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Failure mechanism of surrounding rock with high stress and confined concrete support system

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ABSTRACT

Surrounding rock control is a big challenge in roadway with high stress in deep underground engineering. To address this issue, Zhaolou coal mine – a typical kilometer deep well is taken as engineering background to monitor and analyze the original support scheme. The analysis shows that the following main reasons lead to the support failure in roadway with high stress in deep underground coal mine. Roadway deformation is large and lasts longer with a large extent of damage; all anchor bolts are in severely damaged surrounding rock zone without reliable adhesive basis; and U-shaped steel arch unevenly contacts with surrounding rock without sufficient bearing capacity. With summary of support failure mechanisms on-site, a concept of "high-strength and integrity support" is put forward; a support system with square steel confined concrete (SQCC) is developed; and a full scale in-door comparative test is conducted on its core component – SQCC arch and also on the conventional U29 arch. The research shows the bent and damaged legs of U29 arch result in dramatic reduction of bearing capacity of arch. However, the SQCC arch with similar steel content has a bearing capacity of 2.15 times of that of U29 arch and still has a higher post bearing capacity even after the arch is deformed dramatically. Quantitative evaluation index is established such as vault displacement control rate and bolt strength utilization rate; comparative analysis is made on surrounding rock control mechanism and the mechanical properties of support components under the influence from the four factors – arch strength, geostress, lateral pressure coefficient and surrounding rock mechanical parameters; and good control effect on surrounding rock of SQCC support is verified. Comparative tests are conducted on site. The monitoring results show the roadway surrounding rock deformation on the test section of SQCC support is only 21.2% of that on test section of U29 arch support; and no yield and damage occurs on the test section of SQCC support. Therefore, the SQCC support system is proved to be effective on surrounding rock control.

1. Introduction

Currently, underground coal mining has become deeper and larger in order to keep pace with the increasing demand in energy worldwide. According to incomplete statistics, actual repairing rate of roadway is as high as 90% in deep underground; and the rate in the mining depth of 1000 m is 3–15 times of that in the depth of 500–600 m. The accidents due to deep mining such as roadway surrounding rock large deformation, floor heave, shotcrete spalling and roof collapse account for more than 40% of all the accidents in mine construction and production; and the death toll in deep mining accounts for 50% of that of death rate of million-ton coal-mine in the entire industry in China. In this situation, we need to fundamentally recognize the deformation mechanism and put forward reasonable control measures for roadways in deep underground; and therefore, the production safety is guaranteed and the economic efficiency is increased in coal mine industry.

Researchers have conducted numerous researches on deformation, failure mechanism and control measures for roadway in the deep underground.[1–26] He[1] and Sun[2] proposed a design theory of nonlinear large deformation of surrounding rock in deep underground and developed a bolt with constant resistance and large deformation. Kang et al.[3,4] put forward the reinforcement technique of combined support system of high pretension and strength bolts and cables with grouting. Srisharan et al.[5] made a comparative analysis on the stability between two differently shaped tunnels under significantly high stresses through establishing discrete element analysis model; and their analysis

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provided some references for tunnel shape and support components. Kang and Liu et al.[6] analyzed the supporting difficulties and mechanism of soft fragmentized surrounding rock roadway with high stress; and they proposed a new kind of combined supporting system including a new kind of hollow grouting cable. Jiao et al.[7] made an improvement on the traditional U-shaped steel sets to efficiently support and stabilize the roadways in loose thick coal seam. Li and Yao[8] proposed key technologies for supporting the roadway by stages in different regions after considering time effects, local breakdown characteristics and fracture development. Li et al.[9] developed a support technology of high strength anchorage grouting with the new hollow grouting bolt of high strength as the core; and their technology solved the problems such as soft and seriously broken surrounding rock on site and the frequent supporting component failure of the chambers with large cross-sections. Li and Wang[10] studied deformation characteristics of the surrounding rock in deep roadway with thick top coal; and they designed the pressure relief anchor box beam system. Singh et al.[11] studied the causes of failure of two wire ropes used at high stress levels from two different Indian coal mines. Rama et al.[12] conducted a detailed parametric investigation on roof bolt-based breaker line support (RBBLS) for a better performance, and proposed empirical formulations among the relevant geo-mining parameters for the design of a RBBLS. Hudewentz and Lucker[13] discussed the technologies for developing roadways in deep German coal mines under difficult ground conditions. Sasaoka et al.[14] discussed the applicability of a roof bolting support system in Indonesian coal mines.

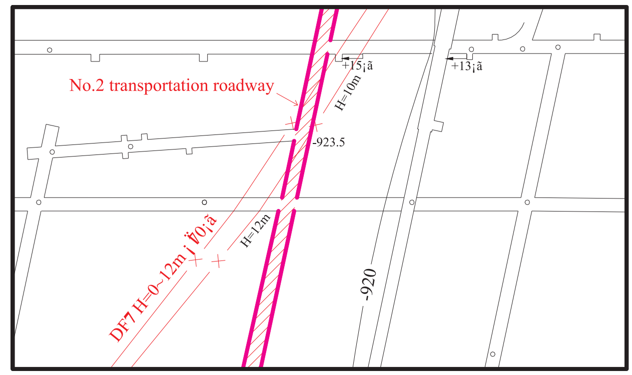
In the previous studies, a certain progress has made in resolving the surrounding rock control problems in deep roadway with high stress. However, the high stress environment on the project site is complicated and changeable; deformation and failure mechanisms of surrounding rock need to be further clarified; the existing supporting technologies can hardly meet the requirements of the surrounding rock control in this kind of roadway; and the support problems still remain serious. Based on previous studies, this paper takes a typical kilometer deep well - Zhaolou coal mine as engineering background to analyze the failure mechanism and control mechanism of roadway with high stress through field monitoring and numerical calculation; a concept of "high-strength and integrity support" is proposed; and a new support system of square steel confined concrete is developed and applied in the field. We hope all we have done could provide some references for solving support problems of this kind of roadway.

2. Monitoring and analysis on deformation and failure of roadway with high stress

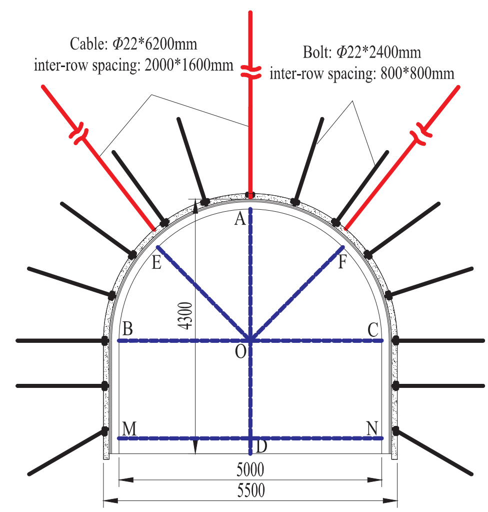
2.1. Project background

As a large coal field, Juye Coalfield is located in China. The burial depth of its coal-bed is 800–1300 m. Zhaolou coal mine is located in the middle of Juye Coalfield. It is a typical kilometer deep well with a designed production capacity of 3.0 million tons / year. The horizontal principal stress is approximately 36.26–45.75 MPa, about 1.50 times of vertical principal stress averagely. The No.2 transportation roadway is selected as the object of our study, a high-dip-angle fault (DF7) goes through the roadway and breaks up to 10 m, as shown in Fig. 1(a). The roadway is arranged in mudstone layer, which is 14 m in thickness, the distance between the roadway floor and the mudstone floor is 1–2 m. Above the mudstone layer is mainly siltstone, which is 11 m in thickness. Below the mudstone layer is mainly siltstone and fine sandstone, which is 21 m in thickness. The hardness of mudstone, siltstone and fine sandstone in Protodyakonov coefficient are 2.5, 4.1 and 5.3, respectively.

The cross-section of the roadway is in a shape of straight wall and semicircular arch with a net width of 5000 mm and net height of 4300 mm; and its support form is bolt-shotcrete + U29 arch combined support, as shown in Fig. 1(b). Bolt model is Φ22*2400 mm with inter-



(a) Location of research roadway



(b) Original supporting scheme and layout of displacement monitor points

Fig. 1. Location and original supporting scheme of research roadway: (a) Location of research roadway, (b) Original supporting scheme and layout of displacement monitor points.

row spacing of 800*800 mm; cable model is Φ22*6200 mm with inter-row spacing of 2000*1600 mm; C25 concrete is sprayed on the roadway surface with thickness of 100 mm; and the row spacing of U29 arch is 800 mm.

2.2. Monitoring and analysis on surrounding rock deformation and supporting components

On-site monitoring and analysis are made on the roadway surface displacement, the extent of surrounding rock damage and the stress on supporting components. That is to clarify the mechanism of deformation and failure of surrounding rock in the roadway in the original support scheme.

2.2.1. Monitoring on convergence of surrounding rock deformation

A corresponding monitoring program is designed for the deformation of roadway surrounding rock on site. As shown in Fig. 1(b), the monitoring points are Point O in the center, and Point A – F, M and N on the boundary of the roadway. The monitoring results are shown in Fig. 2.

The monitoring results of 198 days show the roadway surrounding rock has significant characteristics of large deformation, poor stability and long duration of deformation. Deformation occurs immediately after the completion of the roadway excavation. On the 10th day of monitoring, the convergence of the two sides reaches to 276 mm; in 38 days, the surrounding rock deformation rate increases significantly; and