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Study on failure mechanism of roadway with soft rock in deep coal mine and confined concrete support system

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ABSTRACT

Surrounding rock control is a tough issue in roadway with soft rock in deep underground. To solve this problem, the original supporting scheme is monitored and analyzed on site with Liangjia coal mine of China as engineering background. Located in Longkou seashore mining area, Liangjia coal mine is a typical deep mine with soft rock in China. The analysis shows that roadway deformation is large with a big damage range; anchor bolts are generally in seriously broken surrounding rock; the support potential fails to be played; the support strength of arch is insufficient and the post bearing capacity is low. All of these mainly lead to the failure of the roadway bearing capacity. Numerical test is conducted with the consideration of arch strength, geostress, mechanical parameters of surrounding rock and other factors; it is to comparatively analyze the deformation of surrounding rock, the range of plastic zone and the mechanical properties of support components under different factors; therefore, the failure and control mechanism are defined on deep roadway with soft rock; and a concept of "high-strength, integrity, and pressure-relief" is proposed. Meanwhile, a confined concrete (CC) support system is developed; and a laboratory comparative test for full-size arch is carried out on its core component - CC arch and the conventional U36 arch as well. The research shows that the instability and failure of the entire U36 arch is caused by partially bending and buckling of the arch, and its bearing capacity is drastically reduced. The bearing capacity of CC arch is 2.03 times compared with that of U36 arch, and also has a good post bearing capacity. On the basis of these numerical and laboratory tests, a comparative test is carried out on-site. The monitoring results in the test show the rock deformation in CC support testing section is only 22.4% of that in U36 arch support; and no yield and failure phenomenon occurs in CC support test section, which proved the effectiveness of CC support system on surrounding rock control.

1. Introduction

Soft surrounding rock has been a major problem threating the safety and efficiency of coal production. Especially along with the coal mining gradually developing to deep underground, more and more various nonlinear mechanical phenomena occur on such roadways and make the support more difficult [1,2]. Under the influence of various factors such as geostress, dynamic pressure, geological structure, surrounding rock is broken and loose with a large extent of damage and fractured joints; and its deformation is

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severe and in rheological form. Roof falling, slabbing and floor heave emerge in endlessly, therefore, frequent renovation is needed; and the cost of maintenance is much more than the construction dose. According to statistics, annual maintenance cost can reach as high as one hundred million yuan or more on roadways with soft rock for a coal mine with production capacity of 1.2 million tons/year.

Scholars have carried out a lot of research on deformation and failure mechanism of roadway with soft rock, put forward and developed the supporting technology for the roadway [3–8]. C.C. Li developed an energy-absorbing rock support device, called a D bolt [9]. M.C. He proposed a design theory of large nonlinear deformation of surrounding rock, designed bolt-net-anchor coupling support and a novel energy-absorbing bolt characterized by an extraordinarily large elongation and high constant resistance [10]. S Shreedharan made a comparative analysis on the stability between two differently shaped tunnels under significantly high stress through establishing discrete element analysis model; and provided some references for tunnel shape and support components [11]. H.N. Wang derived a general analytical solution of tunnel with soft rock accounting for time effect, and analyzed the influence of different factors on the continuous excavation of tunnel with soft rock [12]. H.H. Zhu modified an elasto-viscoplastic model, and predicted the long term stability of roadway with soft rock [13]. Y.L. Lu analyzed the rational grouting time for roadway with soft rock by numerical simulation using the strain softening constitutive law, and proposed a method integrating numerical simulation and monitoring for determining the rational bolt-grouting time [14]. In view of the problems of high-stress roadway with soft rock, such as large plastic zone and large deformation, H.T. Liu invented a new type of lengthened bolt to achieve the goal of "yield support" based on the theory of "strong support and yield pressure" [15]. S.G. Jing studied the causes of instability of "three-soft" coal seam, and put forward the strengthening control mechanism with shed and cable, and realized the collaborative bearing of the shed, cable and surrounding rock [16]. According to the field investigation and experiments on a typical mining roadway with soft rock in Liangjia coal mine of China, Q. Wang and R. Pan carried out field contrast tests of bolt-grouting support as a core measure to solve the control problems of surrounding rock [17], and conducted field test on the parameters of bolt-grouting in deep coal seam [18]. Y.S. Kang and Q.S. Liu took Huainan coal mining area of China as an example to analyze the supporting difficulties and mechanism of high stress roadway with soft fragmentized surrounding rock; and proposed a new kind of combined supporting system and three-step grouting technology [19,20]. Y.Y. Jiao made an improvement on the traditional U-shaped steel sets to efficiently support and stabilize the roadways in thick and loose coal seam [21].

The previous studies have made a certain progress in resolving the surrounding rock control problems in deep roadway with soft rock. In summary, the current control technologies for roadway control in soft rock mass are mainly divided into three kinds: (1) Combined support with bolt wire cable and shotcrete, which can meet the needs of shallow surrounding rock control, but could not adapt to large deformation due to the insufficient elongation of anchor cable and bolt support strength; (2) Bolt grouting, which is a widely adopted technique at present, but could not meet the needs of surrounding rock control under the condition of extremely soft rock and the influence of mining, resulting in long-term deformation and secondary damage; (3) Combined support of bolt-shotcrete and U-shaped steel arch, the key component is the U-shaped steel arch of this kind of support form, and the control effect is obvious. It is found that along with the increase of arch strength, the displacement decreases inversely [22]. However, there are two main disadvantages of this kind of support. One is the insufficient strength of the U-shaped steel arch under deep underground; the other is the uneven contact of the U-shaped steel arch with surrounding rock, make the U-shaped steel arch fail to play its supporting potential, the bearing capacity of the U-shaped steel arch under the worst load is about 6.4% compared with that under the uniformly distributed load [23]. In addition, the steel-concrete support system is widely used in ground constructions such as buildings and bridges, and it is a very effective support structure [24,25]. However, the research focuses on steel-concrete columns and pure bending components. The research and application is little on underground steel-concrete support system due to the different mechanical mode and design method from those of ground constructions.

The current pressure-relief technologies are implemented by the following ways: (1) Install some yield devices on the anchor bolt and anchor cable, such as yielding rings; (2) Change the self-structure of the anchor bolt or anchor cable, such as D bolt [9] and He bolt [10]; (3) For the U-shaped steel arch, the self-scalability is used to achieve pressure-relief, but the pressure is not quantified, the pressure-relief time and the amount of pressure are uncontrollable. However, deformation and failure mechanism of surrounding rock still need to be further clarified due to the complicated and changeable engineering geological conditions; and the support problems are getting worse, especially as the coal mining is moving to deep underground.

Based on previous studies, a typical deep mine with soft rock in China – Liangjia coal mine is taken as the engineering background to analyze the surrounding rock deformation and failure mechanism of its roadway; a concept of "high-strength, integrity, and pressure-relief" is proposed; and a confined concrete (hereinafter referred to as CC) support system is developed and tested in the field. The support system is composed of three layers of bearing structure, namely the bearing layer of high-strength, adjustment layer of fillings, and anchorage self-bearing layer. It has characteristics such as high-strength, high-rigidity and pressure-relief. Compared with other pressure-relief technologies, the pressure-relief of the support system is implemented mainly by the following way: The developed quantitative pressure-relief device is installed inside the CC arch to realize the quantitative pressure-relief. The successful field test indicates that the CC support system is a pretty good solution in supporting the roadways with soft rock. We hope to provide some references for supporting the roadways with soft rock.

2. Project background

2.1. Project overview

As shown in Fig. 1, Liangjia coal mine is adjacent to China Bohai Sea and located in Longkou seashore mining area of Shandong