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Plastic zone analysis and support optimization of shallow roadway with weakly cemented soft strata

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ABSTRACT

Based on a shallow roadway with weakly cemented soft strata in western China, this paper studies the range and degree of plastic zones in soft strata roadways with weak cementation. Geological radars were used to monitor the loose range and level of surrounding rocks. A mechanical model of weakly cemented roadway was established, including granular material based on the measured results. The model was then used to determine the plastic zone radium. The predicted results agree well with measured results which provide valuable theoretical references for the analysis of surrounding rock stability and support reinforcing design of weakly cemented roadways. Finally, a combined supporting scheme of whole section bolting and grouting was proposed based on the original supporting scheme. It is proved that this support plan can effectively control the deformation and plastic zone expansion of the roadway surrounding rock and thus ensure the long-term stable and safe mining.

1. Introduction

The range and shape of plastic zones developed in the roadway surrounding rock are deemed to be important factors for the evaluation of rock stability and theoretical basis for the quantitative design of supporting structures [1,2]. The modified Fenner formula or Kastener formula are often used to calculate the radius and stress of plastic zones [3]. A large amount of work has been done on this topic around the world [4–7]. Ma established a mechanical model to simulate the reduction in rock strength after plastic failure [4]. Analytical solutions of radium and stress field of rock plastic zones were obtained; Zhang et al. studied the plastic zones by deducing the boundary equation of plastic zones of circular roadways in a non-uniform stress field considering principle stresses and strata characteristic [5]; Fu et al. carried out orthogonal tests to study the boundary parameters and statistic equations of plastic zones in the roof and slopes of half-circle roadway with straight walls [6]. Gu proposed boundary equations of plastic zones of wall rock in the circular roadway using Hawke-Brown strength criterion [7]. However, compared with studies on the failure mechanism and rock supporting plans, the investigations on the plastic zones of roadway with low strength, weak bond, easy weathering, easy hydrolysis and incomplete diagenesis are rare [8–15]. Based on a practical project of a shallow roadway with weak bond in western China, this paper is to establish a mechanical model of roadways composed of weakly consolidated soft rock based on the measurements of looseness and rupture range and degree by geological radars. The model takes granular material into account. The Mohr–coulomb yield criterion of the granular material is then deduced and is further used to determine the plastic zone radius of strata. This study aims to provide theoretical references for the surrounding rock stability analysis and supporting schemes. Finally, according to the plastic zone range of the weakly bonded soft rock roadway, a unified supporting scheme of “whole section bolting and grouting” is proposed based on the initial supporting method and its validity is proved.

2. Project overview

As the increasing exhaustion of coal resources in the middle and eastern China, the extraction of shallow coal resources in western China has been paid more attention. However, for the mining of shallow mines in the west, it is inevitable to deal with soft strata with low strength, poor consolidation, easy weathering, easy hydrolysis and incomplete diagenesis. These problems will have great effect on the stability of roadways.

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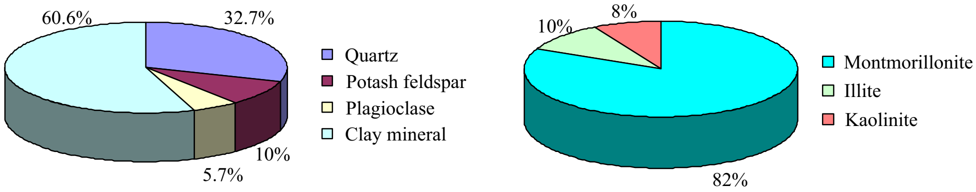
Table 1
Strata's mechanical parameters.

Lithology	σ_c (MPa)	σ_t (MPa)	Cohesion (MPa)	Friction (°)	Bulk (g/cm^3)
Mudstone	0.12–5.12	0.06–0.39	0.24–0.39	25.16–29.01	1.66–2.14
Siltstone	0.64–8.00	0.07–0.61	0.23–0.50	13.70–25.50	2.01–2.65
Fine sandstone	0.42–1.26	0.02–0.10	0.25	14.20	1.52–2.16



(a) Mudstone (b) Clay

Fig. 1. Mineral composition of mudstone and clay.

The prototype coal mine studied in this paper is located in Dongsheng mine area composed of Cretaceous and Jurassic strata. The depth of coal seam is 200 m. Different from the middle and eastern mines in Permo-Carboniferous layers, there are no hard rock layers and the mud strata with low strength, poor bond, easy weathering, easy hydrolysis and incomplete diagenesis develop widely. It has a certain level of strength without diagenesis, as shown in Table 1, but it becomes sand-like after diagenesis, which shows obvious granular behavior. The field sampling and laboratory analysis show that the mudstone is composed of quartz, potassium feldspar, plagioclase and clay (see Fig. 1a). In these minerals, the clay accounts for a content up to 60.6%. The clay minerals are composed of high swelling of montmorillonite, illite and kaolinite, (see Fig. 1b). The montmorillonite accounts for 82% in clay and 49.7% in mudstone.

The depth of main haulage roadway in this mine is 100–110 m. A normal soft rock supporting method was initially applied with bolting and shotcreting with wire mesh as temporary support. High strength left-hand screw steel bolts in the size of 20 mm × 2400 mm and spacing of 700 mm × 800 mm were applied. The permanent support employed 29U steel shields and 150 mm thick concrete spraying layer in an interval of 800 mm, which was applied 2–3 days after the temporary support. It is found that the roadway support leads to significant strata behavior such as obvious subsidence of roofs, movement of slopes, bulging up of floors, crack of slurry skin, rupture of reinforced joint, torsion and bending of U steel frames. These problems may cast serious effect on the site construction.

3. Monitoring of rock loose circle of weakly cemented soft strata roadway

The surrounding rock loose circle is a common physical condition in the underground engineering. It has great influence on the stability of underground projects. The loose circle of surrounding rock is characterized by physical face in the form of macrofracture due to strata failure. The rock masses in the circle are in a state of fracture and loose. Geological radars are used to scan the cross section of roadway. When the radar electromagnetic wave passes through the interface between the loose circle and intact parts, strong reflection or scattering occurs, from which the rock loose circle range can be determined [16].

In order to determine the range and distribution rule of roadway surrounding rock loose circle in the initial supporting scheme, three monitoring sections were arranged in the haulage roadway. Geological radars were used to detect the rock loose circle on the roadway roof, slope and floor. The monitoring results show that the loose circle ranges of the roof, left slope, right slope and floor are 2.4–2.8 m, 1.8–2.4 m, 2–2.6 m, and 2.2–2.6 m, respectively. A local large circle in the range of 3.5–4 m is also observed. In this case, as the plastic zone of the roadway surrounding rock always exceeds the bolting length, the load bearing point or stable compression zone is not easy to form. In addition, if the bolt is too stiff to deform with the surrounding rock, it will be inserted into the rock, thus worsening the loose and fracture of strata. Fig. 2 shows the radar detection of roadway roof, slopes and floor.

4. Plastic zone analysis of surrounding rock in weakly cemented soft roadways

Based on the laboratory test and field monitoring data, it is recognized that the radius of the surrounding rock loose circle is more than two times as large as the roadway radius due to the obvious granular behavior of weakly cemented soft strata. Therefore, the concept of granular material is included in the plastic zone analysis.

4.1. Mechanical behavior of granular material [17,18]

Due to the complexity of three-dimensional model, a two-dimensional stress state is considered in this study, as shown in Fig. 3. The interior stress is represented by stress tensor τ. Only the influence of in-plane stress tensors τ_{xx}, τ_{yy}, τ_{xy} is considered while ignoring the out-of-plane tensor τ_{zz}. The direction of the normal unit is denoted by $n=(\cos\theta,\ \sin\theta)^T$, where θ is the angle between the normal unit direction and the horizontal plane. The normal traction N imposed by the upper granule on the bottom granule can be expressed as:

$$\begin{aligned} N &= (\cos\theta, \sin\theta)\begin{pmatrix} \tau_{xx} & \tau_{xy} \\ \tau_{xy} & \tau_{yy} \end{pmatrix}\begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix} \\ &= \frac{1}{2}(\tau_{xx}+\tau_{yy}) + \frac{1}{2}(\tau_{xx}-\tau_{yy})\cos(2\theta) + \tau_{xy}\sin(2\theta) \end{aligned} \quad (1)$$

Likely, the elemental tangential shearing stress F can be calculated as:

$$\begin{aligned} F &= (-\sin\theta, \cos\theta)\begin{pmatrix} \tau_{xx} & \tau_{xy} \\ \tau_{xy} & \tau_{yy} \end{pmatrix}\begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix} \\ &= \frac{1}{2}(\tau_{yy}-\tau_{xx})\sin(2\theta) + \tau_{xy}\cos(2\theta) \end{aligned} \quad (2)$$