, when the support time are 40 days, the rib displacement is nearly 120 mm. In the later stage, the convergence rates of both ribs decrease, and the rib



**Fig. 4** Bolting failures: **a** loading plates failures; **b** screw nut failures

**Fig. 5** Schematic diagram of the proposed supporting system: 1 indicates short bolts; 2 indicate long bolts; 3 is the steel pipe beam; 4 is the end plate of the steel pipe beam



**Table 1** Specifications of the new support system

Support elements	Diameter (mm)	Size (m)	Spacing (m)	Designed load (KN)
Short bolt	25	2.25 (length)	0.8	200
Long bolt	25	3.5 (length)	0.8	200
Steel net	6.5	0.15 × 0.15 (mesh size)	–	–
Sprayed concrete	–	0.2 (thickness)	–	–
Steel pipe beam	219 × 16	5.6 (length)	1.0	1900

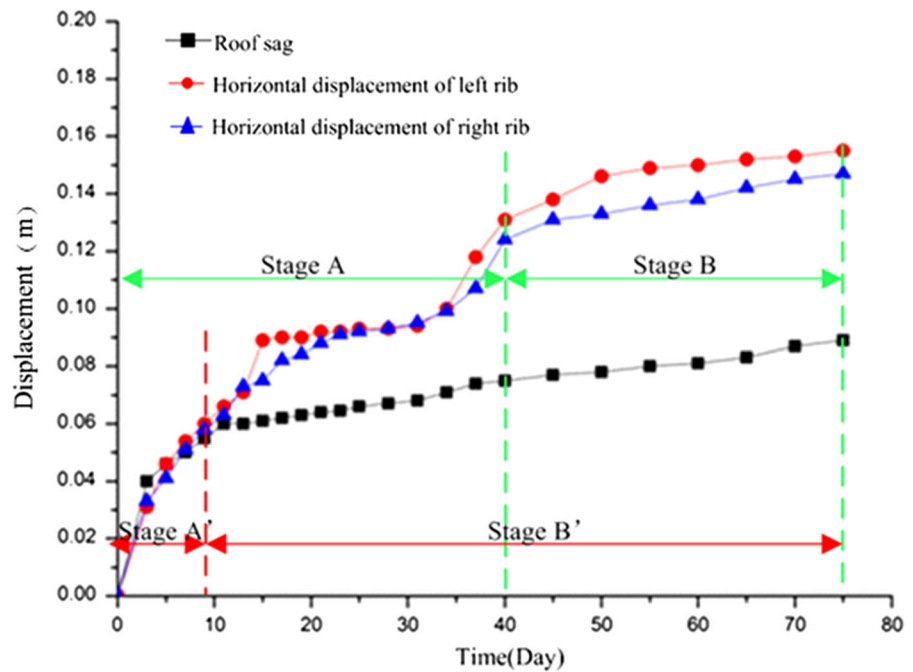
displacements tend to be stable. When the support time is 75 days, rib displacements increase by only 20 mm. A shorter initial stage, Stage A' and a longer steady deformation stage, Stage B' of the roof sag, are encountered. The curve shows that the initial stage

lasts for only 9 days after the installation of the combined support, and the corresponding roof subsidence at this stage is nearly 53 mm. As time goes, the roof sag is nearly 80 mm, which is only 27 mm greater than the value of the former stage, which supporting



**Fig. 6** Construction procedures: **a** installations of fully grouted bolts and nets; **b** installations of steel pipe beams on the floor; **c** locations of monitoring points

**Fig. 7** Typical displacement curves of surrounding rock

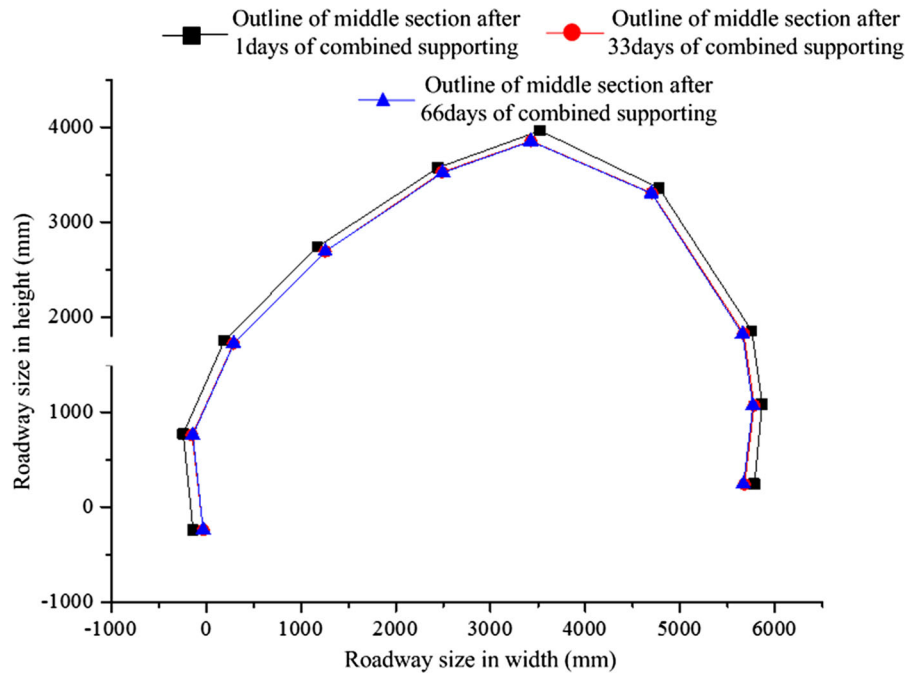


time is 75 days. The difference between Stage A and Stage A' in lasting period may result from the differences of ground stresses in the vertical and horizontal direction.

The corresponding outlines of the middle section with the increase in support time are drawn in Fig. 8. It can be inferred that at the early deformation stage, large deformations of ribs and roof may result from the large roof-sag and rib-convergence rates. However, because of the decreased deformation rates at the later stage, small roadway deformations are caused. With roadway conditions with supporting time of 3 month,

these decreased convergence rates and minor differences in the outlines of cross sections indicate that deformations of ribs and the roof are successfully restrained by the present supporting system. It is interesting to note that the roadway deformation is unsymmetrical when the roadway was perpendicular to the maximum in situ stress. The red investigation point in Fig. 1 illustrate that this unsymmetrical deformation may result from the adjacent chamber excavation on the one side.

**Fig. 8** Outlines of roadway as time after supporting increases



### 3.3.2 Floor Heave

To evaluate the effect of combined supporting system on floor heaves, the distances between the waistline and pipe beam were recorded 1 day and 3 months after the application of the support system. Because of the disturbances from transportations, the values of some pipe beams were unable to obtain and only 13 groups of data were obtained. Figure 9 indicates that the floor heave: the averaged value is 94 mm and it varies from 40 to 215 mm at different roadway sections. Figure 10a depicts the floor heave of roadway which was supported by steel arch, sprayed concrete and short bolts. The maximum floor heave was 1200 mm which was much greater than that of the roadway supported by the combined-support system in Fig. 10b.

Aforementioned results of the effect on roadway deformation indicate that the present combined support system effectively works in the 958 segment in Jin Chuan mine. The period between supporting installation and roadway rehabilitation ranges from 3 to 6 months in the previous supporting system, whereas this period lasts for 10 months in the present support system. However, because of the extremely high ground stresses, some difficulties may arise in roadway rehabilitations. To restrain roadway deformations

more effectively and elongate the period between supporting installations and roadway rehabilitations, more comprehensive investigations should be conducted.

## 4 Numerical Investigations

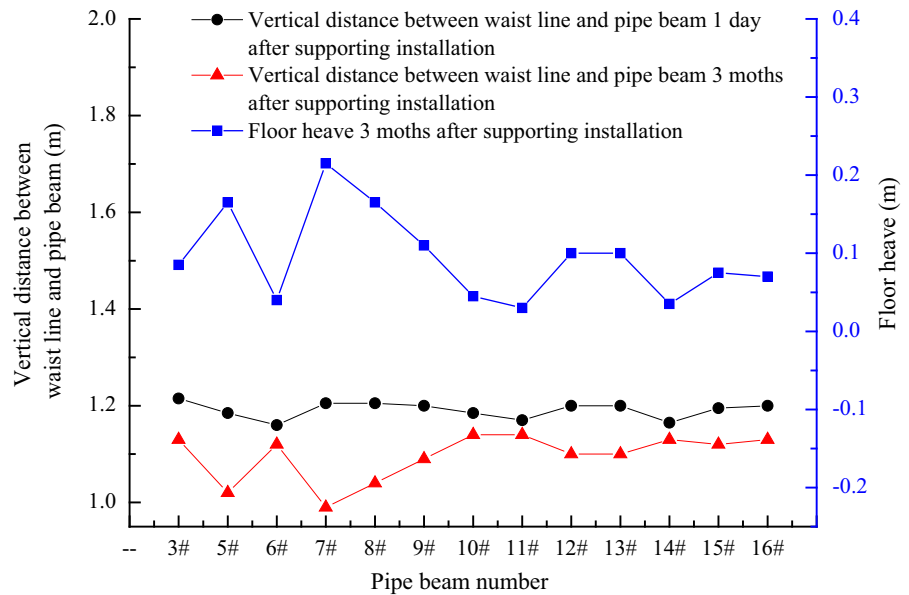
Compared to field tests, numerical investigations, which are more time-saving and economical, have been successfully applied in the roadway deformation analysis (Gao et al. 2015). In the present paper, roadway deformations in old and the proposed combined-support system have been analyzed by using FLAC<sup>3D</sup>. The further investigations on the effects of increasing lengths and densities of bolts and floor bolting on roadway deformations were conducted.

### 4.1 Numerical Analysis on Old and the Proposed New Supporting System

#### 4.1.1 Numerical Model and Model Configurations

The numerical model consisted of 1,108,244 zones is drawn in Fig. 11 with different support systems. This model was 50, 50 and 20 m in length, height and thickness respectively. The distances between the

**Fig. 9** Floor heave 3 months after supporting installation



(a)



(b)



**Fig. 10** Floor heaves of roadways by different supporting system: **a** roadway supported by steel arch, sprayed concrete and short bolts; **b** roadway supported combined supporting system

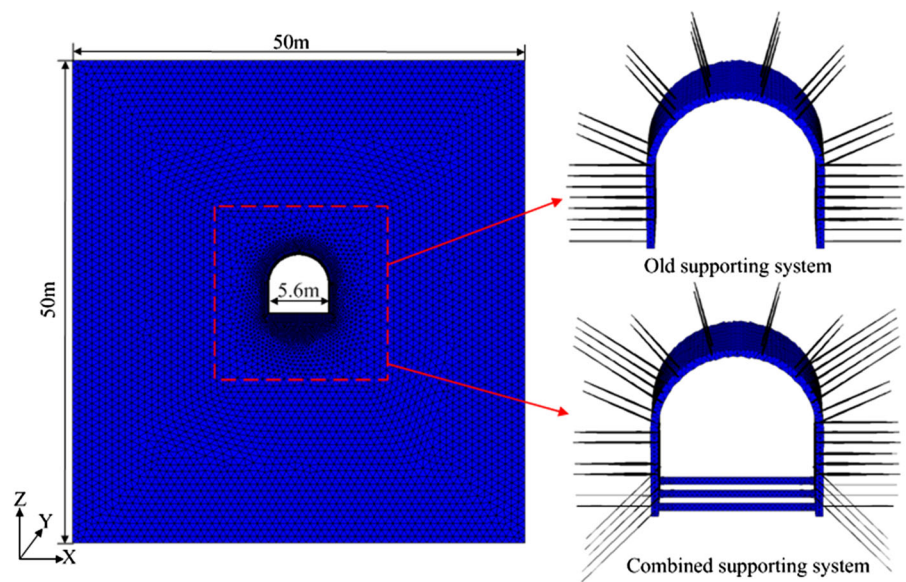
model boundaries and the roadway ribs were 22.7 m which was proven sufficient to eliminate the boundary effects (Kang et al. 2014). The target roadway was located in the rock mass which was thicker than 60 m. Therefore, this model was established in a simulated rock mass with the same mechanical properties. Based on the laboratory tests on specimens from Jin Chuan mine and the scaled reduction on elastic modulus proposed by Shen (2014), the properties of the model where the Mohr–Coulomb failure criterion with a

tension cut-off was applied to are listed in Table 2. According to the field observation on ground stresses, the horizontal in situ stress, which was 44.5 MPa, was applied in the X direction, the other horizontal in situ stress in the Y direction and the vertical stress in the Z direction were 32.9 and 22.2 MPa, respectively.

In the present paper, two kinds of fully grouted bolts are applied in old and the combined-support systems. Based on the suggested calculation methods for the grout cohesive strength and grout stiffness per



**Fig. 11** Numerical model



**Table 2** Mechanical parameters of rock masses

Parameter	Density (kg/m <sup>3</sup> )	Elastic modulus (GPa)	Poisson's ratio	Internal friction angle (°)	Cohesion (MPa)	Tensile strength (MPa)
Value	2750	24.68	0.273	31.3	4.85	1.8

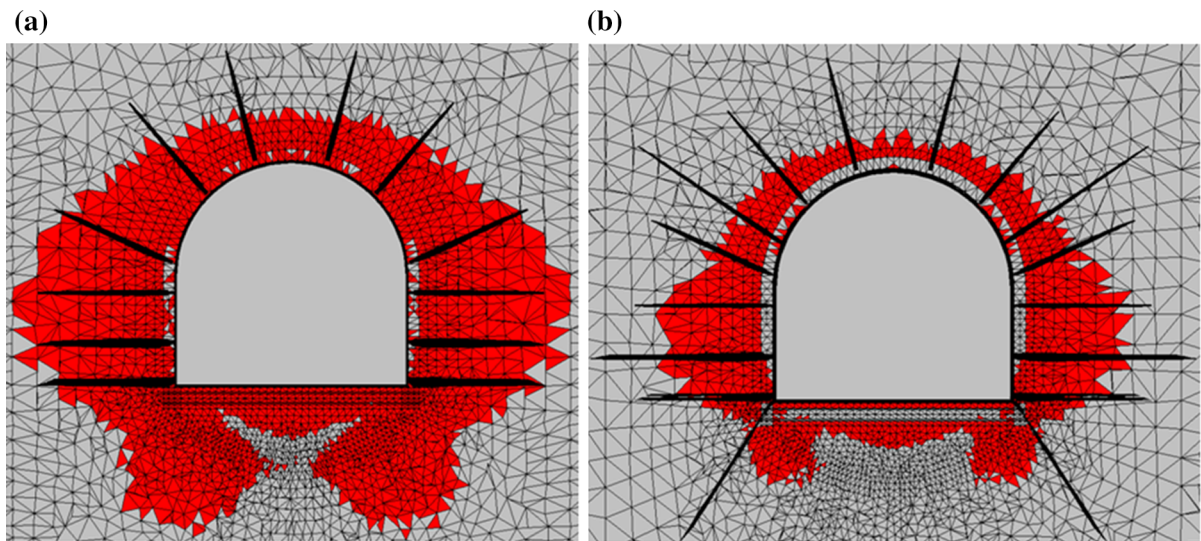
**Table 3** Mechanical parameters of supporting elements

Parameters	Short bolts	Long bolts	Steel pipe beam	Concrete lining
Density	7800 kg/m <sup>3</sup>	7800 kg/m <sup>3</sup>	7800 kg/m <sup>3</sup>	2500 kg/m <sup>3</sup>
Elastic modulus	210 GPa	210 GPa	220 GPa	24.7 GPa
Poisson's ratio	0.28	0.28	0.26	0.18
Internal friction angle	–	–	42°	45.2°
Cohesion	–	–	55 MPa	2.59 MPa
Tensile strength	2e5 N	2e5 N	235 MPa	2.6 MPa
Grout cohesive strength	5.6e5 N/m	5.6e5 N/m	–	–
Grout stiffness per unit length	4.2e9 N/m <sup>2</sup>	4.2e9 N/m <sup>2</sup>	–	–

unit length (Zhang et al. 2015), parameters of the bolts are listed in Table 3. The combination of steel mesh and the sprayed concrete was treated as a concrete lining, and the mechanical parameters were obtained by conducting Schmidt tests on the concrete lining. The tensile strength was treated as 1/10 of the compressive strength. In the supporting system, compressive stresses more likely occur on steel pipe beams. Thus, the Mohr–Coulomb failure criterion was applied to simulate the deformation of a steel pipe beam. Corresponding parameters are listed in Table 3.

#### 4.1.2 Numerical Results and Discussions

The distributions of plastic zones in red and the axial force of bolts in the middle section are shown in Fig. 12. The distribution of the plastic zones indicates that severe rib convergences and the plastic flow at corners are main failures in the old supporting system. The scopes of the plastic zones in ribs and the roof were similar to those of the measured loosen ring in field investigations. However, Fig. 12a demonstrates that most bolts were located in the plastic zones in ribs.



**Fig. 12** Distributions of plastic zones and axial forces of bolts in the middle section: **a** distribution in old supporting system, **b** distribution in new combined-support system

It means that bolts cannot effectively control the horizontal displacements of ribs. Furthermore, the widely distributed plastic zones at the concrete lining indicate that the original support may lose function totally. Thus, the deformation of the roadway cannot be further restrained.

As shown in Fig. 12b, after the installations of pipe beams on the floor, the additions of long bolts at four corners and the elongations of bolts in ribs, the area of plastic zones significantly diminished, especially at the roof and the corners. Similar tendencies of the axial force distribution on bolts were also observed. The internal ends of the bolts were located at the intact surrounding rocks. It indicates that bolts can function effectively, with the great decreases in plastic zone areas at corners. It can be inferred that the deformation of the surrounding rock is satisfactorily controlled.

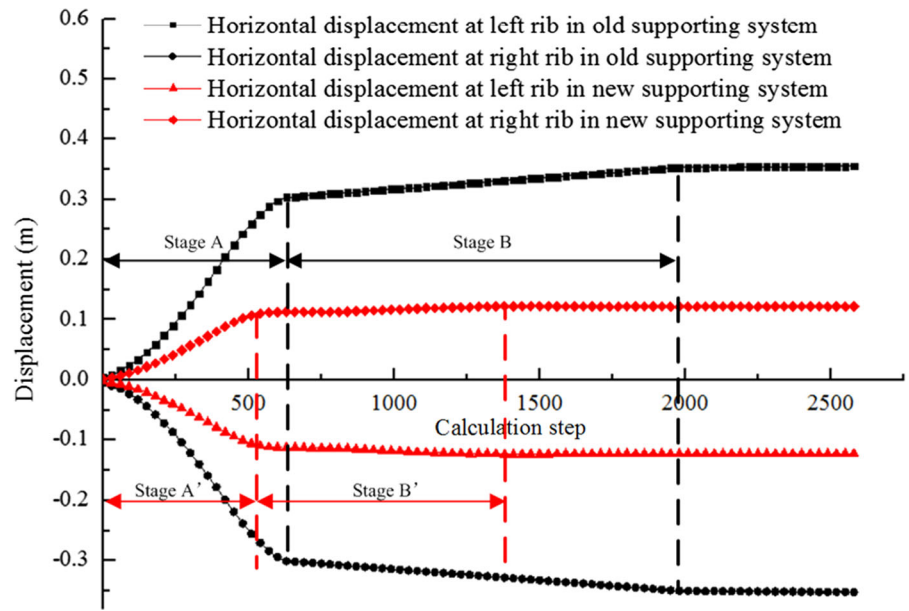
Monitored horizontal displacements at ribs in old and new support systems are drawn in Fig. 13. In the old supporting system, the duration of the initial rib convergence stage, Stage A, lasts for nearly 700 steps, and monitored horizontal displacements of the ribs are higher than 300 mm. At the upcoming steady deformation stage with decreased deformation rate, Stage B, the duration lasts for 1300 steps, at the end of this stage, the displacements increase slightly to 352 mm. In the new supporting system, a similar convergence tendency is observed. However, the convergence decreases by more than 50%, and the duration of

Stage A' and Stage B' lasts for only 1355 steps, these decreases in convergence values and the deformation duration indicate that new supporting system can control the rib convergence more effectively and immediately. The properly functioned short and long bolts may be responsible for these decreases. Furthermore, the horizontal stress of steel pipe beams in Fig. 14 demonstrates that the resistance force exerted by steel pipe beam can also restrain rib convergences. The tensile stress concentrations at the middle parts of pipe beams may partially result from the floor heave.

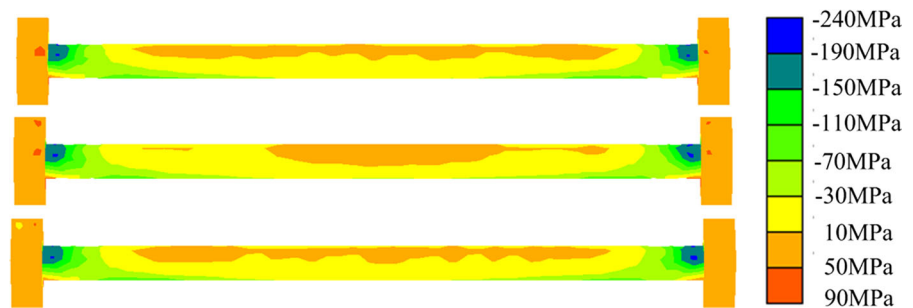
Figure 15 depicts the vertical displacements at middle points of the roof and the floor. In the old support system, the maximum roof sag and floor heave in the roadway section are nearly 300 and 400 mm respectively. While the corresponding values drop to 50 and 172 mm in the new support system. These significant drops indicate that the deformations in the vertical direction are effectively restrained by the added long bolts and steel pipe beams. Similar tendencies of the deformation duration were observed.

Aforementioned numerical investigations show that floor heaves and rib convergences are effectively restrained by the properly functioned bolts at ribs and the resistance forces by steel pipe beams. Figure 12 indicates that the scopes of plastic zones at ribs and the floor significantly diminished by the new supporting system, whereas the area of plastic zones still kept at a relative high value. The target roadway was critical to

**Fig. 13** Rib convergences in old and new supporting systems



**Fig. 14** Horizontal stress on steel pipe beams



the transportation and, thus, to ensure the stability of the surrounding rocks, further investigations on more effective methods for the roadway deformation controlling should be conducted.

4.2 A Numerical Analysis on the Effects of an Increased Bolt Density at Ribs and Added Floor Bolting on Support Effects

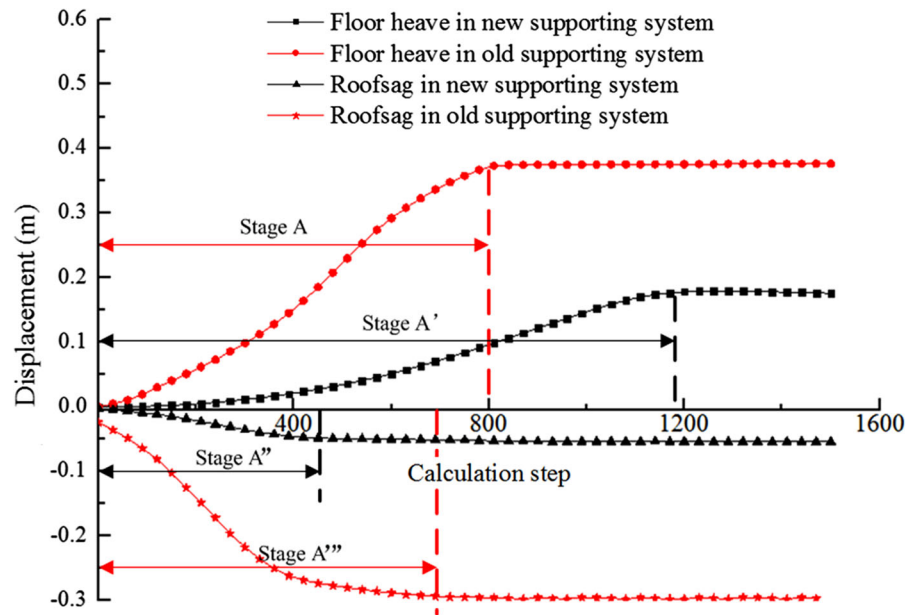
Referring to previous studies on controlling the plastic zones in roadway sections (Kang et al. 2014; Zhang et al. 2015), two support systems, which were characterized by an increased bolting density at ribs and floor bolting respectively, were proposed. Specifications of these support systems are listed in Table 4.

4.2.1 Effects of Increased Bolts at Ribs

Distributions of plastic zones in the roadway section, of which the ribs were reinforced by increasing bolts, are depicted in Fig. 16a. Figure 16a shows that for the increased bolts at ribs, the distribution area of plastic zones at ribs further diminished. Especially, the plastic zones near the concrete arch lining diminished greatly. The internal ends of the bolts exceeded the area of the plastic zones of surrounding rocks. And decreased failure zones of the concrete supporting element at ribs were also observed.

Because of the reinforcement of the ribs, Fig. 16a indicates that the plastic zones on the floor decreased. Accordingly, the floor heave when the ribs were reinforced has also been significantly restrained. This

**Fig. 15** Vertical displacements at middle points of the roof and floor



**Table 4** Specifications of proposed support systems

	Diameter (mm)	Size (m)	Spacing (m)	Diameter (mm)	Size (m)	Spacing (m)	
<i>The support system characterized by an increased bolting density at ribs</i>				<i>The support system characterized by floor bolting</i>			
Short bolt	25	2.25 (length)	0.4	Short bolt	25	2.25 (length)	
Long bolt	25	3.5 (length)	0.4	Long bolt	25	3.5 (length)	
Steel net	6.5	0.15 × 0.15 (mesh size)	–	Steel net	6.5	0.15 × 0.15 (mesh size)	
Sprayed concrete	–	0.2 (thickness)	–	Sprayed concrete	–	0.2 (thickness)	
Bolts on floor	–	–	–	Bolts on the floor	25	2.25 (length)	
Steel pipe beam	219 × 16	5.6 (length)	1.0	Steel pipe beam	219 × 16	5.6 (length)	

tendency has been proven to be reasonable in previous investigations (He et al. 2009).

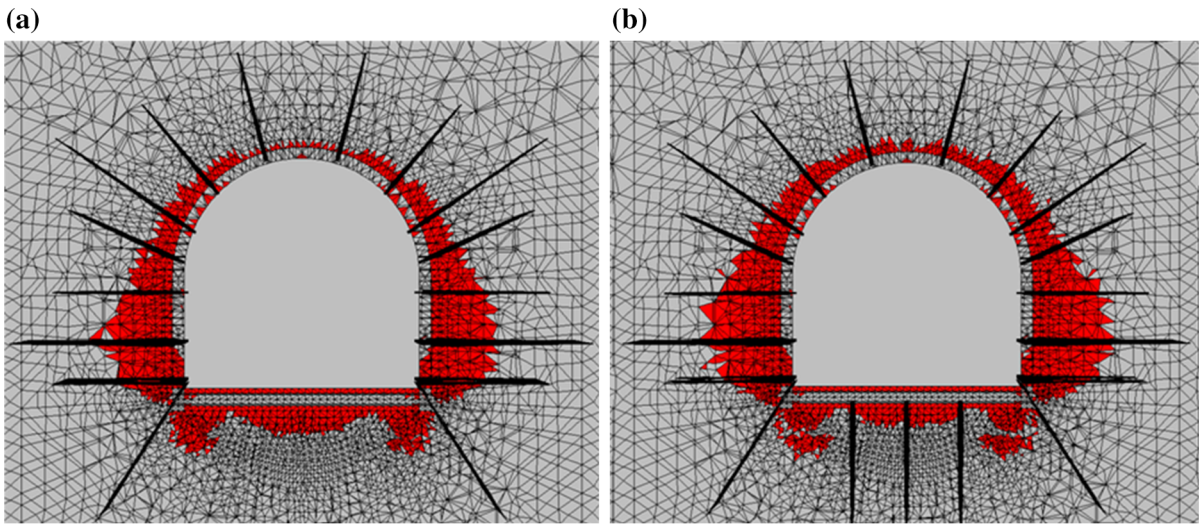
The corresponding maximum rib convergences and floor heaves in these supporting systems are drawn in Fig. 17. It shows that the reinforcement of ribs by increasing rock bolts is a feasible method for controlling rib failures and floor heaves.

4.2.2 Effects of Floor Bolts at Ribs

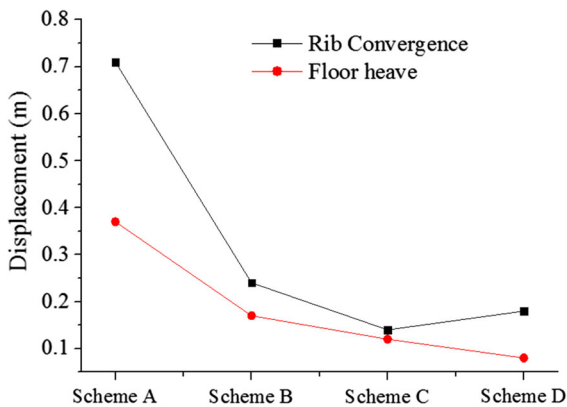
Compared with Fig. 16a, b indicates that plastic zones near the concrete lining were increased in some extent because of the decreased bolting density at ribs and the

arch. However, Fig. 16b shows that the internal ends of the bolts were located in intact surrounding rocks, it can be inferred that surrounding rocks near ribs and the arch are stable. And the distribution of plastic zones is restricted in an acceptable degree. With the help from the floor bolts, Fig. 16b demonstrates that the development of plastic zones on the floor and the corners is further restrained. Comparing Fig. 16b with Fig. 14b, this improved floor stability may contribute to the restraint on the distribution of plastic zones near ribs and the arch.

The displacements of the rib convergence and the floor heave also show that rib convergence increases



**Fig. 16** Distributions of plastic zones: **a** distributions of plastic zones in the support system characterized by increased bolts; **b** distributions of plastic zones in the support system characterized by floor bolting



**Fig. 17** Rib convergences and floor heaves in four supporting systems: *Scheme A* is the old supporting system; *Scheme B* is the new supporting system; *Scheme C* and *Scheme D* are the supporting systems characterized by increased bolts at ribs and the floor bolts respectively

because of the decreased bolting density at ribs and the arch, whereas the decreased floor heave is resulted from the floor reinforcement by the floor bolting. This analysis indicates that the installation of bolts at the floor is another effective method for restraining roadway deformations.

### 5 Conclusions

Field investigations shows that poorly functioned bolts in the old supporting system may be responsible for

the large roadway deformation as well as failure. To restrain the roadway deformation, a new supporting system characterized by installing steel pipes beams at floor and increasing the bolting length at some parts of ribs and the arch was proposed. The field investigation on this new supporting system indicates that the roadway deformation is successfully controlled. Corresponding numerical investigations show that this restraint by the new supporting system results from the improved function of short and long bolts and the supporting effects of steel pipe beams on the floor.

To further restrain the roadway deformation, two additional supporting systems characterized by increasing bolting densities and additional floor bolts were simulated. Simulation results of the former support system indicate that the reinforcements at ribs may contribute to the control of floor heaves. Whereas in the later supporting system, the floor heave is restrained by the installed floor bolts. This reinforcement of floor also contributes to the reinforcement of surrounding rocks near the concrete lining.

**Acknowledgements** The authors would like to acknowledge these financial supports: the State Key Research Development Program of China (2016YFC0600706); the National Basic Research Program of China (2013CB035401); Projects (51604299, 51274249, 51474252) supported by the National Natural Science Foundation of China; Project funded by China Postdoctoral Science Foundation (2016M600636) and Project (14C0746) supported by Water Resources Department of Hunan Province.

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