Destruction Mechanism and Prevention Technique of the Tunnel of Gushing-Water Roof in Xinyi Coal Mine

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Abstract: In view of the deformation and failure of the tunnel of gushing-water roof in Xinyu Coal Mine, this paper analyzes the characteristics and mechanism of tunnel deformation and failure by the combing laboratory experiments, theoretical analysis, and on-site industrial tests. The results show that: 1) the deformation of the gushing-water roof is significant with the maximum deformation value of 700 mm, and the bolt cable and the I-beam bracket are seriously damaged; 2) the failure of 1505 mudstone tunnel roof is considered to be the result of its low strength and easy argillization when it is exposed to water, lack of waterproof measures, unreasonable support methods, etc.; 3) this paper proposes measures such as full anchor cable support, waterproof anchoring agent, and drainage holes, and clarifies their control mechanisms. The field practice shows that the deformation of the ventilation tunnel tends to be stable after about 30 days of the implementation of the plan, thus providing reference for the surrounding rock control in similar tunnels.

1. Introduction
The safe and unblocked coal mine tunnel is of great significance for safe, productive, and efficient coal mining. However, in the process of excavation, the tunnel is inevitably influenced by various factors such as stress concentration, geological structure, mining disturbance, underground water and so on, leading to the problem of tunnel deformation and destruction [1, 2]. Statistics show that most mines in China suffer from water damage of various degrees. The interaction between underground water and the surrounding rock results in significantly lower mechanical properties of the rock, which in turn leads to its significant deformation and lower stability. In addition, water also weakens the anchorage section of the supporting structure, including underground bolts and anchor cables, leading to a plummet of the anchoring effect. Improperly designed supporting structure will lead to the cracking or even instability accidents, thus affecting the safety production of the mine [3]. In recent years, Scholars in China have carried out a lot of explorations on the influencing mechanism between underground water and the surrounding rock and control methods from the perspectives of physics, chemistry, and engineering geology. Yan Hong et al. [4] have analyzed the deformation and failure characteristics of the tunnel of gushing-water roof, conducted quantitative division, and proposed the “four-in-one” control measures with the new waterproof anchoring agent as the core, and have achieved remarkable engineering effect. Yao Qiangling et al. [5] have explored the mechanism of the bearing capacity degradation of the mudstone roof tunnel using indoor test, theoretical analysis, and numerical simulation, pointing out that the clay mineral in the rock layer is the root cause for the...
argillization and expansion of the roof. Qi Yuewei et al. [6] have analyzed the influencing mechanism of water-mud chemistry on the softening and disintegration of mudstone roof from a microscopic point of view, and discussed the effect of time on water-mud action. These studies provide references for analyzing the catastrophic instability mechanism and control measures of water-contained roof tunnel.

Due to the fact that the geological production conditions of coal mines vary widely, different sections of the same tunnel can be different, so the deformation and failure mechanism of the surrounding rock and the corresponding control measures need to be flexibly adopted. This paper conducts field investigation, laboratory experiment, theoretical analysis and field test, based on the typical deformation and failure problems of the gushing-water roof tunnel in Xinyu Coal Mine, in order to analyze the deformation characteristics and failure mechanism of the gushing-water roof and propose corresponding control measures. In this way, this paper can provide technical support for other tunnel support cases in the mine.

2. Overview of engineering geology
Shandong Dongshan Xinyu Coal Mine Co., Ltd. is located in Yanzhou District, Jining City, in the southwest of Shandong Province. The test tunnel is the 1505 transportation tunnel, whose roof is mudstone (3.0 m), coal (0.5 m) and mudstone (2.32 m). The mudstone is in the lamellar structure with relatively developed joint fissure and low strength. The basic roof is made of 2.8 m-thick sandstone, which is dense, hard, and high in strength. The bottom plate is made of 3.0 m-thick mudstone, which is dark gray, muddy, with incomplete plant fossils.

The cracks were developed in the roof sandstone with high water content. The roof water penetrated downwards into the mudstone tunnel through the cracks, which caused argillization and expansion of the mudstone roof, resulting in significant deformation. After tunnel has been excavated for one month, the roof obviously subsided while the deformation of the tunnel continued to increase with time, so the miners had to use the I-beam and single column frame for secondary support. However, since the roof has been damaged with large separation volume, this measure was not effective. In this way, the normal production of the mine has been seriously affected, which has become one of the key issues limiting the efficiency and production of Xinyu Coal Mine. Therefore, it is necessary to study the instability mechanism and prevention technology of the tunnel of the gushing-water roof by selecting the typical area of the 1505 transport channel.

3. Characteristics of tunnel deformation and failure and characteristic test on the surrounding rock
Through long-term observation of the tunnel, the following characteristics of tunnel deformation which mainly occurs in the roof have been found:

1) Large deformation of the roof
The deformation of the roof of the 1505 transport channel is shown in Figure 1. It can be seen that the sinking and deformation of the roof was significant, with the maximum sinking deformation of 700 mm occurring the central part of the roof. The roof rock was severely broken, and the fractured rock mass was pocketed by the diamond-shaped metal mesh. As the roof sank, the bolt moved downward, significantly bending the I-beam.
4. Deformation mechanism and control countermeasures of gushing-water roof tunnel

4.1 Cause of deformation

Although the 1505 transportation tunnel has adopted the strong supporting measure of the anchor cable, large deformation still occurred on the roof. According to the comprehensive analysis of the mechanics environment and characteristics of the surrounding rock, the roof mudstone was low in strength and prone to argilization, expansion, and deformation when it met water, which further leads to loosening of the roof and failure of the supporting structure. The following is the specific analysis:

1) The surrounding rock was low in strength and poor self-stability with developed cracks. According to the previous geological survey, the uniaxial compressive strength of the mudstone roof was only 26 MPa, and the tensile strength was about 3.4 MPa, which was quite low. During engineering, the strength of the surrounding rock was affected by the mining disturbance, so the cracks rapidly expanded, and the mudstone strength decreased rapidly, making it prone to instability and rupture.

2) The surrounding rock shows the characteristic of obvious swelling and deformation when it meets water. From the composition of minerals, it is known that the mudstone roof contains a large amount of clay minerals such as kaolinite and montmorillonite, which will undergo significant expansion and deformation when exposed to water. However, the sandstone of 1505 transport channel contained a large amount of roof water, which had not been handled efficiently. Thereby, the roof water penetrated into the mudstone roof in a large extent, which led to significantly reduced roof strength and further declining stability.

3) No measures have been taken to discharge water. In addition to meeting the strength requirement of the supporting structure in the maintenance of surrounding rock in common situations, gushing-water roof tunnel also requires to inhibit the erosion of the roof rock. What’s more, the effect of conventional anchoring agents tends to be weakened by water, thus lower anchoring effect, which in turn affects the supporting effect and roof stability. Therefore, it is necessary to take protective measures in this regard.
4) The supporting method is inappropriate. Although the anchor cable supporting measure is adopted, the overall strength of the anchor was relatively low with a lot of breakage on the site. The length of the original anchor cable was 4300 mm, so that the anchor point was located inside the mudstone roof, making the anchor cable unable to anchor to the stable rock formation of the roof. In this way, the bearing capacity of the surrounding rock cannot be fully exerted.

4.2 Control countermeasures
Based on the above analysis of the causes for deformation and damage, it is considered that the significant stiffness and strength improvement of supporting structure and effective waterproofing measures are the effective ways to control the catastrophic instability of the gushing-water roof. By improving the anchor cable supporting method, enhancing the bearing capacity of the roof, and taking effective waterproof measures to suppress the erosion of the roof mudstone and the supporting structure, the safety of the tunnel of gushing-water roof can be ensured.

1) Strong short-anchor supporting roof
Compared with the anchor rod, the anchor cable can provide a higher preload and improve the initial support strength and rigidity of the roof panel, thereby effectively suppressing deformation of the surrounding rock of the roof and maintaining its integrity. For the 1505 roof tunnel with the thick mudstone low in strength, it is impossible to ensure roof stability by simply using the bolt support. Therefore, the full anchor cable is used, which can effectively improve the mechanical state of the roof and ensure the high strength and rigidity of the roof supporting structure by increasing the preload of the anchor cable and adopting a reasonable arrangement, thus limiting the expansion deformation of the rock layer.

2) Strong long-anchor cable supporting roof
In order to prevent the accident of the overall cutting of mudstone roof, it is necessary to re-reinforce the roof using the long anchor cable in addition to the short one. In this way, the short anchor cable at the bottom can anchor the deep rock mass, thereby improving the overall stability of the structure, forming a larger bearing structure of support-surrounding rock, and effectively controlling the deformation of the surrounding rock.

3) Waterproof anchoring agent
Anchoring agent is key to the anchoring effect of the anchor cable structure. The anchoring performance of the ordinary anchoring agent is greatly reduced when it meets roof water, so that the anchor cable structure cannot fully function. In this way, the coal rock mass in the anchoring area is prone to separation, resulting in the instability of the supporting structure. The waterproof anchoring agent has strong instantaneous solidification strength and long-term solidification strength, and is less affected by water, which makes it able to guarantee the stability of the supporting structure.

4) Arrangement of roof drainage holes
For the tunnel with abundant roof water, the roof water will leak into the tunnel along the borehole during the installation and support of the bolt. When the water flow is large, it will be difficult to fix and anchor the anchoring agent. Drainage holes in the roof can effectively release part of the roof water, thus reducing the influence of the roof water on the supporting process.

5. Engineering practice

5.1 Supporting plan
Based on the deformation and failure characteristics of the 1505 transport tunnel in Xinyu Coal Mine, combining the existing economic and technical conditions of the coal mine, this paper proposes the high-preload short-anchor cable strong supporting plan, and designs parameters by adopting the theoretical design, numerical simulation optimization, and engineering analogy method.

1) The short anchor cable is made of Ф21.6 mm steel strands, with the length of 5300 mm, the exposed length of 300 mm, the spacing between rows of 720 mm×800 mm, and the preload of not less than 200 kN. One roll of FSCK2340 and one roll of FSK2340 are taken as the waterproof anchoring
agent, and 300mm×300mm×16 mm high-strength ball-type tray is used in this paper. In addition, the 4500 mm×176 mm×6 mm M-shaped belt is used in the same row of anchors. The long anchor cable is made of 1.621.6 mm×7300 mm steel strands, with each strand in each row 1600 mm away from the other. One roll of FSCK2340 and one roll of FSK2340 are taken as the waterproof anchoring agent.

2) The bolts are Φ20 mm×3000 mm screwing threaded steel bolts, and four bolts are arranged per row with a spacing of 870 mm, and a row spacing of 800 mm. They are anchored with one roll of CK2340 and one roll of K2340. The strengthened anchor cable is made of Φ21.6 mm×5300 mm steel strands, with a row spacing of 1600 mm. One row is arranged with one anchor cable. The waterproof anchoring agent is one roll of FSCK2340 and one roll of FSK2340.

3) In order to strengthen roof water discharge, a Φ28 mm×5500 mm drainage hole is arranged every 8 m in the middle of the roof to guide the roof water to the drainage channel in the tunnel.

5.2 Analysis of engineering effect
The monitoring results of the displacement of the surrounding rock surface and the condition of the roof separation during tunnel excavation show that the tunnel deformation tended to be stable about 30 days after excavation, the maximum roof deformation was about 180 mm, and the separation value was 10 mm, which were all within the safety range. No damage or breakage of the anchor cable occurred during the service of the tunnel. Therefore, the proposed supporting plan can effectively solve the problem of deformation and damage of the gushing-water roof.

6. Conclusion
1) The roof of 1505 transport channel is a typical gushing-water roof tunnel with significant roof subsidence. The roof water rendered the anchor cable unreliable, and the support unevenly loaded, resulting in the damage of the anchor cable and the supporting structure.

2) The gushing-water roof tunnel of Xinyi Coal Mine adopts the comprehensive treatment measures combining full anchor cable support, waterproof anchoring agent, and drainage holes. The tunnel deformation tended to be stable within 30 days after tunnel excavation, and the deformation of surrounding rock was controlled within the safety range. In this way, this paper provides technical support for other similar supporting cases in the mine.

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