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Investigation of stability of a tunnel in a deep coal mine in China

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ABSTRACT

Stability level of tunnels that exist in an underground mine has a great influence on the safety, production and economic performance of mines. Ensuring of stability for soft-rock tunnels is an important task for deep coal mines located in high in situ stress conditions. Using the available information on stratigraphy, geological structures, in situ stress measurements and geo-mechanical properties of intact rock and discontinuity interfaces, a three-dimensional numerical model was built by using 3DEC software to simulate the stress conditions around a tunnel located under high in situ stress conditions in a coal rock mass in China. Analyses were conducted for several tunnel shapes and rock support patterns. Results obtained for the distribution of failure zones, and stress and displacement fields around the tunnel were compared to select the best tunnel shape and support pattern to achieve the optimum stability conditions.

1. Introduction

Due to increasing demand and exploitation, shallow resources are decreasing each day, and many mines all over the world exploit resources located at deep formations with time. Mines at depths of more than about 500 m may be called as deep mines. The depth of coal mine exploitation has increased at a rate of 8–12 m per year in China, and 100–250 m per 10 years in eastern China [1]. Recently, numerous coal mines in China have moved into the state of deep exploitation, some even more than 1000 m. Caitun Coal Mine in Shenyang at a depth of 1197 m, Zhaogezhuang Coal Mine in Kailuan at a depth of 1159 m, Zhangxiaolou Coal Mine in Xuzhou at a depth of 1100 m, Guanshan Coal Mine in Beipiao at a depth of 1059 m, Suncun Coal Mine in Xinwen at a depth of 1055 m, Huafeng Coal Mine in Xinwen at a depth of 1160 m, and Gucheng Coal Mine in Yanzhou at a depth of 1050 m are typical examples of mines in China that operate at depths over 1000 m [1–3]. Most of the coal resources are deposited in deep formations in China. The reserves of coal available at depths greater than 600 m and 1000 m are up to 73% and 53%, respectively. It is predicted that more and more coal mines will extend to depths of 1000–1500 m in the next 20 years in China [1]. With increasing depth of exploitation, a series of problems, such as: (a) more complicated geological environment, (b) high in situ stresses, (c) high water flows, and (d) high earth temperatures are encountered. These features lead to: (a) difficult tunnel maintenance, (b) higher risk of rock burst, (c) difficult exploitation conditions, (d) reduction of safety, productivity and economic benefits, and (e) difficult ventilation design. Out of the aforementioned factors, the high in situ stress is the main factor that poses tremendous threat to safe and efficient exploitation of deep resources. High in situ stress is inevitable with deep resource exploitation. Under high in situ stress, large deformations and failure around the tunnel become serious issues. Even with strong rock support systems, control of deformations and failure around the mine tunnel and maintenance of it become an expensive and challenging task. Superior tunnel designs and rock supporting technologies are required to stabilize deep mines having high in situ stresses. Different rock support systems such as rock bolts, cable bolts, shotcrete and wire meshes have been suggested in the literature to strengthen underground excavations [3–9].

Xinwen coal area is one of the largest coalfields in Northern China that has been under production for a significant period of time. Most of the coal mines in this area have extended to a depth of almost 1000 m underground. Xiezhuang Coal Mine located in this area (Fig. 1) is the case study dealt with in this paper. Several development tunnels have been excavated in this mine to a depth of more than 1200 m. The tunnels are located in a sandy shale stratum, which belongs to the soft rock category. When high in situ stress acts on a soft stratum, large deformations and failure zones around the tunnels are expected if the tunnels are not supported. This increases the risk of fatalities and injuries with respect to the mine work force and damages to mine equipment. It slows

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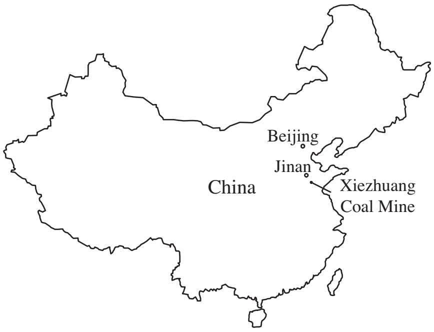

Fig. 1. Location of Xiezhuang Coal Mine in China.

down the mine production and reduces economic gains. Therefore, in order to ensure the safety of the mine work force and mine equipment, and steady, efficient exploration of coal, it is essential to have a stable tunnel system in the mine. It is predicted that there will not be major geological structures in the vicinity of tunnel construction. Several small faults may get exposed during tunnel construction. Also, no adverse hydro-geological conditions are expected in the tunnel crossing areas.

In this paper, stability of an underground excavation in the Xiezhuang Coal Mine is investigated using two different tunnel shapes and several different tunnel support patterns. Based on the results obtained from numerical modeling for deformation, stress and failure zones around the tunnel, the better tunnel shape out of the two investigated and the best rock support system out of the ones tried are determined. In addition, numerical predictions are compared with the field deformation measurements performed around the tunnel at the mine. The stratigraphy obtained through field geological investigations, in situ stress measurements carried out in the mine, physical and mechanical properties of rock and discontinuity interfaces estimated through laboratory tests conducted on different rock material that exist around the tunnels are used in the performed study.

2. Brief literature review on discontinuum numerical modeling applications to tunnels

Most naturally occurring discontinuous rock masses comprise of intact rock interspaced with different types of discontinuities. Such discontinuities include fissures, fractures, joints, faults, bedding planes, shear zones and dykes. The existence and behavior of discontinuities in a rock mass will influence the mechanical behavior of the discontinuous rock mass. In underground excavations, discontinuities will play a significant role on the failure conditions and stability of the rock mass around an underground excavation.

Several numerical methods have been used to perform stress analyses and to evaluate stability of underground excavations in jointed rock masses by incorporating discontinuities explicitly. The finite element, boundary element and Lagrangian finite difference programs have been used with interface elements or “slidelines” to model a discontinuous material to some extent. However, their formulation is usually restricted in one or more of the following ways: first, the logic may break down when many intersecting interfaces are used; second, there may not be an automatic scheme for recognizing new contacts; and third, the formulation may be limited to small displacements and/or rotations [10]. Therefore, the finite element, boundary element and Lagrangian finite difference programs are not suitable to simulate the large displacements and large rotations that may occur in jointed rock masses. The distinct element method (DEM) and discontinuous deformation analysis (DDA) are better suited than the finite element, boundary element and finite difference methods to perform discontinuum analysis of underground excavations in jointed rock masses [11–13].

The distinct element method introduced by Cundall (1971) and further developed by Lemos et al. (1985), Cundall (1988) and Hart et al. (1988) is a powerful technique to perform stress analyses in blocky rock masses formed by persistent discontinuities [11,14–16]. In this method, the rock mass is modeled as an assemblage of rigid or deformable blocks. Discontinuities are considered as distinct boundary interactions between these blocks; joint behavior is prescribed for these interactions. The distinct element algorithm includes not only continuum theory representation for the blocks, but also force displacement laws which specify forces between blocks and a motion law which specifies the motion of each block due to unbalanced forces acting on the block. By taking into account the interaction of intact blocks and joints, the distinct element method can effectively calculate the mechanical behavior of block systems under different stress and displacement boundary conditions. The method employs an explicit solution procedure. An advantage of the explicit method is that, because matrices are never formed, large displacements, rotations and complex constitutive behavior for both intact material and joints are possible with no additional computing effort. The distinct element method has been used to evaluate the stability of underground excavations [17–22]. All these research have been carried out at the two-dimensional (2-D) level using the UDEC software. In the research reported in this paper, the distinct element method is used at the 3-D level in investigating deformation and stability around a tunnel excavated in soft rock.

The DDA is a numerical model for the analysis of discontinuous block systems [12,13]. It treats the jointed rock mass as an assemblage of interacting rock blocks bounded by intersecting joint planes to study the behavior of discontinuous or jointed rock masses. The DDA has been used by some researchers at the 2-D level to evaluate the stability and failure modes of underground excavations [23–26].

3. Cases of tunnel excavation and support

For all coal seams in China, the maximum exploitation depth is set to −1500 m. As depth increases, the effect of increasing in situ stress on the deformation, stress and failure zones around tunnels located in soft strata increases. As the depth of a tunnel increase, in addition to observing instabilities increasing on the roof and the ribs of the tunnel, fracture and floor heave increase on the floor of the tunnel [7,27,28]. This will require reinforcing the floor of the tunnel in addition to reinforcing the roof and ribs of the tunnel.

In order to comprehensively research the deformation, stress and failure zones around a soft rock tunnel under the condition of different rock support patterns, three types of support systems are used in the numerical modeling performed in this research. To study the effect of tunnel shape on stability around the tunnel, two tunnel shapes are considered: a horseshoe shape with a semicircle arch and an inverted arch tunnel shape based on the dimensions of the horseshoe shape. Fig. 2 shows the shapes and dimensions of the cross sections of the two tunnels used in this study.

Numerical stress analyses were performed for the following cases:

Case 1: Horseshoe shape without any support (Fig. 3a).
Case 2: Inverted-arch shape without any support (Fig. 3b).
Case 3: Horseshoe shape with normal bolt support on the roof and ribs as shown in Fig. 4a.