Application of Bolt–Mesh–Cable Coupling Support with High Convex Strip in Deep Roadways

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ABSTRACT

To solve support issues in the deep roadway in coal mine no. 9 of the Hebi Coal Industry in China, the bolt–mesh–cable coupling support used for large deformations of surrounding rocks in the deep roadway is analyzed in this study. The deformation and stress characteristics of surrounding rocks under the bolt–mesh–cable coupling support with high convex strips or normal strips are simulated using the software *FLAC3D*™. On the basis of the theoretical analysis and numerical simulation results, the bolt–mesh–cable coupling support with high convex strips is proposed to support a service shaft underground test roadway. The supporting effects are evaluated by analyzing the in situ data of surrounding rock displacements. Field construction and monitoring results show that the new coupling support design can effectively control large deformations in the deep roadway and ensure the long-term stability and safe operation of roadways. The research results are valuable for similar engineering applications.

KEYWORDS: deep roadway; numerical simulation; coupling support; high convex strip

INTRODUCTION

The nonlinear large deformation phenomenon caused by an environment with complex geological mechanics and high in situ stresses has emerged as the depth of mining activities increases. He[1–3] established coupling support theory for soft rock roadways and proposed the nonlinear mechanics design method of bolt–mesh–cable coupling support. Kang[4–6] proposed high-strength full-section reinforcement with pretension rock bolts and cables combined with grouting to control large deformations in deep roadways. Other typical support technologies implemented in practical engineering have been described by Kang et al., Sinha et al., Mohamed et al., and Seedsman[7–10].

A large amount of deformation energy that accumulated in surrounding rocks should be released in a reasonable manner while excavating deep roadways. Moreover, a low deformation rate for yielding irregularly distributed loads should be generated while simultaneously implementing full rock self-support. Bolt–shotcrete or bolt–mesh–shotcrete applied for initial support is common in deep roadways. As the key component of the bolt–mesh–cable support system, the strip can build an equal-span beam structure of adjacent bolts (anchor cables) combined with surrounding rocks and release harmful deformation in such rocks by controlling radial non-uniform stress in a single bolt or anchor cable. However, minimal work has been performed on the strip effect of the bolt–mesh–cable coupling support.

Nonlinear mechanics phenomena (such as the differential settlement of roofs, side falls in underground operations, and floor heaves) have recently occurred in coal mine no. 9 of the Hebi Coal Industry. A bolt–mesh–cable coupling support with normal strips is difficult to control effectively in large deformations in deep roadways. On the basis of deep coupling support theory, a bolt–mesh–cable coupling support with high convex strips is proposed to support a service shaft underground test roadway. The deformation mechanism of the new coupling support for deep roadways is studied based on theoretical analysis and numerical simulation results using the software *FLAC3D™*. The field application results show that the new supporting system exhibits satisfactory performance.

STRUCTURAL EFFECT OF A HIGH CONVEX STRIP

The high convex strip is manufactured by rolling a ductile steel billet (grade A3) to cover a steel belt (Fig.1).

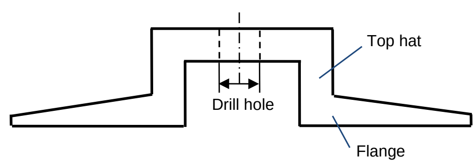

Figure 1: Cross section of a high convex strip.

1. Calculation of support resistance

The surrounding rock pressure calculation model is shown in Fig.2. The relationship between the radial deformation of the support arc sides and the hulking deformation of the surrounding rock is presented as follows (based on loose circle supporting theory):

$$(k-1)\left(R^2-r^2\right)=2r\Delta r-\Delta r^2 \tag{1}$$

Then, the loose circle radius is given by

$$R=\sqrt{\frac{(k-1)r^2+2r\Delta r-\Delta r^2}{(k-1)}} \tag{2}$$

where k is the hulking coefficient of the surrounding rock, and Δr is the radial allowable deformation.

The static force balance for the calculation model is given by [11]

$$P + c\cdot\cot\varphi = \left(\sigma_0 + c\cdot\cot\varphi\right)\left(1-\sin\varphi\right)\left[\frac{r}{R}\right]^{\frac{2\sin\varphi}{1-\sin\varphi}} \tag{3}$$

where c is the cohesion and φ is internal friction angle of the surrounding rock.

When (2) is substituted into (3), we obtain

$$P = \left(\gamma h + c\cdot\cot\varphi\right)\left(1-\sin\varphi\right)\cdot\left[\frac{(k-1)r^2}{(k-1)r^2 + 2r\Delta r - \Delta r^2}\right]^{\frac{\sin\varphi}{1-\sin\varphi}} - c\cdot\cot\varphi \tag{4}$$

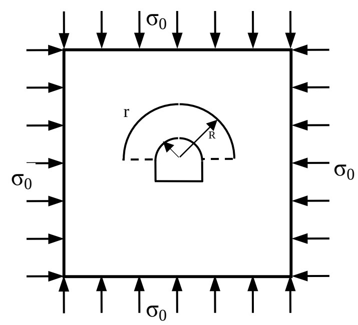

Figure 2: Rock pressure calculation model for a deep roadway. σ_0 is the surrounding rock stress, R is the loose circle radius, and r is the roof arc radius.

2 Structural effect of a high convex strip

Assume that a high convex strip bears a uniformly distributed load P. Then, the rock bolts (or anchor cable) will act on line load F. The unit length force analysis of a high convex strip is illustrated in Fig.3. The typical mechanical equation is given as

$$F = 2PB_1 \tag{5}$$

When (5) is substituted into (4), we obtain

$$B_1 = F/\left\{2\left(\gamma h + c\cdot\cot\varphi\right)\left(1-\sin\varphi\right)\cdot\left[\frac{(k-1)r^2}{(k-1)r^2 + 2r\Delta r - \Delta r^2}\right]^{\frac{\sin\varphi}{1-\sin\varphi}} - 2c\cdot\cot\varphi\right\} \tag{6}$$

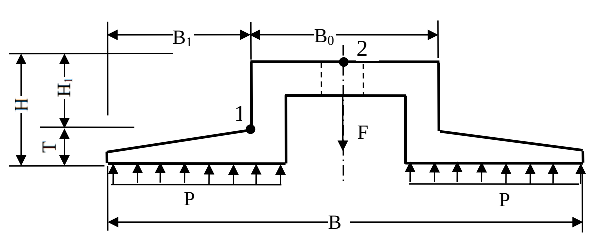

Figure 3: Schematic diagram of the unit length force of a high convex strip.

(1) In case of structural instability in the high convex strip, we obtain the following expression based on the unit load method:

$$\begin{bmatrix} M_1 \\ M_2 \\ F_{2Q} \end{bmatrix} = \begin{bmatrix} \frac{4EI}{H_1} & \frac{4EI}{B_0} & -\frac{24EI}{B_0^2} \\ \frac{2EI}{H_1} & \frac{8EI}{B_0} & -\frac{24EI}{B_0^2} \\ -\frac{24EI}{B_0^2} & -\frac{24EI}{B_0^2} & -\frac{96EI}{B_0^3} \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \\ \Delta_2 \end{bmatrix} \tag{7}$$

where M_1 and θ_1 are the flexural torque and angular displacement of point 1, and M_2 and θ_2 are the flexural torque and angular displacement of point 2, respectively. F_{2Q} is the section force of point 2, and EI is the section flexural rigidity.

On the basis of $M_1 = \frac{PB_1^2}{2}, M_2 = 0, F_{2Q} = \frac{F}{2}$ in (7), we obtain:

$$\Delta_2 = \frac{B_0}{4}\sqrt{\frac{2PB_1^2 B_0 - 8PB_1^2 H_1 + FB_0^2}{6EI\left(2H_1 + 3B_0\right)}} < H_1 \tag{8}$$

(2) In case of intensity failure in the high convex strip, the flexibility of the strip is given as

$$\lambda = \frac{\mu H_1}{i} = \frac{2\sqrt{3}\mu H_1}{T} \le \lambda_P \tag{9}$$

where λ_P is the flexibility limit, and μ and i are constant.

From Euler's formula and the typical mechanical equation, we obtain

$$\begin{cases} \sigma_{cr} = \sigma_K - k\lambda^2 \\ \sigma = \frac{F}{2T} \le [\sigma] \end{cases} \tag{10}$$

where $[\sigma]$ is the allowable stress value, and σ_K and k are constant.

When $k = \frac{\sigma_s^2}{4\pi^2 E}$ (σ_s is the yield strength) is used in (10), we obtain

$$T \ge \frac{2\pi^2 EF}{4\pi^2 E\sigma_K - \sigma_S^2} \tag{11}$$

NUMERICAL SIMULATIONS

1 Simulation procedure

The high convex strip and bolt–mesh–cable coupling support model calculated using the software FLAC3D™ based on the Mohr–Column criterion is shown as Fig.4. A roadway with a depth of 700 m is the subject of investigation. The section shaped as a semicircular arch has a width of 5m and a height of 4m. The computational domain is set as six times the distance of the roadway surrounding area. The model size is 30 m × 30 m × 5 m, with a fixed boundary condition. The parameters of the rock mass, with grades IV to V [12], are as follows: $\gamma = 22.5$ kN/m^3, E = 1.3 GPa, $\upsilon = 0.35$, c = 0.2 MPa, $\varphi = 27^o$, $\psi = 5^o$, and $\sigma t = 0.55$ MPa. The rock bolt and anchor cable are simulated by the cable element, whereas the high convex strip is simulated by the beam+shell element (E = 270GPa, $\upsilon = 0.25$). Two calculation models are shown as follows:

a) Normal strip+rock bolts (anchor cables) support the roof, the rock bolts on the wall, and the grouting bolt on the base bottom;

b) High convex strip+rock bolts (anchor cables) support the roof, the rock bolts on the wall, and the grouting bolt on the base bottom.

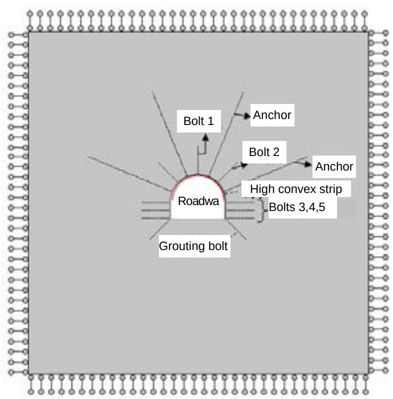

Figure 4: Numerical calculated model for the bolt–mesh–cable coupling support with high convex strips built using FLAC3D™.

2 Simulation results

The vertical and horizontal displacement fields are shown in Figs. 5 and 6, respectively. The vertical displacement exhibits a centerspread-shaped distribution because of overburden load and dead load. The vertical displacement of the high convex strip is reduced to approximately half of the normal strip, and its distribution is more uniform. We can conclude that the high convex strip can coordinate the deformation of the rock bolts and anchor cable. A high convex strip support system can effectively release the unfavorable deformation of surrounding rocks because of the surrounding rock deformation near the high convex strip is evident.

The horizontal displacement exhibits an ear-shaped distribution because of unloading effects. The horizontal displacement of the high convex strip decreases to approximately half of that of the normal strip. We can conclude that the high convex strip can restrict partial side deformation.

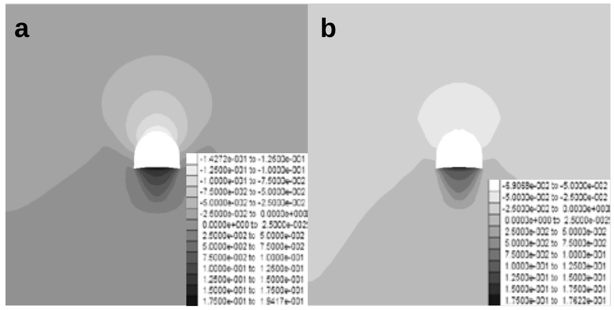

Figure 5: Vertical displacement contour of the deep roadway: (a) normal strip (unit: m) and (b) high convex strip (unit: m).

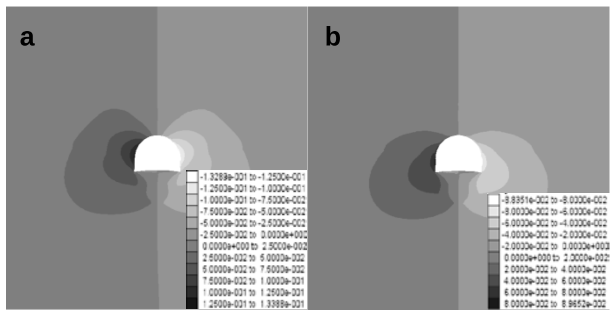

Figure 6: Horizontal displacement contour of the deep roadway: (a) normal strip (unit: m) and (b) high convex strip (unit: m).

The vertical and horizontal stress fields are shown in Figs.7 and 8, respectively. The vertical stress exhibits an elliptical shape distribution that results from surrounding rock pressure. The maximum vertical stress of the high convex strip diminishes to approximately half of that of the normal strip and its distribution is more uniform. We can conclude that the high convex strip can control the deformation of the rock bolts and anchor cables, as well as promote surrounding rock stress transfer to a deep area. The horizontal stress distribution is similar to the vertical stress distribution.

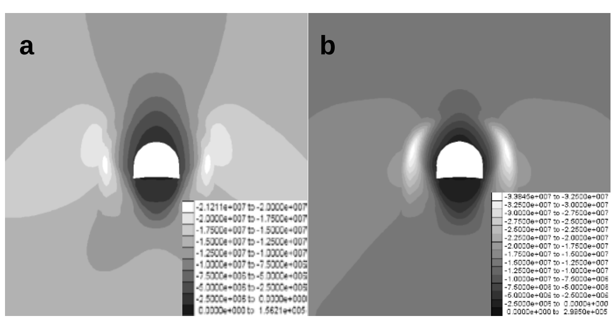

Figure 7: Vertical stress contour of the deep roadway: (a) normal strip (unit: Pa) and (b) high convex strip (unit: Pa).

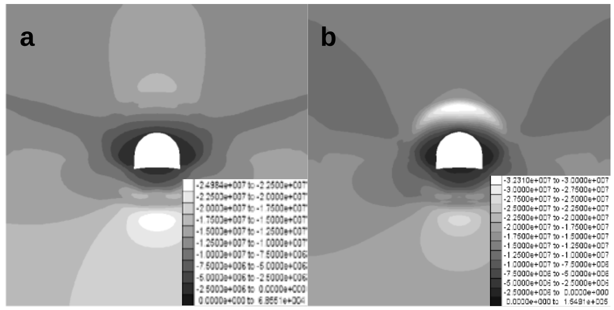

Figure 8: Horizontal stress contour of the deep roadway: (a) normal strip (unit: Pa) and (b) high convex strip (unit: Pa).

APPLICATION EXAMPLES

1 Project overview

Coal mine no. 9 of the Hebi Coal Industry is a deep high-stress soft rock roadway at a level of −420m (depth of approximately 600m). While the shaft inset, waiting chamber, and bottom yard of the service shaft are being excavated, nonlinear mechanics phenomena occur and seriously influence normal mine sinking and drifting engineering. Several areas that appear “before digging and after repairing” are phenomenal and seriously influence normal roadway excavation and safe operation. The central substation and pump chamber are based on subsequent engineering, and the cross section of the chamber is large. Avoiding large deformations is difficult for the traditional U structure and bolt–shotcrete support. Therefore, the proposed support scheme and construction technology should be explored.

The final cross section of the center substation is 5m × 4m (straight wall with a semicircle-shaped arch). The field surrounding rock mass condition of the substation is shown in Fig.9. The exposed surrounding rock mainly consists of charcoal gray sandstone and black flaggy sandy mudstone with auxetic joint cracks. The rock will collapse after being immersed in water.

Figure 9: Surrounding rock mass condition of the central substation in the Hebi coal mine.

2 Coupling support scheme

(1) Old support state

The final cross section of the bottom yard roadway is 3.4m × 3.2m. The original support design is bolt–mesh–cable with a normal strip, and U29 support is used to repair the damaged roadway. The support parameters are as follows:

1) Rock–bolt: roof and side with resin bolt, Φ22 m × 0.7m, l = 2.5m;

2) Anchor cable: steel strand, Φ18.9m × 2.1m, l = 8m;

3) Mesh: round steel, Φ6, the grid is 0.15m;

4) C20 shotcrete;

5) U29 spacing is 0.5m.

(2) Proposed support strategy

On the basis of deep coupling support theory [13] as well as the theoretical analysis and numerical simulation results, a bolt–mesh–cable coupling support with high convex strips is proposed to support a service shaft underground test roadway (Figs.10–11). The proposed support strategy is as follows:

1) The rock bolts, anchor cables, and shotcrete are similar to the original support design;

2) Mesh: round steel, Φ6, the grid is 0.07m;

3) High convex strip: GDT30/140 × 20 × 2000, three rock bolts or two anchor cables share one strip.

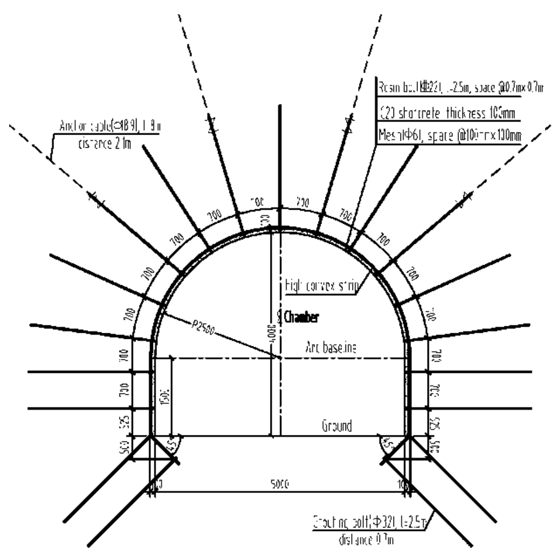

Figure 10: Cross section of the bolt–mesh−cable coupling support for the central substation in Hebi coal mine.

Figure 11: Field usages of the high convex strip in Hebi coal mine.

3 MONITORING RESULTS

The stability of surrounding rocks is monitored via surface displacement observation using the cross-point method. We record surrounding rock deformation data for 200 days (Fig.12). The results demonstrate that the cumulative convergence of two sides is close to 63mm, whereas the cumulative convergence of the roof and the floor is close to 89mm. The deformation rate decreases after 40 days of excavation, and the roadway tends to be stable within 80 days. Hence, the coupling support scheme with a high convex strip can effectively control the large deformations of the deep roadway and ensure long-term stability and safe operation of the roadways. The supporting effect of the substation is illustrated in Fig.13.

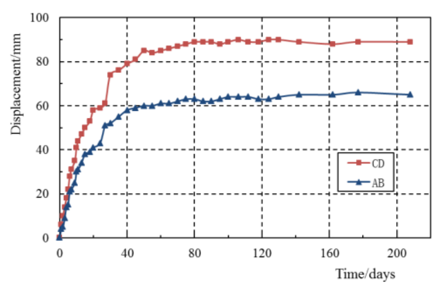

Figure 12: Surface displacements of the substation in the Hebi coal mine. AB is displacement curve of the two sides, whereas CD is displacement curve of the roof and the bottom.

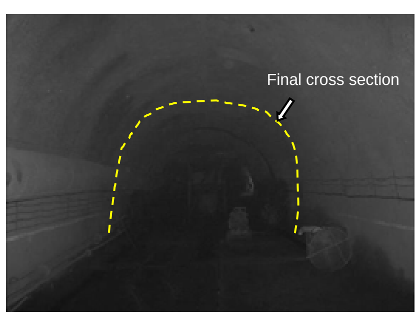

Figure 13: Reinforced states of the substation in the Hebi coal mine.

CONCLUSIONS

As mining depth increases, support issues in deep soft roadways become increasingly serious. To investigate more efficient support methods for deep coal mines, the central substation in the Hebi coal mine in China is used as an example to study coupling support with high convex strips. The following conclusions are drawn.

1. The top hat of the high convex strip can effectively release unfavorable deformation in the surrounding rock mass. The high strength and high stiffness of the strip can restrict nonlinear deformation validity.

2. The simulation results indicate that the bolt–mesh–cable with high convex strips support for deep roadways is better than that with normal strips.

3. Monitoring measures are recorded, and the monitoring results demonstrate that the performance of the new coupling support system is satisfactory.

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