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Numerical modelling of strata movement at footwall induced by underground mining

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ABSTRACT

During metal mining, the deformation and failure of rock mass are very important factors that dominate rock movement and zoning. Numerical modelling provides a feasible way to study the deformation and failure of rock mass. In this study, a numerical method of UDEC was adopted to study strata movement mechanism influenced by NWW-trending joints at the footwall at Chengchao Iron Mine, and the Mohr-Coulomb model and the Coulomb-slip model with residual strength were adopted as the constitutive models of rock masses and joints, respectively. The whole strata movement process was simulated and the strata movement mechanism at footwall and zoning phenomenon was clarified. In the chimney caving development stage, gravity is the driving force and surface deformations are mainly subsidence deformation of the surface above the ore body. In the post-chimney deformation stage, horizontal tectonic stress is the driving force and surface deformation and subsidence are dominated by horizontal deformation of the hanging wall and footwall in the mining area. After the level −395.0 m is mined out, the deformation characteristics of deep surrounding rock were revealed by means of numerical modelling, the maximum failure depth of the cantilever beam and the spatial distribution of deep surrounding rock zones can be determined. At last, the influencing boundary of surface deformation expands rapidly in a linear way with the excavation step and the expanding velocity of the horizontal deformation is greater than that of the subsidence in the post-chimney deformation stage.

1. Introduction

Strata movement refers to the phenomena and processes of deformation, movement, and crack of overlying strata caused by mining.[1] The mechanism of rock strata movement induced by coal mining has been extensively described, including the theory of voussoiring beams proposed by Qian[2] and the theory of transferring rock beams.[3] However, current studies of strata movement in a coal mine mainly focus on the vertical zoning model[4,5] or the horizontal zoning model[6,7] induced by roof strata movement. Palchik[4] proposed that overburdened strata in a coal mine can be divided into three zones along the vertical direction: the continuous zone, fractured zone, and caved zone. Mark[5] divided the overburdened strata in a coal mine into four zones along the vertical direction: the caving zone, fracture zone, dilated zone, and confined zone. Overburdened strata could also be divided into three zones along the horizontal direction[6]: the coal pillar supporting zone, the separation zone, and the re-compacted zone, based on the curve of strata subsidence, in which the separation zone can be further divided into the support zone and the bed-separation zone. Based on different failure mechanisms, Liu[7] also divided the roof rock mass in a coal mine into the tensional stress-dominated zone and the shear stress-dominated zone along the horizontal direction.

The mechanism and zoning models of rock movement have been studied thoroughly for coal mines, but less is known about application to metal mines. The theories on rock strata movement derived from coal mines cannot be directly applied to metal mines due to differences in the ore-body geological conditions, the ratio of mining depth to the height of the goaf, mining methods, and in-situ stresses.[8] Thus, many researchers are currently working to determine the mechanism and zoning model of strata movement in metal mines. Brown[9] studied the block caving method and concluded that if the orebody is vertical with a well-defined cut-off between it and the surrounding country rock, the cave will propagate vertically to the surface, such that inclined surface slopes form only in weak or weathered surface layers. Hoek[10] studied the progressive collapse of a hanging wall in the Gangesborg Mine during a 40-year mining period and concluded that if a major set of

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persistent discontinuities dips steeply in a similar direction to the orebody, toppling of the hanging wall rock mass may occur. He developed a limiting equilibrium analysis to predict hanging wall failure with increasing mining depth from a known initial position. This analysis assumed a flat ground surface and full drainage throughout the caving mass. Brown and Ferguson[11] extended Hoek's analysis to consider a sloping ground surface and groundwater pressures in the tension crack and the shear plane. Brady and Brown[12] categorized surface deformations into three distinct zones: former open pit, zone of surface cracking, and subsidence zone. Lupo[13] categorized surface deformations at several caving mines into three distinct zones, the caved rock zone, the large-scale cracking zone (or fractured zone[14]), and the continuous subsidence zone.

In a metal mine, both rock movement and the zoning phenomenon can be explained by site geological conditions, surface deformation monitoring, and observation data. Thus, the deformation and failure of deep surrounding rock strongly influence the mechanism of rock movement and zoning phenomenon. In recent years, numerical methods have been developed that provide a new way to study the deformation and failure of deep surrounding rock and the whole strata movement process. Numerical modelling is low cost, less time-consuming, and highly reproducible method requiring visual observation of deformation and failure of deep surrounding rock and complex geological structures. Recently, several numerical codes, including FLAC,[15] UDEC,[16] PFC,[17] DDA,[18] ELFEN[19,20] and RFPA2D[21] have been developed and applied to model mining-induced subsidence. The numerical models allow study of the whole process of strata movement induced by underground mining.

Here, the whole process of strata movement induced by underground mining at Chengchao Iron Mine was studied using a numerical method based on field geological survey data, which provided a basis for sensitivity analysis of in-situ stress and joint parameters. The surface deformation induced by strata movement and deformation and the failure of deep surrounding rock are difficult to comprehensively monitor. Instead, numerical simulation is conducted to model the whole process of surface deformation and the deformation and failure characteristics of the deep surrounding rock to reveal the strata movement mechanism.

2. Engineering geology and mining situation

A general geosocial description of the Chengchao Iron Mine was presented in detail by Cheng et al.[8]. In this section, some important issues related to the numerical simulation are briefly introduced. The distribution of rock masses between the footwall and the hanging wall affects the mechanism of strata movement and surface deformation. Because the most important infrastructures of the mine lie on the footwall, this study mainly focuses on the mechanism of strata movement and surface deformation at the footwall.

As shown in Fig. 1, most of the important infrastructure are in the western part of the mine, including the Mineral Processing Plant, the Mine Highway, the former ore stockyard area, the new auxiliary shaft, the Transport Tunnels, the Eastern Main Shaft (abandoned), and the Western Ventilating Shaft (abandoned) are near the No. 35 prospecting line. The locations of two collapse pits and four observation points are indicated in this figure.

The geological profile of the No. 35 prospecting line is shown in Fig. 2. It can be seen from Fig. 2 that the rock mass in the hanging wall is dominated by the hornstone of the Puxi Group in the Triassic System. The marble and diorite are mainly distributed over the ore body, and the rock mass in the footwall is dominated by granite. Obviously, the presence of joints significantly influenced the strata movement mechanism at the footwall in this iron mine. Thus, the distribution of joints in the footwall was studied in the Service Shaft and the Western Ventilating Shaft and the results are listed in Table 1. Four sets of joints are in the granite at the footwall, all of which are designated compression-shear structure planes, and striking N34°E, N75°W, N14°W, and N73°E. Of these, the set of joints striking N34°E were the most developed, with a dip angle of about 87° to the NW with a spacing of about 0.1 m, and a smooth and slicken plane, with high persistence. The second set of joints strikes N75°W, presents a dip angle of about 86° to the NE with a spacing of about 0.5 m, and has a smooth and slicken plane with high persistence. According to a previous publication,[8] this second set of joints has been an important contributor to the surface deformation characteristics and strata movement mechanism.

The western mining area of the mine includes the III#, IV#, V#, VI#, VII# orebodies. The III# orebody is currently being mined, and the mining method is sub-level caving without pillars. This orebody has been mined from −290.0 m level to −393.0 m level. In 1987, an in-situ stress measurement was conducted in a gallery at a level of −290 m and the data indicated that the major principal stress was 18.63 MP, azimuth N87°W. The vertical stress in situ was 9.0 MPa, which was close to the gravity stress from the overlying rock mass, and the principal stress along the north-south direction was equal to the vertical stress.

3. Numerical modelling

3.1. Numerical method

Many numerical modelling studies have analyzed the structure, surface deformation, and stress in the Chengchao Iron Mine. Hoek[10] noted that a set of major joints with a steep dip angle and a trend parallel to the orebody in the footwall might lead to toppling failure of the footwall. Zhu[23] Xi et al.[24] and Huang[25] proposed that NWW-trending joints primarily controlled the surface deformation and geologic hazards in this mine. Cheng et al.[8] also reported primary control of surface deformation and geologic hazards by the NWW-trending joints, with topping deformation and topping failure in some locations in the post-chimney deformation stage. Zhu[22] concluded that toppling deformation and failure is the main surface deformation and failure mode. Xi et al.[23] attributed the surface deformation in the Eastern Main Shaft in the mine to a ladder deformation towards the goaf. Huang[24] reported that horizontal tectonic stress released around the chimney caving area provided the driving force of surface deformation. However, the deformation and failure of deep surrounding rock and the whole strata movement process in Chengchao iron mine are not been revealed. To study the deformation and failure of deep surrounding rock and the whole strata movement process in Chengchao iron mine, a Numerical method must be adopted.

The affected area of rock strata movement in Chengchao iron mine is about 3000 m in length 1500 m in width, and 500 m in depth. The simulation of strata movement in 3D is needed. However, 3D simulation in the case of a large geometrical domain requires fine mesh discretisation resulting in extensive computational times, so this approach is not currently feasible using personal computers. The ore body of Chengchao iron shows a long strip distribution, with a length along the strike direction of about 2000 m, and width along the normal direction (approximate parallel to the strike of prospecting lines in Chengchao Iron Mine) of about 300 m. Because of this geometry, the strata movement induced by mining in Chengchao Iron Mine can be simplified as a plane strain problem along the strike direction of prospecting lines. To clarify the strata movement mechanism induced by underground mining at Chengchao in details, a numerical method of UDEC was employed because many studies[25–27] have shown that this method has great advantages in simulation of the discontinuous deformation of jointed rock mass. In the numerical simulation, the topping deformation and topping failure of cantilever beams due to the NWW-trending joints was emphasized.