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The research of design method for anchor cables applied to cavern roof in water-rich strata based on upper-bound theory

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ABSTRACT

In this study, we use the upper-bound method to develop a collapse failure mechanism of the roof surrounding rock of semicircle arched roadway, with a consideration of the water pressure in the stratum and the support from anchor cables. We consider a cavern with a semi-circular roof and straight walls in a water-rich stratum as a case study. A design method is presented for the required length of and the pre-tightening force of anchor cables on the cavern roof, based on the Hoek–Brown criterion. We analyse the effects of factors such as the cavern width, the pore-water pressure coefficient and the specific weight and the compressive and tensile strengths of the rock mass using established sensitivity indexes for the factors that affect the design parameters of anchor cables. We provide recommendations for controlling the surrounding rock in practical engineering applications for actual scenarios. The design method is used to determine the parameters of anchor cables for the roof of a primary drainage pump station in a mine. The designed anchor cables are used to effectively control the deformation of the surrounding rock. The results show that at the early stage of the excavation of a cavern, the collapse of the surrounding rock of the roof can only be effectively controlled using anchor cables with lengths that meet the design requirements and to which a sufficient pre-tightening force has been applied. In addition, the required length of anchor cables increases with the cavern width, the pore-water pressure coefficient and the specific weight of the rock mass and decreases as the compressive strength of the rock mass increases. The cavern width has the highest sensitivity among the influence factors for the length of anchor cable. Furthermore, the required pre-tightening force for anchor cable for the roof decreases as the tensile and compressive strengths of the rock mass increase and increases with the pore-water pressure coefficient, the cavern width and the specific weight of the surrounding rock. The cavern width also has the highest sensitivity among the influence factors for the pre-tightening force. Finally, the cavern shape and width should be carefully selected for the design and construction of a cavern with weak surrounding rock in a water-rich stratum. The intactness of the surrounding rock should be improved by using high-strength and high-toughness anchored supporting components, applying a high pre-tightening force to the anchored supporting components and using grouting reinforcement to mitigate the effect of water. In this way, relatively good control of the surrounding rock can be realised.

1. Introduction

Rapid societal development has resulted in the construction of increasing numbers of underground caverns. However, increasingly specialised geological challenges are being encountered in the construction of these caverns. Under water-rich conditions, particularly when the cavern roof comes into contact with groundwater, the water–rock interaction caused by disturbances such as excavation and support can easily compromise the stability of the surrounding rock, which may result in significant deformation or even roof collapse phenomena.

Several studies have been conducted on the stability of the roofs of caverns in water-rich strata. Sofianos and Kapenis (1998), Indraratna et al. (2010), and Zhang et al. (2013) studied the failure mechanism of roofs of caverns in thick water-rich coal seams using numerical computation software. Li et al. (2009) and Yao et al. (2011) studied the instability mechanism of the roofs of tunnels in water-rich coal seams by analysing the micro-structural cracks

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in the roofs and hydrophilic minerals. Gao (2004), Zeng et al. (2009), Shin et al. (2010) and Wang et al. (2012) used elastic–plastic theory to determine the stress and deformation in the rocks surrounding cavern roofs under various conditions (e.g., percolation conditions). Fraldi and Guarracino (2009, 2010) and Wang et al. (2014) used the limit analysis method to investigate the fracture mechanism of the rock surrounding cavern roofs. However, the results of the aforementioned studies have been limited to the failure mechanism, and there have been few studies on controlling the behaviour of the rock surrounding cavern roofs.

Anchor cables are an effective form of support in roof design. Strongly pre-tightened anchor cables can be used to actively exert radial constraints on the surrounding rock at the early stage of cavern excavation, thus increasing the self-bearing capacity of the post-peak surrounding rock and effectively curbing the failure of the rock surrounding the roof by loosening deformation. Although numerous studies have been conducted on anchor cables (Chen et al., 2000; Liu et al., 2005; Kang et al., 2007, 2008; Wei and Gou, 2012; Zhai, 2013; Meng et al., 2014) very few theoretical studies have been performed on how to select an appropriate design length for anchor cable and the corresponding pre-tightening force, particularly under water-rich conditions. In the present study, we consider a cavern with straight walls and a semi-circular roof under water-rich conditions. We investigate the effects of the non-linear strength failure characteristics of the rock mass to determine the water pressure in the stratum and the support provided by the anchor cables, from which we develop the mechanism for the roof collapse of the rock surrounding the roof. We use upper-bound analysis to develop a design method for the selection of the two primary indexes of anchor cables for the roofs of caverns in water-rich strata – the length and the matching pre-tightening force. The effects of different factors on the aforementioned two indexes are discussed and analysed. We present recommendations and measures for practical engineering applications and conduct a design analysis for a field engineering case study.

2. Non-linear strength failure theory of rock masses

The Mohr–Coulomb strength criterion is one of the most important strength theories in the geotechnical engineering field. This criterion has a simple form and can capture the characteristics of both brittle and plastic failure of a rock mass. Therefore, the Mohr–Coulomb strength criterion has been extensively used in geotechnical mechanics and plasticity theories. However, the Mohr–Coulomb strength criterion is limited in that it cannot satisfactorily explain the strength characteristics of rock masses in tensile stress zones, low stress zones and high stress zones, capture the structural effects of rock masses (in particular, the structural planes of rock masses) or describe the non-linear relationship between the maximum and minimum principal stresses when the rock mass fails. There are numerous joint planes and fracture zones inside rock masses. Extensive experiments and theoretical studies have already proven that the failure envelopes of nearly all rocks are non-linear and that linear failure envelopes are only a special case.

Hoek and Brown (1980) developed the world-renowned Hoek–Brown criterion based on the non-linear failure characteristics of rock masses. Later, Hoek et al. (2002) modified the criterion to produce the general Hoek–Brown criterion:

$$\sigma_1 = \sigma_3 + \sigma_c\left(m_b\frac{\sigma_3}{\sigma_c} + s\right)^a \tag{1}$$

where m_b denotes the value of an empirical parameter, and m, s and a are constants related to the characteristics of the rock mass.

Eq. (1) can be expressed in the σ–τ Mohr plane as (Fraldi and Guarracino, 2009)

$$\tau = A\sigma_c[(\sigma_n + \sigma_t)\sigma_c^{-1}]^B \tag{2}$$

where A and B are two dimensionless parameters related to the characteristics of the rock mass, the specific calculation method can be referred in accordance with the references (Hoek and Brown, 1980; Hoek et al., 1992, 2002; Song et al., 2002). σ_c and σ_t represent the compressive and tensile strengths of the rock mass, respectively.

The Hoek–Brown criterion is a typical non-linear strength criterion. In the Hoek–Brown criterion, the effects of various factors, such as the strength of a rock mass, the strength of a structural plane and the structure of a rock mass, are comprehensively considered. Thus, the Hoek–Brown criterion can better reflect the non-linear failure characteristics of rock masses than the traditional Mohr–Coulomb strength criterion. The rock surrounding the roof of a cavern fails by typical tensile–shear failure. Thus, the Mohr–Coulomb strength criterion is not suitable for describing the failure characteristics of the surrounding rock in this case. Hence, the non-linear Hoek–Brown strength criterion is used in the present study for rock failure analysis.

3. Use of Hoek–Brown strength criterion in an upper-bound analysis of failure of cavern roofs in water-rich strata supported by anchor cables

Fraldi and Guarracino (2009) established a calculation model that considers the self-weight stress of a rock mass and calculated the shape of the collapsing surface of the rock surrounding the roof of a tunnel based on the Hoek–Brown failure criterion and the upper-bound analysis method. In addition, Fraldi simulated and analysed the plastic strain, displacement contour and plastic zone of the roof using the ANSYS v11s, Examine 2Ds and FLAC 5s numerical simulation software packages, respectively. Furthermore, Fraldi compared the simulation results with the calculation results and thus verified the reliability of the model. Based on the model established by Fraldi, Huang and Yang (2011) further considered the impact of the pore-water pressure on the caving of the roof and compared the results with those of Fraldi and Guarracino (2010), thereby further verifying the effectiveness of the model. The aforementioned two studies have demonstrated the correctness of the model used in our article. Therefore, because of limitations regarding the length of the article and the aim of emphasizing the key content of the present study regarding the design method for anchor cables, we did not verify this method again.

The results of existing research studies and analyses show that without cable support, the stress redistribution from cavern excavation will cause the rock surrounding the roof to collapse in a semi-ellipsoidal shape, followed by the collapse of the roof. However, applying a sufficient pre-tightening force to anchor cables can provide timely support and effectively prevent the subsidence failure of the rock surrounding the cavern roof. We use the failure characteristics of the rock surrounding the cavern roof to develop a failure mechanism for the collapse of roofs of caverns with straight walls and semi-circular roofs (Fig. 1). The rock surrounding the cavern roof is modelled as an ideal rigid plastic body. The rock mass within the range of roof collapse failure is modelled as a rigid body with dimensions of $l \times h$ that is symmetrical about the y-axis. The rock mass subsides at a speed $\dot{u}$, and the corresponding curve equation of the fracture of the surrounding rock is $f(x)$. The pressure of the water in the stratum where the cavern is located is modelled as a load distributed around the collapsed rock mass, P_w. The corresponding shear stress and principal stress at the fracture plane of the surrounding rock are denoted by τ_n and σ_n,