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Back analysis of long-term stability of a 92 m span ancient quarrying cavern

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A B S T R A C T

Long-term stability of large-span caverns is a challenging issue for design and construction of underground rock engineering. The Heidong cavern group consisting of 21 caverns was constructed about 1400 years ago for quarrying in massive Cretaceous tuff. The cavern No. 5 of the Heidong cavern group is characterized by an unsupported span up to 92 m, with the overburden thickness of only 3–25 m. To analyze its long-term stability, a detailed investigation was conducted to obtain its geometry and rock mass characteristics, and to monitor surrounding rock displacements. Based on field survey and laboratory tests, numerical simulations were performed using the finite difference code FLAC^{3D}. The analysis results revealed that for the long-term stability of the cavern No. 5, some major factors should be carefully considered, such as cavern excavation method in hard massive rocks, site investigation using trial pits, tools like short iron chisel and hammer for manual excavation, geometric dome roof, and waste rocks within abutment or on the floor. The highlights of the technologies obtained from this large-scale ancient underground project can provide reference for other similar project excavations in practice.

1. Introduction

At present, various ancient quarries are observed across the world, in particular in the areas with earlier civilization, such as the Mediterranean, Mesopotamia, and East Asia. They basically appear in different times, such as the basalt quarry formed in 3000 BC at the ancient kingdom of Egypt (Harrell and Bown, 1995). Some caverns exist for a few hundreds of years (e.g. the Shepan Island and Feifeng underground quarries for about 800 years, and the Wieliczka underground salt quarry for 700 years), or more than one thousand years (e.g. the Changyudongtian quarry for 1500 years, and the Bet Guvrin quarry for 1400 years). It should be noted that above-mentioned quarries are featured by small-scale, varied shape open pit quarries (Bloxam, 2009; Beardsley and Goles, 2001; Klemm and Klemm, 2001; Harrell and Storemyr, 2013; Heldal and Storemyr, 2015). Recently many large-scale ancient underground quarries were also found (Hallett, 2002; Waltham and Swift, 2004).

Hatzor et al. (2002) analyzed the stability of two systems of bell-shaped caverns excavated about 1000 years ago at Bet Guvrin National Park. Their results were obtained using a continuum model framework (i.e. FLAC) and a discontinuous approach (i.e. block theory). After that, Tsesarsky et al. (2013) adopted three-dimensional (3D) finite element software ABAQUS to analyze caverns' stability. In a global sense, the surrounding rock is basically considered as a continuum medium for the purpose of stability analysis of cave group. As for local or a single cavern, structural plane is introduced into the simulations to model the discontinuity. Tsesarsky et al. (2013) suggested that this continuous–discontinuous method was expected to provide reference for stability analysis of similar underground cavern group.

For modern large-span caverns, Barton et al. (1994) numerically predicted and measured the performance of a 62 m span Norwegian Olympic Ice hockey cavern in granitic rocks. While for ancient large-scale caverns excavated in absence of gunpowder, the excavation technique and working environments are significantly different from the present ones. So some important factors, except for the shape and reinforcement method, should be included in the stability analysis. These were the topics presented in an international symposium held at Longyou County, China in 2015, highlighted by the results focusing on the scientific issues and long-

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term preservation of ancient underground structures (e.g. Yang and Tanimoto, 2015).

In this paper, the site-specific engineering geological conditions, rock mass quality, and excavation procedures were used to back analyze the long-term stability of a 92 m span ancient quarrying cavern in massive Cretaceous tuff. To analyze the long-term stability of the cavern No. 5, regional field investigation, surrounding rock deformation measurement, as well as 3D numerical analyses of stress and displacement distributions, are conducted. The factors involved in the long-term stability of this carven are also revealed. Moreover, the excavation technology adopted by the ancients is presented.

2. Geometric features of the cavern group

The dome-shaped cavern No. 5 with the span of 92 m is one of the 21 caverns of the Heidong cavern group. The Heidong cavern group is located below Xie Hill in Tiantai County, Zhejiang Province, South China (Fig. 1). Two cross-sections of the cavern No. 5 (I–I′ oriented N22°E, and II–II′ oriented S60°E) show the cavern geometry and thickness variation of overburden, as well as the dimensions of waste rocks stacked in the cavern (Fig. 2). It can be seen in Fig. 2b that the thickness of overburden at the main portal to the southeast is only 3 m, and the maximum thickness to the west gate (cross cut) reaches 25 m, i.e. the ratio between the thickness of overburden and the span of the cavern (92 m) ranges from 0.033 to 0.272. In this sense, the cavern No. 5 can be classified as ultra-shallow cavern (Fig. 3). Though local instability was observed in some locations of this cavern, no overall failure occurred in history in a global sense. Although the Heidong quarry was originally excavated over 1400 years ago (Yang et al., 2013), this ultra-shallow cavern nevertheless remains stable for such a long period of time.

3. Geographic background

Heidong cavern group sits in the mountainous area (elevation ranging from 500 m to 800 m) in the west of Tiantai Basin, extending along a strike of 47° with a height difference of 52 m. Its length is 650 m, and the width is 300 m. Shifeng River runs from west to east and goes through the Tiantai Basin at the north of Xie Hill (Fig. 1a). Therefore, Shifeng River is convenient for boating transportation as a quick way for the ancients. However, the main river channel has migrated for about 600 m northward during the past 1400 years, which is recorded by the relict river beds from satellite images.

Tiantai County is located in the region of subtropical monsoon climate, with the average annual humidity ranging from 15% to 18%. The average annual precipitation is 1400 mm, and the rainfall is mainly concentrated in monsoon seasons lasting from May to June in a year.

4. Geological conditions

4.1. Geological setting

4.1.1. Lithology

The strata of Heidong cavern group belongs to Tangshang Group of Upper Cretaceous (K_2t), which consists of gray–purple and yellow–green massive rubble vitric tuff, vitric welded tuff, tuffite with rhyolite, purple–red blocky tuffaceous conglomerate, and sandy conglomerate. The strata can be divided into 17 layers with a total thickness of 1000–1200 m (Table 1). K_2t lies to the north of Huangtanyang–Nanping volcanic doom (Fig. 4), and mainly consists of intermediate siliceous tuff, a pyroclastic rock formed in explosive eruption era (RGE, 1978).

4.1.2. Structural geology

According to the investigation of regional geology in this regime, Xie Hill sits at Xinchang–Dinghai fault uplift, belonging to Lishui–Ningbo uplift in Southeastern Zhejiang folding belt in South China folding system. Volcanic tuff and breccia formed from continental margin activation at late stage of the Yanshan movement were found being extensively distributed in Xie Hill (BGZJ, 1989).

Considering regional tectonics, the Quzhou–Tiantai fault (about 250 km long, extending NEE–EW direction) located at 12 km south of Tiantai County and other contemporaneous faults striking NE and NW all controlled the formation of Tiantai fault basin (Fig. 4). It is inferred that Quzhou–Tiantai fault controlled the occurrence and distribution of discontinuities in Xie Hill because it straightly cuts the Cretaceous strata. Faults and joints are well developed in the cavern area, while folds are rarely observed. Besides, the NNE-striking Neo-Cathaysiantectonic system is formed in the early stage of the Yanshan movement, and constructs tectonic framework.

4.2. Engineering geological conditions

4.2.1. Rock mass structure

The Heidong quarry caverns were excavated through Layer 6 (at the bottom) to Layer 8 (at the top), as shown in Table 1. The three layers from bottom to top are respectively composed of light gray massive rubble-bearing vitric tuff, purple–red blocky tuffaceous conglomerate, and gray–purple blocky vitric tuff. The attitude of Layer 7 measured at the cavern No. 5 is N10°–24°W/NE∠15°–28°. Layer 6 serves as the target layer, where the ancients excavated stones for use. If the quarrying conditions were feasible, Layer 8 was excavated as well. The thickness, attitude, and degree of weathering of those three layers are identified in field survey, as shown in Table 2.

At the cavern No. 2, the fault F_1 (200°∠65°) is exposed at its south wall (Fig. 1b) with thickness of 0.3–0.4 m. Besides, the attitude of 85 joints was measured on site. The rose diagram of the discontinuities with two principal sets (N7°E/NW∠89° and N82°W/SW∠50°) is shown in Fig. 5a. These two strikes apparently follow the pillar orientations as shown in Fig. 1b. Meanwhile, most of the dip angles are over 50°, dominated by 80°–90° (Fig. 5b). The results mentioned above confirm that the faults and joints in Xie Hill are controlled by Quzhou–Tiantai fault. Small dip angles with some variations were observed on the bedding planes. For instance, the attitude of the gently inclined strata measured in caverns Nos. 2 and 21 was 340°∠24° and 330°∠20°, respectively. That is to say, the bedding plane is generally inclined to NNW with a dip angle of about 20°.

4.2.2. Physico-mechanical strength of intact rocks

The physico-mechanical testing results of cylinder samples obtained from intact rocks are listed in Table 3. According to the uniaxial compressive strength (UCS) of three groups of samples, it is known that intact rocks at Layers 6 and 8 belong to moderate-to-low strength (50 MPa and 37.49 MPa, respectively) rocks, while that at Layer 7 has very low strength (22.44 MPa) (Brown, 1981; CIGIS, 2008).

Drastic reductions in the modulus of deformation are noted due to very gentle changes in water content at initially dry conditions (Talesnicka et al., 2001). In this case, as the cavern No. 5 is sitting above the water table, the effect of water content could be negligible.

4.2.3. Rock mass quality

To assess the rock mass quality, different classification schemes have been developed. Considering the limitations of each scheme, four rock mass classification schemes are adopted subsequently.