Journal of Rock Mechanics and Geotechnical Engineering 9 (2017) 1041–1053

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Unloading performances and stabilizing practices for columnar jointed basalt: A case study of Baihetan hydropower station

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ARTICLE INFO

Article history:
Received 11 January 2017
Received in revised form
1 June 2017
Accepted 12 July 2017
Available online 7 November 2017

Keywords:
Columnar jointed basalt
Diversion tunnels
Rock unloading
In situ test
Hydropower station

ABSTRACT

The columnar jointed rock mass (CJR), composed of polygonal cross-sectional columns cut by several groups of joints in various directions, was exposed during the excavations of the Baihetan hydropower station, China. In order to investigate the unloading performances and the stability conditions during excavation of the columns, an experimental field study was performed. Firstly, on-site investigations indicated that the geotechnical problems, including rock relaxation, cracking and collapse, were the most prominent for the CJR Class I that contains intensive joint network and the smallest column sizes. Comprehensive field tests, including deformation measurement by multi-point extensometers, ultrasonic wave testing, borehole television observation and stress monitoring of rock anchors, revealed that the time-dependent relaxation of the CJRs was marked. The practical excavation experiences for the Baihetan columnar jointed rock masses, such as blasting scheme, supporting time of shotcrete and rock bolts, were presented in the excavations of the diversion tunnels. These detailed investigations and practical construction experiences can provide helpful information for similar geotechnical works in jointed rock mass.

1. Introduction

The Baihetan hydropower station is located in the lower reaches of the Jinsha River in southwest China, between the borders of the Sichuan and Yunnan provinces. It connects the Wudongde cascade (upstream) and the Xiluodu hydropower station (downstream). Baihetan hydropower station will be the second largest hydropower project in China, next to the Three Gorges hydropower station. The primary aim of the project is the electricity generation and flood control. It also has an integrated function for sediment trapping, which can enhance the development of reservoir and downstream shipping conditions. The hydropower station comprises a hyperbolic concrete arch dam, two underground powerhouse caverns in each bank, five diversion tunnels (three located in the left bank and two in the right bank), and other structural elements. The dam is approximately 289 m high, with a total reservoir capacity of 205×10^8 m^3. The power plant has an installed capacity of 16,000 MW, with a total of 16 hydro-turbine generating sets, each having a capacity of 1000 MW (eight on each bank).

During the excavations of the Baihetan hydropower station, the columnar jointed rock masses (CJRs) were identified in the tailrace tunnels and underground power generation system (Fig. 1), more specifically, in the zones of the diversion tunnels, surge shafts, and at the dam base. Although the CJRs were also observed in other hydropower projects in China, such as the Tongjiezi and Xiluodu projects, they were not exposed over such a large area as that of the Baihetan project (Zhu et al., 1983; Xu, 1995; Chen et al., 2008; Fang et al., 2011; Fan et al., 2015). Consequently, the stability issues of the CJRs were not extensively discussed. In the case of the Baihetan project, the CJRs are extremely prone to cracking and slacking due to the large scale and rapid release of normal stresses on the internal joints during unloading excavation of tunnels and caverns (Yoshida and Horii, 2004; Barbero and Barla, 2010; Bonini et al., 2013; Shao et al., 2015). As a result, the stability of the columnar jointed basalt has become one of the key problems and challenges in the design and construction of the Baihetan hydropower station.

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

https://doi.org/10.1016/j.jrmge.2017.07.003

Fig. 1. Exposed columnar jointed basalt in the diversion tunnel of Baihetan hydropower station.

In terms of geometric shape, CJRs are composed of polygonal cross-sectional columns that are cut by several groups of joints in various directions. They are produced from lava condensation and contraction in the basalt rock masses with a flat-shaped attitude, in a perfect heat exchange environment. Previous researches on the columnar joints predominantly focused on the aspects such as geological origin and tourism geology (Peck and Minakami, 1968; Degraff et al., 1989; Müller, 1998), with few reports on the mechanical properties (Ishida and Uchita, 2000; Waltham and Swift, 2004; Singh and Singh, 2008; Fuenkajorn and Phueakphum, 2010; Panthee et al., 2016a). Previous researches on the CJRs are mostly related to geological aspects (e.g. Peck and Minakami, 1968; Degraff et al., 1989; Müller, 1998). Only a few studies addressed the mechanical behaviors of the columns (e.g. Ishida and Uchita, 2000; Waltham and Swift, 2004; Singh and Singh, 2008; Fuenkajorn and Phueakphum, 2010; Panthee et al., 2016a). A detailed investigation performed by Kim and Cramer (1982) presented the results of elastic wave tests of columnar jointed basalt specimens buried under nuclear waste disposal to analyze the anisotropic behaviors.

As the construction of the Baihetan hydropower station proceeds, the stability of the CJRs has become the major issue in terms of the safety of its caverns and the dam foundation. Some researchers have studied theoretically the Baihetan dam foundation, specifically with respect to the mathematical model of columnar joints, transversely isotropic constitutive jointed surface yield criterion, equivalent elastic modulus, and the like (Zhu et al., 2009; Zhang and Xu, 2011; Yan et al., 2012; Singh et al., 2012; Jain et al., 2016). In fact, because the CJRs were seriously crushed, it is difficult to collect intact samples directly in field for laboratory experiment purposes due to the opening along pre-existing weak joint planes. At the same time, the unloading mechanical properties of the jointed rock masses also cannot be fully exposed due to the lack of opening practices with large size. Therefore, a detailed experimental analysis to assess its mechanical properties using in situ monitoring tests is more reasonable and realistic (Hudson and Priest, 1983; Sun et al., 1993; Hoek and Brown, 1997; Bergamin et al., 2001; Li et al., 2013a; Brown, 2015; Qian and Lin, 2016; Singh et al., 2016). In order to understand the time-dependent relaxation and cracking properties of the columnar jointed basalt during unloading excavation, as well as to improve the excavation and supporting optimization techniques, several observation techniques, including displacement measurements by multi-point extensometer tests, anchor stressometer tests, ultrasonic wave tests and borehole television tests (Li et al., 2013b), had been used to study the unloading and relaxing properties and the corresponding failure mechanisms. In addition, this practical experience can guide the proposed design methodology adopted for the support system and the establishment of mechanical parameters for the CJRs, as well as new construction procedures suited for CJR stratums.

2. Field observed properties of the Baihetan CJRs

2.1. Geological background

In the Baihetan hydropower station dam site, the rock strata can basically be divided into 11 sub-layers. The general lithological characteristics are tholeiitic basalt, aphanitic basalt, almond-shape basalt, and breccia lava, showing a layered distribution with the top layer of the rock flow being tuff. The aphanitic basalt zone in which the columnar structures are well developed is called the columnar jointed basalt.

Columnar joints are mainly developed in eight sub-layers: $P_2\beta_2^2$, $P_2\beta_2^3$, $P_2\beta_3^2$, $P_2\beta_3^3$, $P_2\beta_4^1$, $P_2\beta_6^1$, $P_2\beta_7^1$ and $P_2\beta_8^2$. The pattern of the columns is irregular for their diameter and length are not the same. The CJRs are mostly developed along columnar joints sub-layers $P_2\beta_3^2$ and $P_2\beta_3^3$. The average plunge angle of columnar cylinders is about 75°. Field geological surveys indicated that the columnar joints' density in the basalt was very high and the corresponding RQD (rock quality designation) values were generally low (Barton et al., 1974; Bieniawski, 1976; Hoek et al., 1998; Zhang, 2016). By analyzing the statistics of the CJRs exposed on the project area surface and inside the caverns, we can classify the columns into three types in terms of engineering geological characteristics as follows.

(1) Class I: the diameter of the cylinders is in the range of 13 cm–25 cm, and the lengths generally range from 0.5 m to 1 m. The density of the developed columnar joints is large, and most of them are not completely cut through to form columns. The rock is gray-black with micro-fractures fully developed but interlocked. The lump size of the cut rock mass is approximately 5 cm, and is mainly distributed in the sub-layer $P_2\beta_3^3$.
(2) Class II: the diameter of the cylinders is 25–50 cm with lengths roughly ranging from 0.5 m to 2 m. Irregular development of the columnar joints is observed, and they are also not cut through to form columns. The micro-fractures are developed and interlocked and the columns have a lump size of approximately 10 cm. They are mainly distributed in sub-layers $P_2\beta_3^2$, $P_2\beta_6^1$, $P_2\beta_7^1$, and $P_2\beta_8^2$.
(3) Class III: the diameter of the cylinders ranges from 0.5 m to 2.5 m, and the lengths vary from 2 m to 5 m. The irregular development of the columnar joints is also observed, and they are not cut to form columns but are interlocked. The Class III columnar jointed basalt cylinders are thick and tight fitting; their rock structure and mechanical properties are close to those of aphanitic basal, thus they are often treated as aphanitic basalt consequently.

Field investigations show their regular cross-sections of the columns, exhibiting quadrangular, pentagonal and hexagonal shapes. The columns are not fully cut. A typical map gained from an exploration tunnel is shown in Fig. 2.

Various micro-fractures are observed inside the columns in association with different densities of micro-fractures. One set of micro-fractures is nearly parallel to the columns' axis (longitudinal micro-fractures), while another set is approximately perpendicular