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Stability analysis and failure mechanism of the steeply inclined bedded rock masses surrounding a large underground opening

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ABSTRACT

The stability of high sidewalls of large-span underground openings is a crucial geological engineering issue when the steeply inclined rock strata form a small angle to the cavern axis. In this study, detailed field surveys, in-situ tests and numerical simulations were performed to investigate the stability and failure mechanism of bedded rock masses surrounding a large underground cavern at the Wudongde hydropower station in China. First, a 3D real time, movable microseismic (MS) monitoring system was installed to analyze the stability of the underground caverns. The micro-fracturing processes and potential failure mechanism of cataclinal layered rock masses were revealed by the spatial distribution evolution and seismic source parameters (i.e., S-wave to P-wave energy ratios, namely E_s/E_p) of the MS events. Then, an approach integrating the field surveys, MS monitoring and conventional measurements, is proposed for evaluating the cavern stability and identifying the high risk regions in the bedded rock masses during the staged excavations. Subsequently, discrete element method (DEM) was adopted to depict the progressive failure processes of the layered rock masses. The relationship between the failure in the upstream sidewall and the orientation and spacing of bedding planes was analysed. Abovementioned investigations allow us finally to conclude that the failure mechanism of the steeply cataclinal layered rock strata after cavern excavation is a combination of (1) the composite bending and sliding occurring in the lower part of the upstream sidewall with no supports, and (2) the opening and shear dislocation of bedding planes in the middle area. Timely supports for the rock strata at the toe of sidewall might be an effective way for preventing the occurrence of the studied failure.

1. Introduction

All the rocks have been modified for hundreds of millions, or even billions of years. The sequence of modification that sedimentary rocks typically experienced is deposition at the earth's surface, gradual burial to depths of up to several kilometers subjected to high-pressure diagenesis (Wyllie et al., 2004). During the aforementioned diagenetic processes, one set of dominant and parallel discontinuities (i.e., bedding planes) is generated by the breaks in the continuity of sedimentation. Consequently, the assemblages of rock blocks separated by bedding planes constitute the so-called bedded rock masses. In low-stress underground openings, the mechanical behavior of bedded rock mass has its own distinctive features and is mainly controlled by the presence of bedding planes due to their much lower strength properties (Hoek, 2007; Tsesarsky, 2012). In addition, many large-scale underground openings are excavated in bedded rock masses, covering the majority of land area. Therefore, it is significant to investigate the stability and failure mechanisms of bedded rock masses during underground excavation.

A general way to investigate the mechanical behavior of bedded rock masses around underground openings is to perform physical model tests. Considerable physical modeling studies have been conducted in the literature. Ran et al. (1994) conducted laboratory tests on the voussoir beam structure to analyze the shear sliding failure, which greatly affected the stability of cave roof in bedded rock masses. Adhikary and Dyskin (1997) manufactured two small-scale underground openings and tested them on a loading frame to model the deforming behavior of bedded rock masses. Wu et al. (2004) used the trap door tests to investigate the surface subsidence and stress distributions in the inclined layered jointed rock masses during tunneling.

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Amini et al. (2009) proposed a theoretical model with the inclined superimposed cantilever rock layers to analyze the stability of underground openings against flexural toppling failure, which is a typical failure in layered rock masses. Then, a newly proposed method was compared with the results of centrifuge tests for further verification. Fuenkajorn and Phueakphum (2010) conducted physical model tests to investigate the influences of the thickness and orientation of discontinuities on the maximum unsupported span of shallow underground caverns under both static and cyclic conditions. Sagong et al. (2011) and Zhang et al. (2012) performed the laboratory tests to investigate the mechanical behavior of intact rocks and a set of discontinuities with different dip angles, which presents the rock failure mechanisms and joint sliding behavior around the underground openings in layered rock masses.

Previous studies have shown that physical model tests can provide a relatively realistic simulation of the underground openings in bedded rock masses. However, it is difficult, expensive and time-consuming to reproduce the discontinuities in a physical model and to accurately predict the mechanical behavior of layered rock masses, due to the presence of complicated patterns of discontinuities and uncertainties involved in estimating their geo-mechanical and geometrical properties (Kulatilake et al., 2006; Sagong et al., 2011). Compared to laboratory experiments, in situ tests (Cai et al., 2007) can provide direct and actual data for investigating the failure mechanisms of underground openings, especially for layered rock masses where accurate descriptions via physical model test are difficult. Conventional in-situ testing methods (e.g., multipoint extensometers and acoustic velocity measurements) are useful for detecting the deformations and stresses of the surrounding rock masses near the surface (Cai et al., 2001 Salvoni and Dight, 2016; Dai et al., 2016). However, it is unrealistic for these methods to accurately capture the micro-cracks inside the rock masses, whose propagation and coalescence can trigger the failure or instability of rock mass (Cai et al., 2001). Therefore, to evaluate the stability and failure trends of rock masses surrounding the underground openings, it is crucial to effectively capture the micro-fracturing details inside the rock masses.

Microseismic (MS) monitoring techniques can detect the micro-fracturing signals with a frequency between 0.1 and 10 kHz, termed as MS events and recorded as seismograms. By analyzing these seismograms, large amounts of seismic source information (e.g., three-dimensional location, radiated energy, and moment magnitude, etc.) can be obtained; the changes of stress or strain in the rock can also be indirectly revealed. Moreover, MS monitoring techniques can be applied as a 3D real-time "body" in-situ testing method to assess the stability of underground openings in real-time and to delineate the relevant potential hazards. Over the last two decades, this technology has been successfully adopted in many underground engineering projects (Friedel et al., 1997; Martin et al., 1997; Cai et al., 1998, 2001, 2007; Young et al., 2004; Luxbacher et al., 2008; Kaiser, 2009; Hudyma and Potvin, 2010; Westman et al., 2012; Aminzadeh et al., 2013; Cai et al., 2014; Zhang et al., 2015, 2016; Xu et al., 2015, 2016a,b; Dai et al., 2016, 2017, Ma et al., 2016; Yu et al., 2017). For instance, Friedel et al. (1997), Luxbacher et al. (2008), Westman et al. (2012) and Cai et al. (2014) investigated the applications of seismic velocity tomograms in underground mines. They found that seismic tomography can infer stress redistribution, and thereby assess rock burst hazard or locate high-seismicity zones during the mining of longwall panels. Cai et al. (1998, 2001, 2007) and Young et al. (2004) utilized acoustic emission (AE) and MS techniques to provide feedback information of the mechanical parameters of rock masses and quantify the variation of rock properties around the underground caverns at the Underground Research Laboratory (URL) in Canada. Hudyma and Potvin (2010) developed a new construction risk-based approach on the basis of the microseismic data. Dai et al. (2016, 2017) and Xu et al. (2015) focused on the stability assessment and deformation forecasting of the surrounding rock masses of underground powerhouses using microseismic monitoring techniques. All these in-situ monitoring methods (i.e., conventional measurements and MS monitoring technique) can be employed to better investigate the responses of layered rock masses in underground excavations.

In addition to in-situ monitoring, numerical simulation is also an effective and promising approach for investigating mechanical behavior of layered rock strata in underground openings. Numerical methods can be classified into two main types: continuum modeling approaches and discontinuum modeling approaches. Continuum modeling approaches, in which the effects of discontinuities are considered through the equivalent continuum hypothesis, have been extensively applied for simulating layered rock masses (Cai and Horii, 1992, 1993; Yoshida and Horii, 2004; Xia et al., 2007; Jia and Tang, 2008; Wang and Huang, 2009, 2014; Tsesarsky, 2012; Asadi and Bagheripour, 2015; Xu et al., 2017). Although these approaches may provide rapid modeling results in relatively fast calculation speed, they fail to explicitly capture the initiation and propagation of cracks, and thus the failure region cannot be directly identified. Therefore, discontinuous modeling approaches are more appropriate for simulating the bedded rock masses excavation responses and promoted our understanding on the failure mechanism of layered rock masses (Shen and Barton, 1997; Hsu et al., 2004; Sagong et al., 2011; Zhang et al., 2012; Bejari and Hamidi, 2013; Gu and Ozbay, 2014; He and Zhang, 2015; Fu et al., 2015; Karampinos et al., 2015; Ma et al., 2016).

Although the mechanical features of bedded rock masses have already been recognized and extensive researches have been done in the literature, few detailed cases or studies, particularly actual cases, are available regarding the stability of high sidewalls of large-span caverns against typical failures occurring in the bedded rock masses. This scenario urges the demand and highlights the importance of better investigating layered rock masses surrounding underground openings. This study aimed to investigate the stability and failure mechanisms of large-scale underground caverns in bedded rock masses. In Section 2, the geology, excavation sequences and failure characteristics of the underground powerhouse caverns at the Wudongde hydropower station, Southwest China, are briefly presented. The MS monitoring system in the underground powerhouse is introduced in Section 3, and the stability and potential hazards of bedded rock masses are comprehensively analysed, based on in-situ monitoring data, including MS data and conventional measurements. In Section 4, the formation mechanism of typical failure occurring in the bedded rock masses is numerically investigated using UDEC. Section 5 provides further interpretations on the failure mechanism and process of bedded rock masses and proposes an effective way on prevention and control of these failures.

2. Site characterization of the underground powerhouse caverns

2.1. Project description

The Wudongde hydropower station is constructed in the downriver region of the Jinsha River, where Yunnan Province meets Sichuan Province in south-western China (Fig. 1). It will be the fourth largest hydropower station in China. The large-scale underground powerhouse cavern system is positioned along the right-bank mountain with horizontal depths of 100–120 m and vertical depths of 180–390 m. As shown in Fig. 2, the cavern system mainly consists of main powerhouse, transformer chamber, semi-cylindrical surge chambers, diversion tunnels, busbar tunnels and tailraces. The axis of two main caverns, including the main powerhouse and transformer chamber, are aligned towards N65°E. The excavation sizes of the three main caverns, including the main powerhouse, transformer chamber and surge chambers, are 333 × 30.5 (32.5) × 89.8 m (length × width × height), 272 × 18.8 × 35 m (length × width × height), and 25 × 113.5 m (diameter × height), respectively. The thickness of the rock pillars between the main powerhouse and transformer chamber are