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Failure Mechanism of Bolts and Countermeasures in Swelling Soft Rock Support

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Abstract: The effect of conventional bolt support is not ideal due to the large deformation character of soft rock. As an innovative bolt, constant resistance large deformation (CRLD) bolt has been successfully applied to swelling soft rock engineering, but the reinforcement mechanism is not yet clear. To investigate the interaction mechanism between bolt and surrounding rock, Nanshan Coal Mine of China was selected as the engineering background. The plastic zone of surrounding rock mass and the axial force of three bolts were obtained by theoretical analysis and FLAC3D numerical simulation. Failure processes of conventional pretension bolts in soft rock were reproduced, and the interaction between CRLD bolt and soft rock was investigated in comparison. The results indicate that: (1) The fracture zone of surrounding rock exceeds the anchorage range of the low pretension bolt, the bolt slides with surrounding rock and finally fails. (2) The fracture zone of surrounding rock does not exceed the anchorage range of the high pretension bolt. However, with the accumulation of deformation energy, stress concentration makes the bolt break. (3) CRLD bolt can effectively absorb the deformation energy released by soft rock and maintain constant support resistance. The conclusions obtained in this study provide significant references in the selection of bolts in soft rock engineering.

Keywords: constant resistance large deformation (CRLD) bolt; failure mechanisms; pretension bolt; swelling soft rock

1 INTRODUCTION

As roadway is the necessary passage for underground coal mining, a smooth and stable roadway is a guarantee for safe and efficient mining. Bolt has been widely used in roadway support, the allowable deformation of surrounding rock supported by conventional bolts is generally up to 200 mm [1, 2]. However, more swelling soft rock roadways appear with the increase of mining depth. The mechanics and physicochemical condition of roadway surrounding rock are changed in the soft rock, the sliding and breaking of conventional pretension bolts in surrounding rock bring a dilemma to the control of soft rock roadway [3, 4]. Though the conventional pretension bolt can provide certain support resistance to surrounding rock, the deformation capacity is insufficient to adapt the expansion of soft rock [5-7]. Thus, the deformation capacity of bolt should be considered in soft rock engineering.

To improve the stability of a roadway, various types of innovative bolts have been invented in decades. Jager [8] developed the first type of energy absorbing bolt called Conebolt in 1992, but it appeared non-constant resistance. Ansell [9] developed a non-bushing absorbent rock bolt, the average working stress and maximum deformation reached 300 MPa and 240 mm, respectively. In 2007, Charette and Plouffe [10] developed a Roofex bolt suitable for soft rock roadway support, which showed the character of constant resistance and the average deformation reached 300 mm. Li [11] developed a D-type bolt with the performance of energy absorption in 2010, the maximum deformation amount is about 60 mm in the static tensile test. Nevertheless, the bolts have not been widely applied in soft rock practice. The main reason is that the bolts cannot meet the requirements of high support resistance and large tensile deformation in swelling soft rock engineering.

As stiffness of bolt material cannot fully adapt to the large deformation, especially in the strong swelling soft rock roadway, a new type of bolt with innovative structure design, known as the constant resistance large deformation (CRLD) bolt, has been developed by M. C. He [12]. It is characterized with high constant resistance and excellent deformability, and the cumulative deformation can reach 1000 mm during the swelling process of surrounding rock.

Although the CRLD bolt has been applied in swelling soft rock engineering successfully [13-18], the interaction mechanism between the CRLD bolt and soft rock is not yet clear. The failure mechanism of the conventional pretension bolt in soft rock roadway and the detailed working principle of the CRLD bolt need further research.

2 STATE OF THE ART

Plenty of studies have been done on the failure mechanism of bolt in surrounding rock. In view of the mechanism of bolt support, Indraratna et al. [19] investigated the fracture mechanism of surrounding rock in a tunnel supported by bolts through physical model tests. The results revealed that grouted bolts can control the failure modes of the tunnel in jointed rock, and the employment of high bolt density can improve the stability of surrounding rock. Based on the numerical simulation of UDEC, Kanget al. [20] researched the mechanism of bolts within soft rock, and presented that a competent rock bolt system can suppress the propagation of tensile cracking and shear cracking within the anchored zone. High bolt density and pretension force were employed as the improvement measure. Jiang et al. [21] studied the failure mechanism of a deep soft rock roadway in China. He pointed out that the alternately occurring of fracture zone and crack zone in surrounding rock is one of the internal causes for the instability of the roadway, and a new design with detailed parameters was proposed. Based on the soft rock roadway with high stress in a deep coal mine, Li et al. [22] concluded that the frequent failures of bolt support are closely related to the lower bond strength. The anchoring force of bolt on surrounding rocks can be improved with the increase of bond strength. A new hollow grouting combined bolt with high strength was developed, which can achieve the purpose of grouting reinforcement. Wang et al. [23] detected the destructive range of surrounding rock and monitored the stress of anchor bolt in Juye coalfield. The monitoring results showed that the cracks are extremely developed in severe damage zone, the bolt stress experienced a hump-like course and finally failed. The study revealed that the high-strength and high-rigidity support are necessary for the control of surrounding rock, and a support system of square steel confined concrete was proposed. Fenget al. [24] investigated the failure mechanism of bolt system with the aid of acoustic emission. From the analysis of AE energy and location, the results revealed that different loading stages of bonding types exhibit different energy emission characteristics. The research indicated that the final failure of bolt system mainly due to the elongation of bolt and the decoupling of interface, and the embedded cement annulus combined with resin annulus can reduce the amount of damage locations. Zhenget al. [25] investigated the serial decoupling mechanism of bolt at the interface of resin–rock by theoretical analysis, the study indicated that the stress state along the interface is different during the decoupling of interface and corresponding equations have been derived.

The above researches have made great contribution on the development of bolt support technology. The scholars analysed the relationship between bolt and surrounding rock under different conditions, and corresponding improvement measures were proposed. However, the effect of the soft rock on bolt failure is seldom studied, and the above measures are not suitable for the soft rock roadway with strong swelling character. The large deformation of soft rock roadway seriously threatens the safe and efficient production of a coal mine. Thus, an appropriate improvement measure of the bolt is of great significance to the control of soft rock roadway.

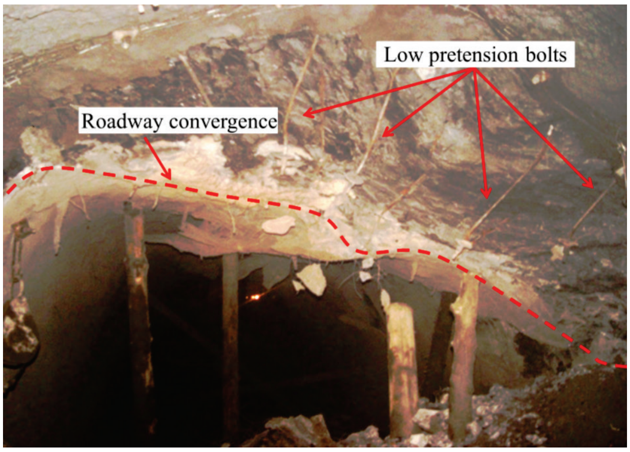
In order to investigate the mechanism of action between the CRLD bolt and the swelling soft rock, it is necessary to make a comparative study on the failure mechanism of conventional pretension bolts. In this paper, the characteristics of swelling soft rock and the key for control were analysed. FLAC3D was used to get the distribution of plastic zone and the deformation of surrounding rock that was supported by the conventional pretension bolts and the CRLD bolt, which was conducted to evaluate the stability of the soft rock roadway under different bolts support. Detailed failure processes of the low pretension bolt and the high pretension bolt within swelling soft rock roadway were reproduced. The mechanism of swelling soft rock strengthened by the CRLD bolts was also expounded. The research findings provide a significant reference for soft rock roadway support design.

The remainder of this research is organized as follows. In Section 3, the comprehensive research methods, such as the engineering background, theoretical analysis, and numerical model are introduced. In Section 4, simulation results are analysed and discussed. Conclusions are given in Section 5.

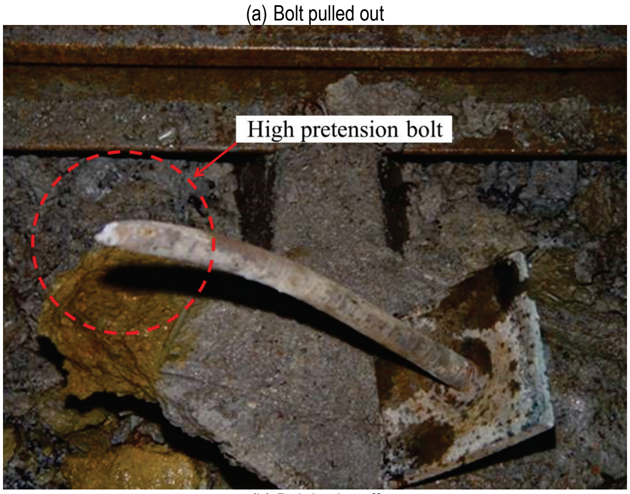
3 METHODOLOGY

3.1 Engineering Background

To investigate the failure mechanism of the bolt in soft rock engineering, a soft rock roadway in Nanshan Coal Mine, China, was selected as the engineering background. The geological structure of the roadway is complex, and the geostress is large. The surrounding rock is grey sandstone with large amounts of clay minerals such as illite and smectite, which belongs to swelling soft rock and features strong water absorption and expansion. The roadway cross-section consists of a semi-circular arch and two vertical ribs, the rib height and the arch radius are 2000 mm and 1880 mm, respectively. The surrounding rock has been repaired many times but finally failed. A lot of money and time are wasted. The conventional pretension bolts, including the low pretension and high pretension bolts, both failed in the swelling soft rock support of Nanshan Coal Mine. Fig. 1(a) shows that the low pretension bolts were pulled out, and the high pretension bolt in Fig. 1(b) was broken.



(a) Bolt pulled out



(b) Bolt broke off

Figure 1 Failure of bolts in Nanshan Coal Mine

In addition to the engineering geological conditions, the soft rock roadway of Nanshan Coal Mine mainly faces the following problems:

(1) The geostress is large. The geological structure in the eastern part of Nanshan Coal Mine is extremely complex, with a large number of faults and great geostress. The geostress is an important factor for roadway stability, and the requirement on supporting material is higher.

(2) The strength of surrounding rock is low. The strength of gray sandstone is 40-50 MPa and the surrounding rock is broken because of the numerous faults. The clay minerals in the rock mass have extremely strong water imbibition, and the softening coefficient is 0.8 when water was absorbed. The low strength of surrounding rock is extremely unfavorable for roadway stability, and the low pretension bolt cannot improve the strength of surrounding rock.

(3) The deformation energy that the surrounding rock releases is large. Coal was subjected to a multi-period geological tectonic stress field, and the rock formation

stores the deformation energy at elastic deformation. With the excavation of roadway, the deformation energy can be released into the roadway in the form of expansion and deformation. Although the high pretension bolts inhibit certain energy at the early stage of surrounding rock deformation, the ability to withstand the deformation is limited. With the release of deformation energy in soft rock, the bolts were finally broken as the shear stress goes beyond its design.

The state of surrounding rock has great influence on the supporting effect of the pretension bolt. Li investigated the bond strength on the interface between the bolt anchorage zone and the surrounding rocks, which can be written as [22]

$$\tau_{\mathrm{m}} = c + (\sigma_v + \sigma_q)\tan\varphi \tag{1}$$

where c is the corresponding cohesion of surrounding rock. φ is internal friction angle of surrounding rock. σ_v and σ_q are the interface dilatancy stress and the surrounding rock compressive stress on the interface by, respectively. σ_v and σ_q can be expressed by [26]

$$\sigma_v = \frac{E}{(1+\upsilon)a} v_{\mathrm{m}} \tag{2}$$

$$\sigma_q = \frac{2b^2(1-\upsilon)}{b^2 + a^2(1-2\upsilon)} q \tag{3}$$

where E is the elastic modulus of the surrounding rock. υ is the Poisson ratio. a and b are the borehole radius and the influence radius of the anchorage body, respectively. v_{m} is the maximum dilatancy displacement that formed on the anchorage interface, which can be written as [27]

$$v_{\mathrm{m}} = u_{\mathrm{m}} \tan\phi_{\mathrm{m}} \tag{4}$$

where ϕ_{m} is the maximum interface dilatancy angle. u_{m} is the corresponding interface shear displacement.

From Eqs. (1) to (4), the bond strength on the interface between the bolt anchorage zone and the surrounding rocks can be finally written as

$$\tau_{\mathrm{m}} = c + \left(\frac{E}{(1+\upsilon)a} u_{\mathrm{m}} \tan\phi_{\mathrm{m}} + \frac{2b^2(1-\upsilon)}{b^2 + a^2(1-2\upsilon)} q \right) \tan\varphi \tag{5}$$

Eq. (5) represents that the bolt starts to fail when the tensile force imposed on the bolt exceeds the value. The value has a positive correlation with the interface dilation angle, internal friction angle. Thus, considering the complex geological condition of the mine, the bolt easily fails in the swelling soft rock compared to the well integrated surrounding rock.

3.2 Key to Soft Rock Support

The stress state of surrounding rock changes with roadway excavation. Bolt strengthens the surrounding rock and controls the deformation mainly in the following three aspects:

(1) Increasing the strength of surrounding rock. Bolt improves the mechanical properties of surrounding rock by improving the cohesion value and the internal friction angle, and mainly improves the strength after it yields. Thus, the deformation of surrounding rock can be limited.

(2) Strengthening junction between structural planes. As bolt through its axial and tangential forces prevents the sliding of structural planes, the contact between the structural planes enhances [28]. The strength and integrity of the joint rock mass enhance simultaneously.

(3) Improving the stress state of surrounding rock. The pretension bolt exerts certain compressive stress on surrounding rock so that the rock returns to the three-dimensional press state from the two-dimensional press state after the excavation. In the tensile zone, the compressive stress provided by a bolt can offset part of the tensile stress. In the shear zone, the shear resistance of surrounding rock can be improved by the friction force generated by compressive stress.

Different supporting materials must be considered for different conditions of surrounding rock in soft swelling rock engineering. Only the targeted use of supporting materials can realize the coupling of surrounding rock-support in stiffness, strength, and structure. However, neither the low pretension nor the high pretension bolts presented an ideal effect. In the swelling soft rock roadway, bolts that can withstand large deformation of surrounding rock and maintain constant resistance are needed.

3.3 Countermeasures

Fig. 2 shows the structure of the CRLD bolt. The CRLD bolt consists of the shank of bolt, constant resistance unit, pallet, and nut.The constant resistance unit includes constant resistance sleeve and a cone, which is sleeved on the tail part of the shank. Both the inner surface of the sleeve and the outer surface of the shank have thread structures, which increase the friction force while reducing their weight. The cone would be broken easily if its strength were less than the sleeve's strength, thus the bolt would fail, which would dramatically reduce the constant resistance performance of the CRLD bolt. In the current design, the material strength of the constant resistance sleeve is less than that of the cone. Due to this unique design, the cone is unbroken when it slides in the sleeve.

The relationship between elongation and load of the rebar bolt can be divided into two stages, i.e. elastic deformation stage and stick-slipping motion stage. The resistance of the CRLD bolt was given as [29]

$$P_0 = 2\pi f I_{\mathrm{s}} I_{\mathrm{c}} \tag{6}$$

where P_0 is the overall resistance. I_{s} is the elastic constant of sleeve. I_{c} is the geometrical constant of cone. f is the frictional coefficient. I_{s} and I_{c} are given respectively by the following formula

$$I_{\mathrm{s}} = \frac{E(b^2 - a^2)\tan\alpha}{a\left[a^2 + b^2 - \upsilon(b^2 - a^2)\right]} \tag{7}$$

$$I_{\mathrm{c}} = \frac{ah^2}{2}\cos\alpha + \frac{h^2}{3}\sin\alpha \tag{8}$$

where a and b are the inner radius and outer radius of the sleeve, respectively. α and h are the angle and height of cone, respectively. E is the elastic modulus, and υ is the Poisson's ratio.

Finally, the constitutive relation of the CRLD bolt can be expressed by

$$P=\begin{cases} kx, 0\le x\le x_0, P<P_{\max} & \text{(elastic deformation)} \\ P_{\max}-P_{\min}=k\Delta x, x>x_0 & \text{(stick-slipping motion)} \end{cases} \quad (9)$$

where P is the tensile load. x is the elongation length; k is the stiffness of the bolt shank. x_0 is the maximum elongation length of the bolt before the stick-slipping motion. $P_{\max}$ is the working resistance of CRLD bolt when the bolt is at rest. $P_{\min}$ is the working resistance of the CRLD bolt at the cycled elongation stage. Δx is the elongation length at the slipping stage.

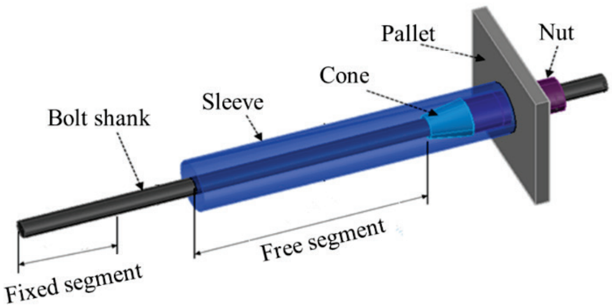


Figure 2 Structure of the CRLD bolt

The constitutive relation illustrates the characteristic of no yield strength of the CRLD bolt. Due to the specific structure, the CRLD bolt can maintain constant working resistance and stable deformation when surrounding rock deforms slowly or abruptly. The working principle of the CRLD bolt will be expounded in detail in section 4.5.

3.4 Building Computational Model

The -120 total return airway of Nanshan Coal Mine was selected as the engineering geological background. Based on model sensitivity analysis with regard to size and mesh density, the dimensions of the model were determined as 30 × 30 × 30 m (Fig. 3). The cross-section of the roadway consists of two vertical ribs and a semicircular arch, the rib height and arch radius are set as 2000 mm. The model is divided into 20,480 units and 41,055 nodes. The four vertical planes of the model limit horizontal motion, and the bottom is fixed. At the top model boundary, a vertical stress of 16 MPa was applied to simulate the gravity stress. The bolt length is 2.5 m, and the inter row space is 0.8 × 0.8 m. To make the simulation accurate, a servo-controlled testing system (MTS815) was conducted to get the mechanical parameters of the rock mass. The coal and rock samples collected from the -120 total return airway were tested in laboratory. Tab. 1 shows the mechanical parameters of the engineering rock mass.

Table 1 Mechanical parameters of the engineering rock mass

Rock strata	Density (kg/m^3)	Bulk modulus (GPa)	Shear modulus (GPa)	Tensile strength (MPa)	Cohesion (MPa)	Friction angle (°)
Conglomerate	2580	2.67	1.23	1.85	2.35	34
Coal	1350	0.78	0.71	0.35	0.6	21
Medium-grain sandstone	2360	2.35	1.21	1.4	2.1	29
Pack sand	2230	1.93	1.16	1.1	1.85	32
Fine sand	1560	1	0.5	0.5	0.9	19

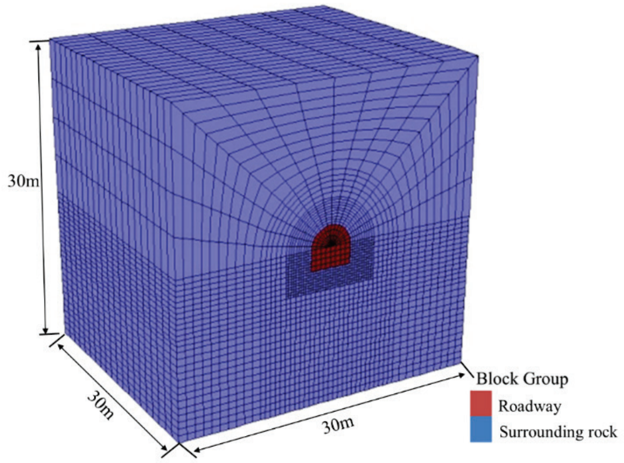


Figure 3 Schematic diagram of the global model

4 RESULTS AND DISCUSSION

The calculation results were saved every 100 time steps, and the distribution of plastic zone with different time-lapse was used to reveal the development of the surrounding rock state and the bolt failure process. According to the theory of elasto-plastic mechanics, the stress state of surrounding rock contains elastic state, elastic-plastic state, and plastic state. The plastic zone expands to the deep part of surrounding rock with the increase of time step. The plastic zone expands to the deep part of surrounding rock with the increase of time steps, and the surface displacement of the roadway increases continuously in the mean time.

4.1 Simulation of Low Pretension Bolt Support

The pretension force of the low pretension bolt was set as 50 kN. The development of the plastic zone in surrounding rock is shown in Fig. 4. At the early stage of the roadway deformation, the bolt had a certain restraining effect on the shallow surrounding rock, and the plastic zone developed slowly. The range of plastic zone extended to 1.5 m after 300 time steps, which is the boundary between free section and anchorage section of the bolt. The inhibition effect of the bolt on surrounding rock was weakened with the further development of plastic zone. The depth of plastic zone reached 2.5 m at 800 time steps, the low pretension bolt lost its anchorage ability and moved together with surrounding rock. Subsequently, under the action of gravity and tectonic stress, the plastic zone developed rapidly, the deformation of the roadway continued increasing. It can be concluded that the roadway finally reached unstable state as the area of plastic zone appeared certainly large.

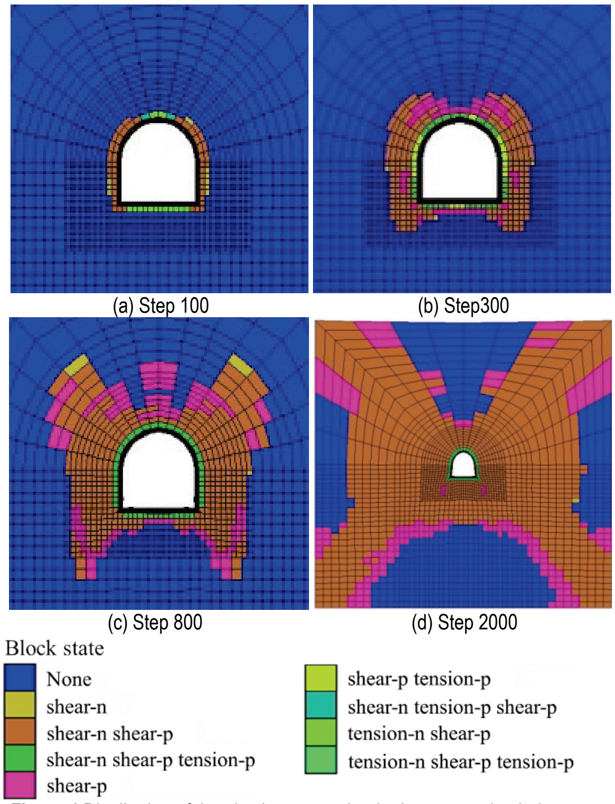


Figure 4 Distribution of the plastic zone under the low pretension bolt support

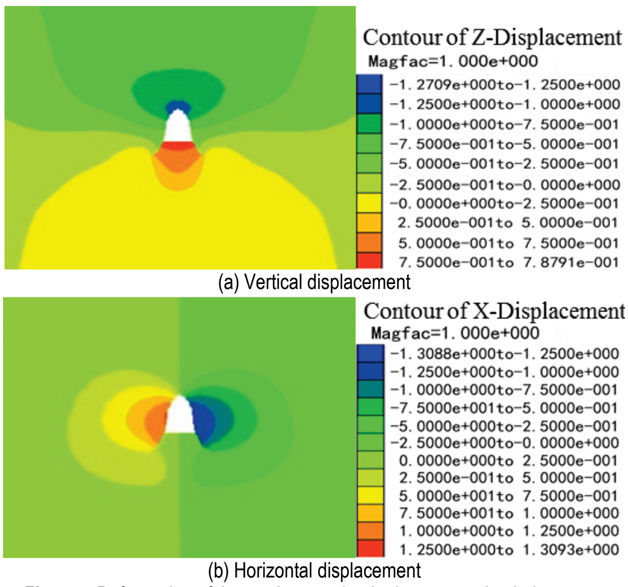


Figure 5 Deformation of the roadway under the low pretension bolt support

The deformation and destruction of the roadway supported by the low pretension bolts developed rapidly after the failure of the bolt. Finally, the maximum deformation amount between the roadway roof and floor was up to 2060 mm, and the roadway-rib reached to the maximum of 2620 mm (Fig. 5). The large deformations in the vertical and horizontal direction verified the failure of the support system.

4.2 Simulation of High Pretension Bolt Support

The strength and pretension force of the bolt gradually increase with the development of technology, the high pretension bolt has been applied in the support of soft rock roadways. The pretension force was set as 100 kN in this condition, and the other support parameters were the same as those of the low pretension bolt simulation. Fig. 6 shows the distribution of plastic zone in the surrounding rock under the support of the high pretension bolt.

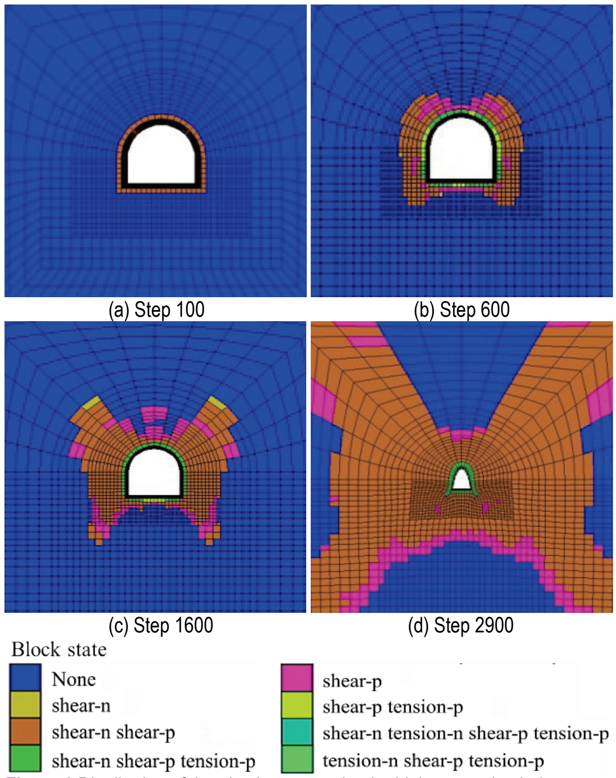


Figure 6 Distribution of the plastic zone under the high pretension bolt support

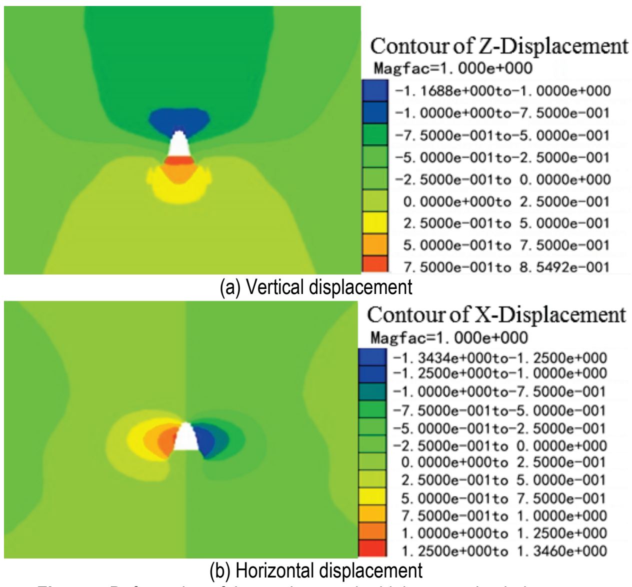


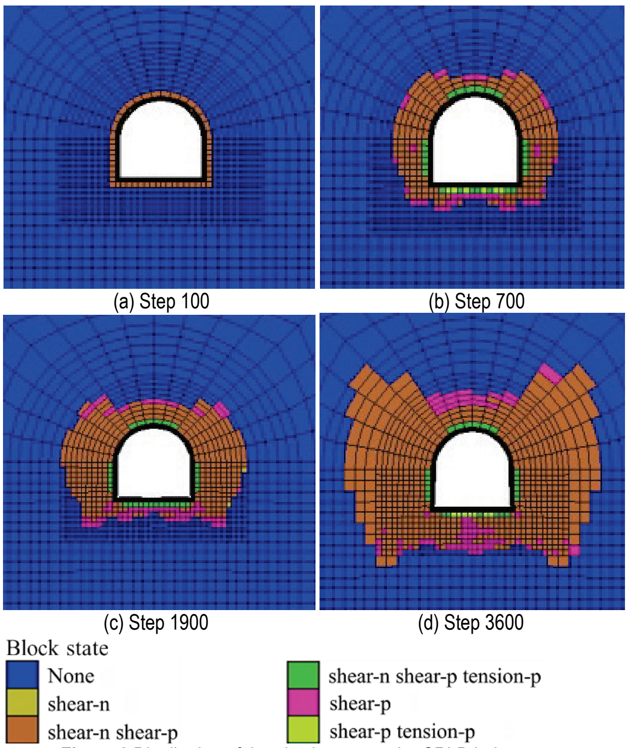
Figure 7 Deformation of the roadway under high pretension bolt support

At the early stage of the roadway deformation, the bolt had the inhibition effect on the deformation of the shallow surrounding rock, and the plastic zone developed slowly. The plastic zone range reached 1.5 m at 600 time steps, which is the boundary of the free section and anchorage section of the bolt. With the continuous development of the plastic zone, the roadway continued deforming. As the deformation energy of surrounding rock accumulated in the bolt, the bolt inhibition to surrounding rock deformation was further weakened. The plastic zone expanded to 2.5 m at 1600 time steps, and the software stopped calculation at 2900 time steps. The large area of the plastic zone indicated that the roadway was finally damaged.

The displacement results of the simulation (Fig. 7) show that the maximum deformation between the roof and floor of the roadway was up to 2020 mm, and the roadway-rib moved up to a maximum of 2690 mm. Both the vertical and horizontal deformations of the roadway are obvious.

4.3 Simulation of CRLD Bolt Support

According to the design, the constant resistance of the CRLD bolt is 200 kN and the pretension force was set as 160 kN. The plastic zone distribution and the displacement of surrounding rock were obtained by simulation.



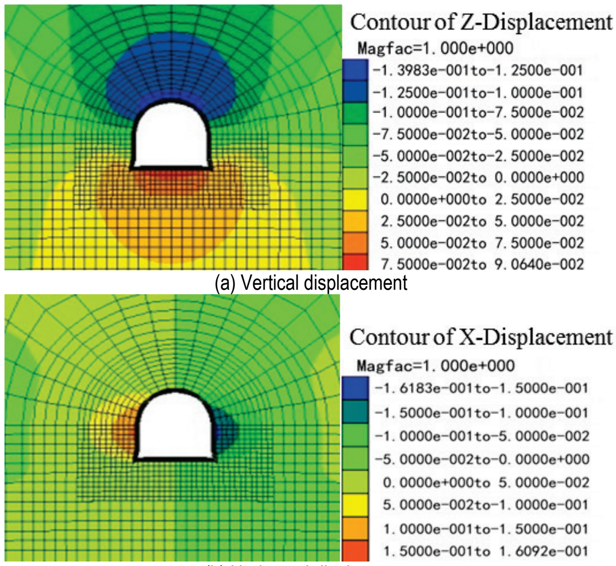
(a) Step 100 (b) Step 700

(c) Step 1900 (d) Step 3600

Figure 8 Distribution of the plastic zone under CRLD bolt support

The simulation results in Fig. 8 show that the area of the plastic zone only reached 200 m^2 at 3600 time steps, which is less than that of the bolts mentioned above. Due to the large deformation capacity of the CRLD bolt, the development of the plastic zone did not exceed control range of the bolt. Thus, the bolt anchoring force remained and the failure of the bolt was avoided.

When the roadway was finally stable, the displacement amount of roof-to-floor and rib-to-rib was 230 mm and 322 mm, respectively (Fig. 9).The roadway convergence was far less than that of the surrounding rock supported by the conventional pretension bolt.



(a) Vertical displacement

(b) Horizontal displacement

Figure 9 Deformation of the roadway under CRLD bolt support

4.4 Comparison of the Bolts

The axial force variation curves of the three bolts are shown in Fig. 10. It can be seen that the axial force of the low pretension bolt is less than that of the other two bolts, and the effect on the surrounding rock is limited. Due to an accumulation of deformation energy of surrounding rock, the axial force of high pretension bolt increased instantaneously. The axial force of high pretension bolt exceeded that of the CRLD bolt in the 1400-1800 time steps. However, the high pretension force decreases rapidly later, the reason is that high pretension bolt was broken with the continuous accumulation of deformation energy. On the contrary, the axial force of the CRLD bolt maintains a constant value after the initial increase, which verifies the characteristic of constant resistance that CRLD bolt acts on surrounding rock.

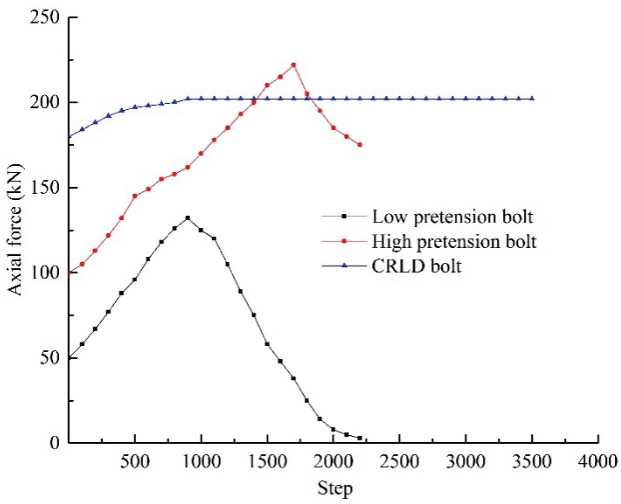


Figure 10 Monitoring curves of the axial force for different bolts

The variation curves of the plastic area supported by the three bolts are shown in Fig. 11. The following results can be obtained: (1) The ultimate area of the plastic zone ranges as follows: low pretension bolt > high pretension bolt > CRLD bolt. (2) Due to the failure of the conventional pretension bolts in the later stage of support, the development of the plastic zone area in surrounding rock has obvious acceleration period under the support of the low pretension and high pretension bolts. The failure of the pretension bolt accelerates the instability of the roadway. (3) The development curve of plastic zone under the support of the CRLD bolt is relatively gentle and finally tends to be stable, and the area is the smallest. The excellent effect of CRLD bolt in soft rock support is verified from the analysis of the plastic zone area.

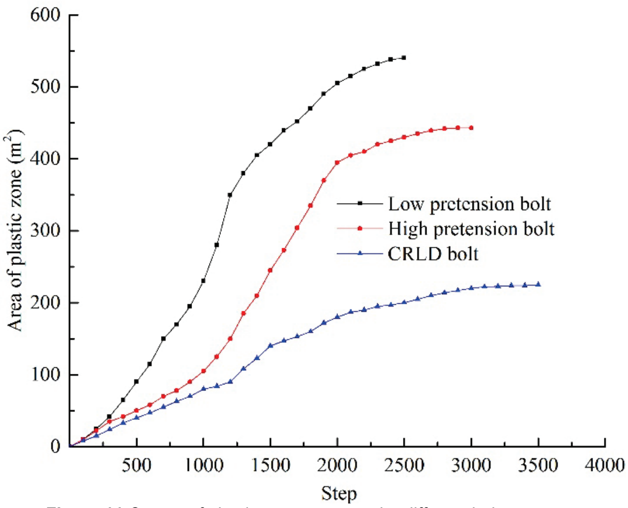


Figure 11 Curves of plastic zone areas under different bolts support

In summary, under the conditions of the conventional pretension bolt support, the surrounding rock deformation has different failure modes. Both of the two bolts failed in the control of soft rock roadway. The low pretension bolt has low restraint capacity to the surrounding rock. The fracture zone of surrounding rock expands outside the anchorage range of the low pretension bolt, causing the bolt slides with surrounding rock and the failure of support system. To prevent the deformation of surrounding rock and suppress the development of plastic zone timely, the high pretension bolt provides active stress on surrounding rock at the early stage of the roadway deformation. The weakening process of surrounding rock is retarded through this approach, and the purpose of rock reinforcement is achieved. The initial deformation of surrounding rock is limited under the action of the high pretension bolts. With the deformation energy releases from surrounding rock, the concentration of the stress on the high pretension bolt increases. As the bolt finally breaks off, the destruction of the roadway is further intensified. Compared with the two bolts above, the CRLD bolt can adapt the deformation and absorb the deformation energy while maintaining constant resistance.

4.5 Interaction between Bolt and Soft Rock

According to the analysis of numerical simulation results, the failure modes of the low pretension and high pretension bolts are different. We may describe the failure process of the conventional pretension bolts and the mechanism of the CRLD bolt in soft rock as follows.

4.5.1 Failure Process of the Low Pretension Bolt

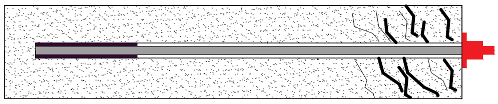
The failure process of the roadway under the low pretension bolt support can be summarized in four stages (Fig. 12):

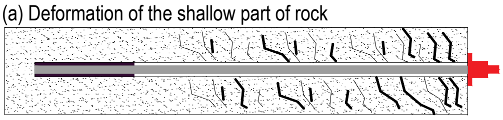
(1) With the excavation of a roadway, the stress state of surrounding rock changes from the three-dimensional pressure state to the two-dimensional pressure state. The low pretension bolt restores the surrounding rock to the three-dimensional pressure state, but the fracture zone has appeared in the shallow part of the surrounding rock.

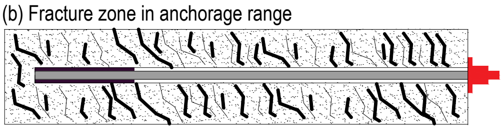
(2) The fracture zone relates to the plastic zone. The fracture zone of surrounding rock extends in depth, but the fracture zone is still in the anchorage range of the bolt. The bolt still has the anchorage function.

(3) The plastic fracture zone of surrounding rock continues to develop and finally exceeds the anchorage range of bolt. The anchorage force decreases with the expanding of fracture zone.

(4) The bolt moves together with surrounding rock and loses its anchorage function. The deformation of surrounding rock continues increasing and the roadway under the low pretension bolt support will be damaged eventually.


(a) Deformation of the shallow part of rock


(b) Fracture zone in anchorage range


(c) Fracture zone exceeds anchorage range

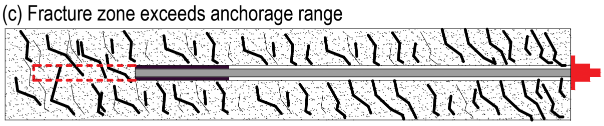

(d) Bolt slides within surrounding rock

Figure 12 Failure stages of low pretension bolt

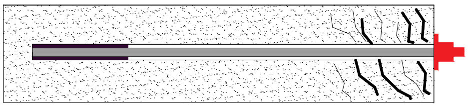
4.5.2 Failure Process of the HighPretension Bolt

The failure process of the roadway supported by the high pretension bolt can be summarized into three stages (Fig. 13):

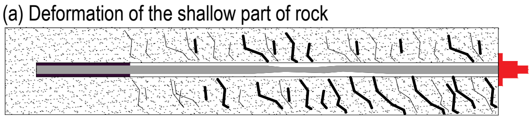
(1) The high pretension bolt restores surrounding rock to the state of three-dimensional pressure, but the fracture zone has appeared in the shallow part of the surrounding rock.

(2) Due to the high pretension force of the bolt, the fracture zone of surrounding rock only can extend to the free section of the bolt. As the deformation of the surrounding rock is blocked, the stress accumulated on the bolt continues increasing.

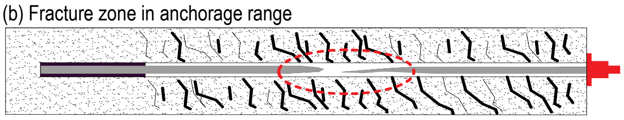
(3) The stress acting on the bolt reaches the ultimate strength of the bolt, finally resulting in the break of the bolt. The deformation of surrounding rock continues increasing without bolt support, and the roadway will be damaged eventually.



(a) Deformation of the shallow part of rock



(b) Fracture zone in anchorage range



(c) Bolt break off in anchorage range

Figure 13 Failure stages of high pretension bolt

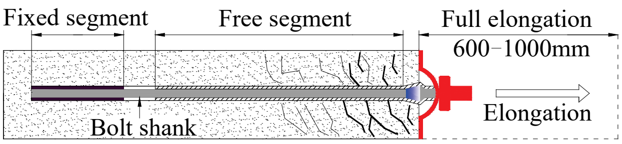
4.5.3 Working Mechanism of the CRLD Bolt

Fig. 14 shows the working principle of the CRLD bolt. The working mechanism of the CRLD bolt in swelling soft rockcan be summarized in three stages.

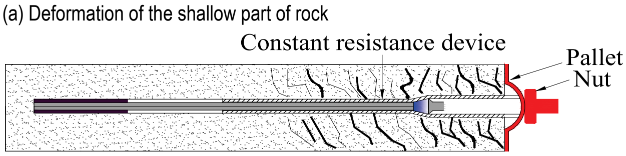
(1) Elastic deformation stage. As the deformation energy releasing from the surrounding rock is small, the axial force applied on the bolt shank is less than that of the constant resistance force. The constant resistance device remains stationary. At this time, the CRLD bolt absorbs the deformation energy by the elastic deformation of the bolt shank, and the surrounding rock deformation is controlled at the early stage.

(2) Structure deformation stage. With the gradual accumulation of deformation energy in surrounding rock, the axial force applied on the shank exceeds the designed constant resistance force. In the constant resistance device, the cone slides along the inner wall of the sleeve with friction, the bolt maintains its constant resistance in the process. Due to the structural deformation, the constant resistance device can absorb the deformation energy released from surrounding rock.

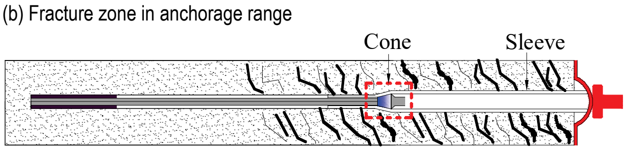
(3) Extreme deformation stage. The deformation energy of surrounding rock has been fully released through the above two stages. When the force acting on the bolt is less than the designed magnitude, the slippage of the cone stops.The surrounding rock rests on a relatively stable state again.



(a) Deformation of the shallow part of rock



(b) Fracture zone in anchorage range



(c) Bolt elongated to accommodate large deformation

Figure 14 Working principle of CRLD bolt

5 CONCLUSION

The control of the soft rock roadway, especially to the swellings of the rock, is a typical challenge for underground coal mining. This paper presents an investigation on the bolt support pattern of soft rock roadway. In order to find an effective method of soft rock support, numerical simulation and theoretical analysis were performed to study the failure mechanisms of different bolts in soft rock roadway support. The main conclusions are as follows:

(1) The expansion range of the fracture zone exceeds the anchorage range of the low pretension bolt, resulting in the overall bolt sliding with surrounding rock deformation. Therefore, the bolt loses its supporting effect on surrounding rock.

(2) The high pretension bolt can reduce the surrounding rock deformation at the early stage. Because of the high pretension force, the fracture zone only can extend to the free section of the bolt. With the continuous deformation of surrounding rock, the concentrated stress of the bolt results in the failure.

(3) To support the soft rock roadway effectively, certain deformation energy must be released. The CRLD bolt can absorb the deformation energy of surrounding rock through its structural design while maintaining constant working resistance. Compared to the conventional pretension bolts, the CRLD bolt avoids the failure modes such as sliding or breaking in soft rock support.

The choice of the bolt should consider the surrounding rock condition. The conventional pretension bolts have been applied in the roadway with stable and integral surrounding rock successfully. Nevertheless, the conventional bolts failed in the soft rock roadway support of Nanshan Coal Mine. The comparative study of the bolts indicates that the CRLD bolt is appropriate for the soft rock support. The advantages of the CRLD bolt can be summarized as follows: The constant support resistance is high, which can reach up to 200 kN; The deformation of the bolt is large, which is more than that of the conventional bolt; The energy absorption capacity of the bolt is strong, which can absorb the deformation energy released by surrounding rock. The study provides guidance for the same type soft rock roadway support.

This study investigated the mechanism of the soft rock reinforcement by the conventional bolts and CRLD bolt. However, the performance of each component of the CRLD bolt in soft rock support has not been investigated. To improve the performance of the CRLD bolt, the relationship between components and soft rock needs to be further studied in the future.

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