Numerical Study of TBM Excavated Coal Mine Roadway Support Design

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Abstract. In TBM excavation projects of Zhangji coal mine which is the first application of TBM at deep underground coal mine, computational modelling was conducted in surrounding rock stability study and support design of coal mine TBM excavated roadway due to lack of experience in similar projects. This paper presents a support design methodology of TBM excavated roadway at deep underground coal mine. A three-dimension finite element model was established, and the non-uniform tectonic stress filed was also been simulated in the model. Stress redistribution, displacement and plastic zone range of surrounding rock under different support patterns were analyzed and support design of the roadway was made on the base of simulation results. During roadway excavation, instrument rock bolts were installed for monitoring stress distribution and roadway convergence. The monitoring results suggest that computational simulation results correspond with in-situ monitoring data, horizontal stress concentrates on the roof and floor of roadway and vertical stress concentrates on lateral sides. The roadway convergence increased significantly after excavation and then slowed down and finally stopped after 40 days.

1. Introduction
Tunnel boring machine (TBM) had been widely used in tunnelling, municipal, and hydropower Engineering since 1960’s due to its well safety and high penetration rate[1]. However, the applications of TBMs in deep-buried coal mine were barely reported. The methane drainage roadway excavation project at Zhangji coal mine is the first application of TBM in deep strata at underground coal mine, and the depth of TBM excavated roadway reaches up to 500 m. The project introduced in this paper is different from the previous TBM excavation works on two main aspects: geological setting and stress field. The coal mine roadway was excavated within sandstone layer, the geological setting of roadways at deep underground coal mines usually differs from that of mountain tunnels and metro tunnels (sedimentary rock vs igneous rock and soft soil). Therefore the successful supporting experiences of mountain or metro tunnels cannot be applied in TBM-excavated coal mine roadways without modifications[2].
Moreover, Stress field at underground coal mine is also different. In shallow strata, the ground stress is determined by thickness of overburden, and the maximum principle stress is vertical stress. But at underground coal mines, ground stress condition cannot be studied simply through the thickness and density of overburden[3], the tectonic stress plays a more important role than gravity stress in deep strata at underground coal mine. The maximum principle stress at deep ground of underground coal mines usually is horizontal stress. Therefore the stress distribution near the TBM excavated coal mine roadways must be different to that near shallow tunnels due to different stress field. In addition, the stress distribution and deformation features of roadways are influenced by roadway geometries, the conventional coal mine roadways are rectangle, trapezoid or arched shape while the TBM excavated roadway is circular, therefore the support design methodology of TBM excavated roadway is different to that of conventional roadways[4].

In this paper, computational model was established by three-dimension (3D) Fast Lagrangian Analysis of Continua (FLAC). Rock bolt support system has also been established in the model for studying surround rock displacement behaviours and stress redistribution mechanism. After excavation and supporting, the monitoring works were conducted for getting data of roadway convergence and stress field of surrounding rocks.

Based on FLAC3D model simulation, critical elements of the actual roadway’s behaviour had been studied, and the simulation results were verified by in-situ monitoring data. The modelling methodology was used in similar projects for evaluating the reliability and stability of support systems before support design been finally decided. The study will also provide a primary data for future applications of TBM at underground coal mines.

2. Brief description of working site
The Zhangji TBM excavation project is the first application of TBM at shaft coal mine globally. The roadway is 1598 m in length, and excavated by a hard rock TBM with the diameter of 4.53 m, and located in west-2 panel, north mining area[5].

The roadway was excavated by an open face hard rock TBM that manufactured by Northern Heavy Industry, China. The TBM with a diameter of 4.53 m equipped with a hard rock cutterhead and two rock bolters and could be operated in hard rock strata in underground coal mines. The cutterhead which equipped with 17-inch single and double disk cutters is driven by four 360 kW electric motors. Four thrust cylinders with two gripper shoes are installed on the TBM providing a total thrust force of 12,000 kN.

2.1. Geological setting
Geological setting had been studied through a series of measurements and surveying. Along the roadway alignment, the strata consist of medium sandstone, fine sandstone and siltstone, and the UCS (uniaxial compressive strength) of which various from 41.6 to 105.7 MPa[6].

The roadway is located in a 27-meter thick sandstone strata and No.1 coal seam is 25 to 30 m beneath the roadway. Overburden of roadway consists of clay layers, sand layers, mudstone and sandstone strata and the total thickness is 480 to 500 m.

2.2. Ground stress field
Ground stress is a principal element which causes rock deformation and failure, and its magnitude and orientation significantly affect the stability of roadway[7]. In order to investigate the in situ stress of Zhangji project, borehole stress relief measurements were conducted in the roadway. The measurement results suggest that the ground stress field is controlled by tectonic stress: vertical stress is approximately 14.3 MPa and related to overburden of approximately 500 m. The maximum horizontal stress is 21.6 MPa and oriented 130.72°, and the minimum horizontal stress is 13.2 MPa and oriented 223.55°[8].
3. Numerical simulation
The model was built by three-dimension (3D) Fast Lagrangian Analysis of Continua (FLAC). In-situ stress and rock property parameters had been learned by in-situ measurement and laboratory testing.

3.1. 3D finite difference model
According to Saint Venant principle and construction experience, the stress redistribution, surrounding rock deformation, and other effects of excavation out of a domain with 3 to 5 times of roadway radius are negligibly small[9]. The diameter of roadway is 4.53 m, therefore the model size is taken as 60m×120m×60m (X, Y, Z axis direction). The model consists of 40000 elements and 41041 grid points, excavation part was modeled using cylinder elements with 6 grid points and surrounding rock is modelled using radcylinder elements 8 grid points. The model geometry is shown in figure 1.

![Model geometry and parameter](image1)

For simplicity, the ground profile was idealized as a homogeneous rock. For this model, average rock parameters determined from the geotechnical data report. Model element lengths equal the TBM stepping length of 1.0 m in the longitudinal direction within the roadway excavation zone. The details of rock properties are provided in table 1.

| Property       | Value  |
|----------------|--------|
| Density (kg/m³)| 2500   |
| Elastic modulus (10⁴MPa) | 4.5    |
| Bulk modulus (10⁴MPa)   | 2.5    |
| Shear modulus (10⁴MPa)  | 1.875  |
| Passion ratio         | 0.20   |
| Cohesion (MPa)        | 9.0    |
| Friction angle (°)    | 45     |

Table 2. Rockbolt mechanical property.

| Property        | Value  |
|-----------------|--------|
| Diameter (mm)   | 20     |
| Length (mm)     | 2000   |
| Elastic modulus (10⁴MPa) | 20.6   |
| Tensile strength (MPa)  | 345    |
| Passion ratio   | 0.30   |
| Rigidity of resin (kN/m) | 1000  |
| Friction angle of resin (°) | 54    |

Rock bolts were modeled using cable elements. The rock bolt parameters input are shown in table 2. Three different support patterns (non-support, roof support and roof-and-ribs support) are applied in the model. The stress filed redistribution and displacement of surround rock under three support conditions are simulated and analyzed and the most feasible support layout can be decided base on simulation results. Support layouts are shown in figure 2.
4. Simulation results analysis

The model is launched in three conditions: no support, roof support and roof-and-ribs support. Stress redistribution, surround rock displacement, roadway convergence and stress concentration under three conditions are recorded and analyzed.

4.1. Stress redistribution

After excavation, the stress filed of surround rock near the roadway is redistributed. The maximum horizontal stress on roadway surface under three support patterns (no support, roof support and roof-and-ribs support) are: 41.33 MPa, 41.35 MPa and 40.55 MPa respectively, which occur on the top and bottom of roadway, and the maximum vertical stress under three support patterns are: 20.9 MPa, 22.3 MPa and 24.4 MPa respectively, which occur on the lateral sides of roadway. The calculated stresses indicated that the horizontal stress concentrated on the roof and bottom of roadway and the vertical stress concentrated on lateral sides. The stress concentration also occurred on the top of rock bolts.

4.2. Displacements

Under the tectonic stress, the displacements at roadway roof under three support patterns are: 4 mm, 2.2 mm and 2.1 mm. The displacements at roadway bottom under three support patterns are: 2.29 mm, 2.3 mm and 2.5 mm. The lateral displacement of roadway under three support patterns are: 7.63 mm, 7.2 mm and 2.01 mm. The simulation results suggest that after rock bolt supporting, the surrounding rock of roadway deformation was controlled significantly, from 4 mm to about 2 mm on the roof and from 7.63 mm to around 2 mm on lateral sides. When the roof and lateral sides were supported and displacements on those sections were reduced, the displacement on roadway bottom increased slightly.

4.3. Plastic zone

The plastic zones under three support patterns are shown in figure 3. The plastic zone under support pattern 1 is an approximate circular with the largest depth of 2.2 m. In pattern 2, the range of plastic zone shrinks to 0.9 m in maximum due to the rock bolts support system. While in support pattern 3, the plastic zone distributes mainly on rib sides and bottom of the roadway and the maximum depth is 0.77 m. The plastic zone range is significantly shrunk after supporting, while there was no significantly difference on plastic zone range under roof support and roof-and-ribs support pattern.
4.4. Decision making of support scheme
The initial support scheme was decided based upon the simulation results. After support, the stress redistribution has changed slightly, while the roadway convergence and the range of plastic zone did decreased significantly. Between support pattern 1 and support 2, there was no significant difference on roadway convergence and plastic zone range. Compare with support pattern 2, support pattern 3 leads to larger support range and higher safety. While support pattern II was able to meet the requirement of roadway supporting according to simulation results and in-situ practices. Therefore, support pattern 2 which is roof support scheme had been chose for the roadway.

5. In-situ monitoring
In order to verify the precision of modelling simulation and study the surrounding rock deformation behaviour and bolt stress, monitoring stations were set in the roadway. Each station contains four bolt dynamometers and a set of convergence monitors. The bolt dynamometers were installed on the bottom of rock bolt for monitoring axial force of rock bolts. Roadway convergence behaviour can be studied through measuring distance changing between two convergence monitor spots by laser geodimeter[10]. The monitoring station layout is shown in figure 4.

![Monitoring station layout](image)

**Figure 4.** Monitoring station layout.

![Monitoring results of bolt axial force](image)

**Figure 5.** Monitoring results of bolt axial force.

![Monitoring results of roadway convergence](image)

**Figure 6.** Monitoring results of roadway convergence.

5.1. Rock bolt axial force
Figure 5 shows the monitoring results of bolt axial force. The largest bolt stress was measured on the 40th day after excavation at west side of No.3 station, which was 69.1MPa. Monitoring data illustrated that after rock bolts were installed, the bolt axial force increasing fastly on the rock bolts installed near the roof of roadway in 10 days, then the increasing speed slowed down and the bolt axial force remained stable after 20 days. In contrast, the axial force of rock bolts installed near the shoulders and lateral sides of roadway decreased rapidly in 10 days and then leveled off at around 45 kN. Monitoring data suggested that the surrounding rock reached to a stable state and the rock bolt supporting system works.

5.2. Roadway convergence monitoring
Convergence monitors were installed on upper hemisphere of roadway because belt conveyor installed on floor. The roadway convergence is shown in figure 6, the lateral convergence shot up to 8 mm within 10 days after roadway excavation, and then the increasing of convergence slowed down gradually and stabilized at 12mm after 30 days. The monitoring data indicates that the surrounding rock deformation had been controlled significantly under support pattern 2 (roof support). The convergence is extremely small when considering that the roadway width is 4.53 m.

6. Conclusions
The stress and displacement distribution behaviour of TBM excavated roadway at underground coal mine had been studied and a feasible support design of installing rock bolts on roadway roof was proposed base on simulation results and consideration of field conditions. On the base of analysis from both computational simulation and in-situ monitoring, the main conclusions can be drawn as follows:
The numerical model is established base on the actual parameters of the Zhangji TBM excavated roadway and computational simulation was conducted to analyze the roadway stability under three support patterns. The simulation results indicated that the support pattern 3 creates the minimum displacement value and the strongest supporting strength, while considering various factor of roadway supporting such as: safety, efficiency of supporting structure and the cost, the support pattern 3 (roof support) was adopted.

The in-situ monitoring suggested that roof support significantly reduced roadway convergence. Despite the floor of roadway was unsupported, it still kept well with no significant upheaving within 40 days and the convergences of various directions were within the acceptable range. The surrounding rock of roadway had reached stable state and convergences no longer increased 40 day after roadway excavation.

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