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Mine-Tunnel Design and Monitoring Analysis for Major Faults and Complex Geological Conditions

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Abstract

Mining operations at Nanyang-Slope Coal Mine are considerably challenging. The Nanyang-Slope Coal Field has a complex tectonic structure; having major faults, large fissures and fracture- zones, and great changes in coal-seam thickness. Mine tunnel-way 301 traverses multiple complex faults with developed fractures, broken surrounding rock, and high tectonic stresses. The original rectangular-section tunnel design using anchor-bolt-mesh retainment was prone to rib-spalling, and the problem could not be controlled by use of additional encryption anchors on the tunnel sides. The mud-rock above the tunnel-ceiling is soft and argillized, which expands and softens on contact with water. This caused problems with the epoxy bonding agent failing to effectively secure bolt-anchors to the rock, resulting in anchor-bolt-mesh failure. In consideration of the complex geological conditions, a tunnel construction utilizing a curved wall arch-section and anchor-bolt- mesh-concrete spray was proposed. MJ-40 anchor-rod dynamometers were used to measure the forces in the tunnel rock-anchor bolts; and tunnel-rock deformation and surface displacement was monitored over the course of several weeks using a measuring station. Results show that the construction design effectively lowers the effects of the tectonic stresses on any one part of the tunnel, and demonstrates the safety and reliability of the tunnel-retainment and support design.

Keywords: *major fault, curved-wall arch-section, anchor sprayed support, axial force monitoring, displacement monitoring*

1. Introduction

Nanyang-Slope coal tunnel 301 traverses many major faults with large fissures and fracture-zones. These fault-structures cause variations in the stress properties in the surrounding rock, resulting in fragmentation of the tunnel ceiling and problems with the retainment of the surrounding tunnel-rock. The fault fracture-zones have highly fragmented rock; and this; combined with the great pressures and stress- concentrations; brought problems associated with supporting the tunnel-ceiling rock, and also for any subsequent tunnel repair or modification. It was difficult to carry-out any tunnel restoration-work by front-digging or hind-mending, and do so in full accordance to safety standards. A safe and quick method for traversing the faults was of prime importance for any subsequent mining operations.

The faults and fracture-zones are adverse geological phenomena that are regularly seen in the tunnel; being the unstable parts of the tunnel-passage. The faults and fracture zones traversed in tunnel 301 are typically regions of low-strength rock that are highly permeable, weak in water resistance and prone to plastic deformation. Fault-rock is typically a zone of rock that differs greatly in its physical and mechanical properties to more stable rock on either side of it. In places where the tunnel-way traverses the faults and fractures, the complex geological conditions cause changes in stress concentrations, with the fault changing the stress distribution and deformation in the tunnel-rock. Conventional tunnel construction techniques were inadequate in this situation; as during excavation, it was difficult to prevent ceiling-collapse and water inrush; and during the operating period, the retainment devices were prone to instability and rupture. It was therefore necessary to design a practical retainment and support system that would provide optimal stability for the tunnel.

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2. Project Overview
2.1. Project Overview of Nanyang-Slope

The Nanyang-Slope Coal-Mine and Coal-Field is located to the southeast of the village of Zeng Zifang in Yuan Puzi township; Youyu County; and being 27km from Shuozhou City. Youyu county connects with the No.109 National Road; 79 km from the city of Datong; and also with the No.208 National Road; northwest of Shanyin Country. The region is also serviced by the Dayun highway and BeiTongPu railway networks. Basic highways and simple asphalt raods constitute the main traffic routes in the immediate vacinity. The No.8 coal layer of the tunnel lies on the bottom of a group of coal-field layers that are referred to as the Tai-Yuan Group of coal layers. The No. 8 coal layer is; on average; about 14.46 meters below the No.5 coal layer; and is about 14.44m on average above the top of the K2 sandstone ceiling. The seam direction trends from the SW to the NE. The seam-width tapers; being wide in the SW; and narrowing towards the NE. The vertical-depth undulates in a wave pattern over the same direction. The relative high point of the K_2 plate lies in the vicinity of drill-holes No.309 and No.508. The relative low point is in the vicinity of holes No. 310, T2, T3, T1, and the No. 516 hole. The lowest point of the seam is at the No. 511 hole, and the seam rises to its highest point at the T_4 hole in the northeast. The No.8 coal layer is the stable minable seam distributed throughout the coal-field; being well developed; and having a coal-layer thickness ranging from 2.18m to 10.38m; on average being 6.44m thick (Hole No. 409). The No.8 coal layer has a complex structure, and contains between 0-4 layers of embedded stone; generally having 2 layers. Directly above the tunnel ceiling; is mainly immediate roof; with the top-plate further above. The upper lithology is mainly mudstone and the lower lithothogy is mainly siltstone. There is also some scattered false-roof under the immediate roof; with the scattered-roof ranging in thickness from 0.2m-0.8m. The top-plate is discontinuous, having a lithology of grit-stone and medium or fine-grained sandstone; And ranges in thickness from 2.9m to 7.0m. The bottom-plate lithology consists mainly of sandy-mudstone or mudstone, with silt-sand and fine-sand being in the southwest. Fine-sand also occurs in the northeast (Hole No. 511) and to the mid-east (No T6, Hole No. 516). The bottom plate thickness ranges from 1.47m to 4.50m. The parameters for the top and bottom plates are listed in Table 1.

Table 1. Rock Mechanics Experiment Results

Top or Bottom plate	Rock Type	True density (kg/m^3)	Apparent density (kg/m^3)	Porosity （%）	Moisture content （%）	Stress strength MPa saturation	dry	Soften coefficient	Stain strength （MPa）	Shear strength （MPa）
The top plate	mudstone	2390	2445	9.85	1.19	4.0	32.0	0.88	3.38	1.76
The bottom plate	siltstone	2600	2559	1.58	0.27	17.1	58.4	0.29	0.57	1.87

2.2. Tunnel Damage-Survey

Nanyang Slope Coal Mine Field has a complex structure; having major faults, large fissures and fractures-zones, and great changes in coal thickness. In our survey of tunnel 301; we found ten faults (ranging from 5m through 20m in size); two collapsed columns; and one magmatic rock dyke, all within a short distance of each other. Tunnel 301 traverses multiple complex faults with developed fractures, broken surrounding rock, and high tectonic stresses. The original rectangular shaped tunnel using only anchor bolt and mesh retainment was prone to rib-spalling, and the problem could not be controlled by installing additional encryption anchors on the tunnel sides. Figure 1 shows specific tunnel damage and destruction.

3. Tunnel-Section Design
3.1. Section Design

As already mentioned in the prior analysis, the stability of the surrounding tunnel-rock was found to be very poor. Surrounding rock is fractured and loose, and easily prone to plastic deformation and creep. Mine pressures are large and multi-directional; due to the coal-field tectonic stresses; causing instability of both the tunnel-ceiling and sides.

Figure 1. Tunnel Damage & Destruction

In order to both reduce lateral pressures on the tunnel-wall sides, and to also control tunnel-ceiling subsidence and rib-spall effectively, a curved-wall arch-section was adopted. The project was designed in optimum accordance with Chinese tunnel-design speciation: "Coal Mine Safety Regulations", "Coal Mine Design Specifications", “The Mining Design Manual", "Design Specifications for Coal-Mine Tunnels and Intersections" and “Tunnel Anchor Retainment & Support Technical Specifications". The net-section dimensions of the new tunnel are almost the same with those of the original rectangular-shaped tunnel-section. In calculating the tunnel-section dimensions; first; the sizes for the mine-machinery, worker-pathway, and other necessary safety clearance-gaps need to be considered. The rectangular section is then inscribed with a horseshoe curve; conforming to "Coal Mine Safety Regulations"; for both optimal safety and for an improved utilization-rate. Section dimensions can be seen in Figure 2 and Figure 3.

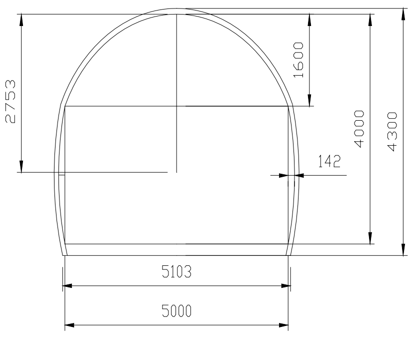

Figure 2. Tunnel Section Sizes

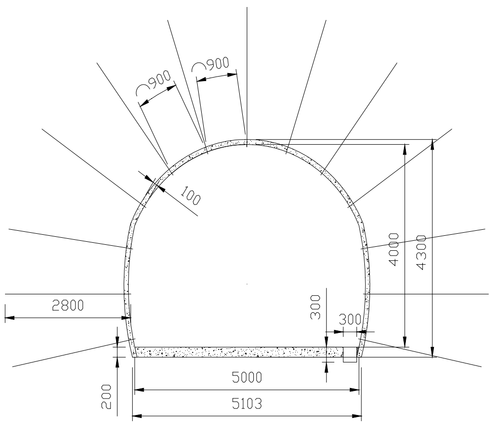

Figure 3. Sectional Drawing of Tunnel Retainment & Support-System

3.2. Tunnel Retainment & Support-System Design

The new design for the tunnel retainment and support-system adopted an anchor-bolt-mesh system with concrete mesh-spray. The combined use of the anchor-bolts, steel mesh and concrete-mesh-spray work together to function as multi-layered arch system that withholds the overlying strata very effectively. In addition, the somewhat flexible nature of the design allows adjacent tunnel-rock to release some pent-up energy, and so control deformation to within an acceptable range.

Figure 4. New Tunnel-Retainment & Support System

Table 2. New Tunnel - Design Specifications

Name	Tunnel Width (m)	Tunnel Height (m)	Spray-Layer Depth (mm)	Section Area (m^2)	Net Section Area (m^2)	Anchor Bolt Length (m)	Anchor Bolt Spacing (mm)	Anchor Bolt Row Spacing (mm)
Amount	5.0	4.0	150	20.36	18.20	2.8	900	900

4. Anchor-Bolt Axial Force Monitoring

4.1. Purpose and Monitoring-Station Settings

The anchor-bolt installation system was monitored under real working conditions so as to know the tensile forces in the selected bolts. Bolts were monitored from their initial preset load-force through to their final working-load force. The monitoring results could then provide information as to: (1) the bolt-spacing's around a tunnel section; and (2) the spacing between each row. The working resistance for any one anchor bolt corresponds to the axial force exerted on it at any one time, and matches the surrounding rock deformation. This allows for the actual working conditions of the anchor-bolt to be evaluated in relation to the actual rock deformation, so that it is possible to evaluate the differences between the initial force in the bolt and the final working resistance, and then correct any unsatisfactory support-system design. For the monitoring of bolt working-resistances, type MJ-40 bolt dynamometers were used, with 5 dynamometers being spaced around a tunnel-section. Initial bolt-load measurements were taken by pre-stressing the bolt, with the dynamometers being placed between the bolt anchor-tray and bolt head nut first, and the nut then slowly tightened. The dynamometer set-up can be seen in Figure 5.

4.2. Stress-Monitoring Data and Results-Analysis

The anchor-bolt monitoring data showed that stress-values in any one bolt ranged from a minimum of 1kN, through to a maximum of 17kN. Peak stress leveled-off and stabilized at 17kN. The maximum working-load reading of 17kN was well below the maximum design-value of 100kN; showing that the proposed design was quite safe. The results for the stress-monitoring can be seen in Figure 6.

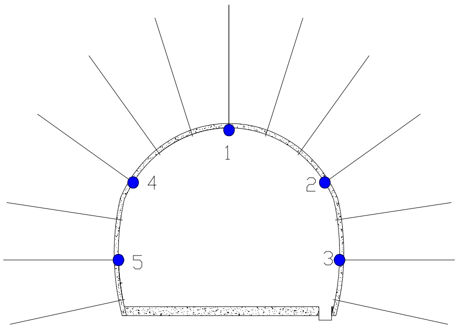

Figure 5. Axial-Force Monitoring-Point Arrangements

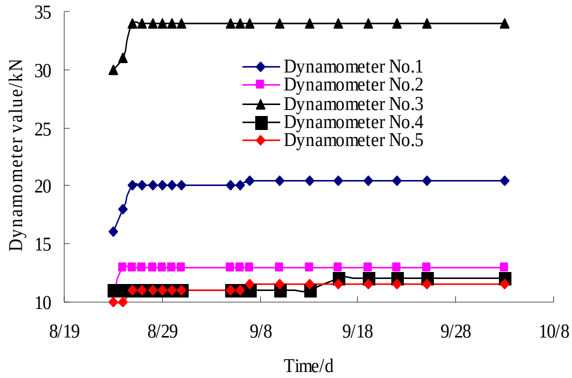

Figure 6. Dynamometer Measurement Readings

5. Tunnel-Surface Displacement Monitoring

5.1. Monitoring Purpose and Station-Settings

Monitoring of the tunnel-rock convergence provides vital information as to the inherent stability and effectiveness of the retainment and support design. A 50m length of the 301 tunnel was chosen for the monitoring, and three different locations along the tunnel were chosen as places at which to monitor the convergence-deformation of the tunnel. Choice sites for monitoring were sections of the tunnel with particularly broken rock. At each chosen tunnel-section, the convergence and deformation was measured by using three monitoring points; with one point being on each side of the tunnel; and one point being on the tunnel-ceiling. The arrangement is shown in Figure 7.

The monitoring method was as follows:

(1) Instrumentation: A Nikon TC-452 monitoring station was used. The angle measurement accuracy is 2" and the distance accuracy-range is ±(2mm+2ppm).

(2) Monitoring points: $A^{\#}$, $B^{\#}$ & $C^{\#}$

The relative heights for points $A^{\#}$, $B^{\#}$ & $C^{\#}$ are first measured and recorded. Another point; $D^{\#}$; is then chosen by placing the instrumentation at another known location-point within the tunnel that is deemed as being relatively stable. Point *D#* is then used as a reference point from which to monitor the relative change of the other three points ($A^{\#}$, $B^{\#}$ and $C^{\#)}$. The relative convergence-deformation for each is then compared, which then allows the amount of tunnel-ceiling subsidence to be observed.

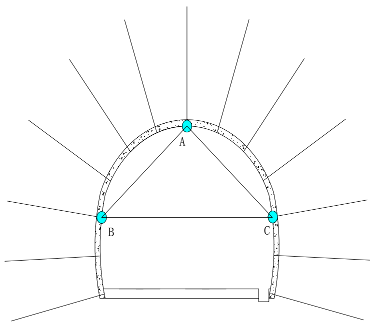

Figure 7. Tunnel-Convergence Measuring Point

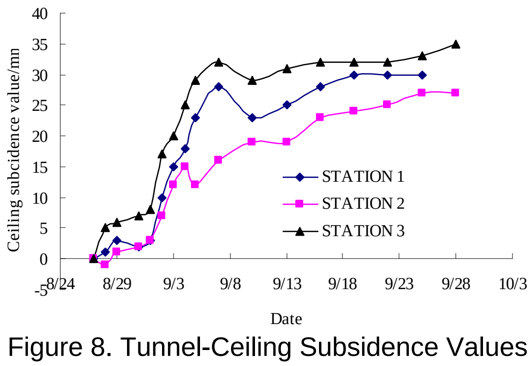

Figure 8. Tunnel-Ceiling Subsidence Values

(3) For displacement monitoring of the two tunnel-wall sides:

First, measure the horizontal distance *(L)* between the two corresponding points $B^{\#}$ and $C^{\#}$, along with the horizontal sextant angle of *(A)*, between the two points $B^{\#}$ and $C^{\#}$. Next, calculate the relative distance (*S*), between the points ($B^{\#}$ and $C^{\#}$) on both sides, according to their triangle cosines.

$$S^2=L^2\ (\text{left})+L^2(\text{right})-2\times L(\text{left})\times L(\text{right})\times \cos A \quad (1)$$

(4) The relative distances measured for each are then compared to the initial measurements; so as to be able to observe the relative displacement for each point on the either side of the tunnel. The results for the displacement monitoring are shown in Figure 8 to Figure 11.

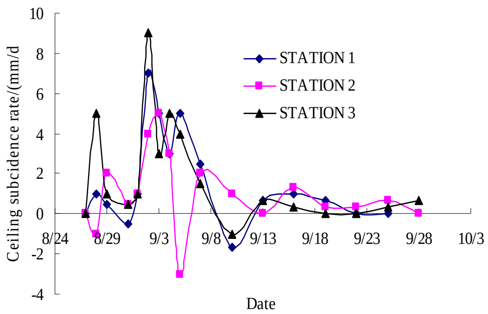

Figure 9. Ceiling Subsidence-Rate Measurements

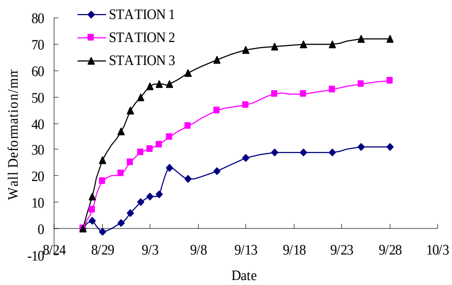

Figure 10. Tunnel-Wall Deformation Measurements

5.2. Tunnel Subsidence: Monitoring Results Analysis

Monitoring results from the No.1 monitoring station showed that after a period of 23 days, the subsidence-rate and convergence of the tunnel-ceiling stabilized and was close to 0 (zero). The total tunnel-ceiling subsidence was 31mm, and the total inward convergence of the 2 tunnel-sides was also 31mm. Monitoring results from the No.2 monitoring station showed that the tunnel ceiling first moved upward slightly in the first day and then started to sink from the 2nd day onwards.

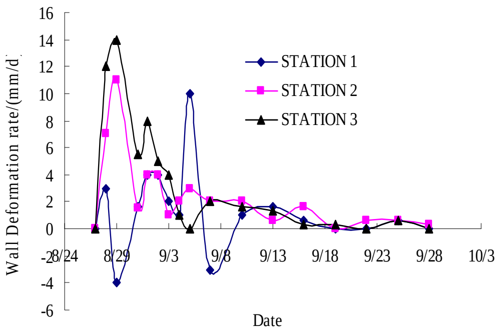

Figure 11. Wall Deformation Rates

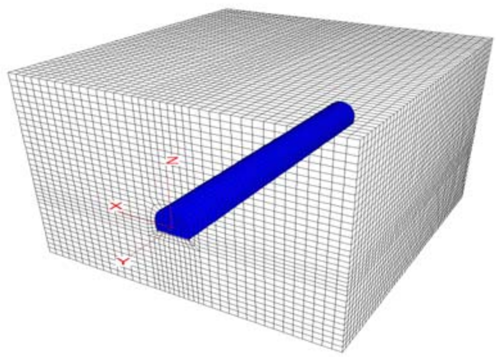

Figure 12. Tunnel-Way Tectonic Stresses - 3D Model

After a period of 30 days, the tunnel-ceiling subsidence was close to 0. The total subsidence was 27mm. The tunnel-wall deformation-convergence stabilized after a period of 31 days. Total tunnel-wall convergence was 56mm. Monitoring results from the No. 3 monitoring station showed that the tunnel-ceiling sank immediately from the time of excavation, with the subsidence continuing for a period of 23 days. After 23 days, subsidence was negligible and close to 0 (zero). The total tunnel-ceiling subsidence was 35mm. The two tunnel-walls deformed and converged inwardly from the time of excavation, stabilizing after a period of 25 days. The total inward-convergence of the two sides was 72mm.

5.3 Monitoring Data-General Summary

A general analysis of the monitoring data shows that tunnel-deformation is greatest near the time of excavation and then gradually reduces. Generally speaking, tunnel deformation, subsidence, and convergence stabilized within a period of 25 days. The maximum subsidence for the ceiling was 35mm, and the maximum inward convergence of the two sides was 72mm. In addition, there was an expansion phenomenon which occurred on the two sides of the tunnel at monitoring location No.1.

The tunnel-ceiling at monitoring location 2 had a slight bulge phenomenon, the specific reason for which needs further research. Monitoring station No.3 showed a large convergence and deformation of the tunnel wall sides, the cause for which also needs further investigation and research. It may be necessary to improve the strength of the sides by installing additional anchors in these sections of the tunnel. In short, the horse-shoe shaped tunnel-section and anchor-sprayed support proved remarkably effective in controlling subsidence and deformation in places where the tunnel traversed the major faults and complex geological conditions.

6. Mathematical Simulation

A mathematical simulation-model of the tunnel was created in accordance with the known geological conditions and rock-mechanic parameters (Figure 12).

The Mohr-Coulomb model was adopted for the mathematical component of the computer simulation. Parameters for the rock mechanics are shown in Table 1. Figure 13 shows the displacement diagram for the tunnel after the installation of the retainment and support system. Figure 14 shows the stress diagram_after installation of the tunnel retainment and support system.

Tunnel rock displacement was able to be controlled effectively, being limited to about 7.5mm, after implementing the anchor-sprayed support system,. At in-ground distances of 20 meters away from problematic tunnel faults, the tunnel rock tended to be stable. In parts where faults were traversed, subsidence and deformation gradually decreased over time, with the anchor-sprayed support proving effectively able to control deformation.

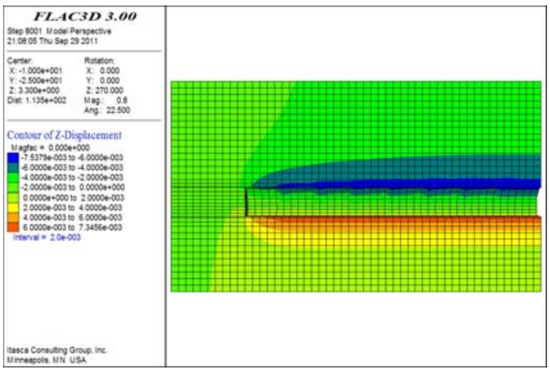

Figure 13. Displacement Diagram - After Retainment & Support

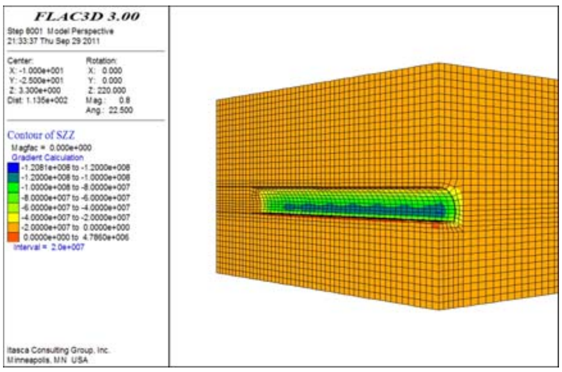

Figure 14. Stress Diagram - After Retainment & Support

The author suggests that an anchor-cable support should be used in addition with and to further reinforce the anchor-spray supported tunnel-rock when the working surface distance reaches a further 100 meters during the following excavation. Use of the anchor-cable will effectively control the otherwise continuous displacement and deformation of the surrounding rock, absorbing the stresses and improving the stability. Figure 14 shows that the stress was mainly concentrated on the two sides of the tunnel-way. After the horse-shoe shaped section was adopted, the stress concentrations in the surrounding rock were able to be effectively controlled. The horse-shoe shaped tunnel clearly provides more advantages than a semi-circle arch or a rectangular shaped tunnel-way.

7. Conclusion

(1) Use of the curved-wall arch section greatly reduced the large, multi-directional, unstable mine-pressures, and tectonic stresses caused by the geology; compared to the initial

rectangular section.

(2) Spraying of the anchor-bolt support system improved the stress situation in the surrounding rock, verified both through in-field monitoring and computer simulation results. Spraying also prevented ceiling collapse, rib-spall and accident; and also reduced the looseness of surrounding tunnel-rock. The anchor, steel mesh and other required materials are all easily obtainable, and; as such, will both save on investment costs and speed-up the construction process.

(3) Utilizing an information-based feedback method for the design of the tunnel retainment and support proved an effective method for safely traversing the major faults and complex geological conditions. The proposed method utilizes: 1) Standard industry-practice safety design parameters for anchor-bolt tunnel engineering; 2) Geological conditions data input: 3) In-situ dynamic monitoring of the support system; 4) A 3-*D* mathematical computer-simulation.

(4) The scheme allows the NanYang Slope Mine-Tunnel 301 to achieve an additional monthly extension and mining excavation amount of 36.9m, saving an overall direct investment of 1026.70 Yuan per meter in total mine-operating costs. The system significantly reduces tunnel maintenance, increases production, and improves the economic performance and safety environment of the mine.

Acknowledgements

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