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Stability analysis of abutment slopes based on long-term monitoring and numerical simulation

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ABSTRACT

The Shimenzi Roller-Compacted Concrete (RCC) arch dam is built in a soft rock region where faults and intercalations have developed. The abutments are divided by major faults and intercalations into several potential sliding wedges, which bring difficulties and threats to the construction of the dam and the operation of the reservoir. Several types of large-scale reinforced concrete structures, such as shear keys, shear wells and shear tunnels, are constructed in the faults and intercalations in order to increase the stability of the abutments. Long-term monitoring data, which reveal the deformation of the faults and intercalations, are used to investigate the stability of the stabilized abutments. A three-dimensional finite difference numerical model, in which the faults and intercalations of the dam and reinforced concrete structures are considered, is established to improve understanding of the abutment behavior and to calculate the factor of safety for every major sliding wedge. The rationality of a controversial design method, in which the upstream and the downstream parts of the right abutment are stabilized according to different standards, is also discussed. Based on the analysis of the monitoring data and the results of the numerical simulation, it is concluded that the FOSs of the stabilized sliding wedges have reached their design values. The abutments have been in a stable condition since 2000, when the dam construction was completed. It would be a cost-effective method if the downstream part and the upstream part of large-scale unstable abutment were stabilized according to different FOSs.

1. Introduction

With the major growth in the economy in China, many large dams have been constructed to meet the increasing requirements for energy. A location with good geological and geotechnical conditions will be the ideal site for the construction of a dam. In practice, however, many dams are constructed in mountainous region where poor geological and geotechnical conditions, such as faults, fractures, shear zones and other structures, are the key factors influencing the safety of a dam. The abutments are cut by the structures into several potential sliding wedges, which bring complexity to the stability analysis and difficulty in making a plan for stabilizing the abutments.

Numerous studies have proved that structural control plays a very important role in large rock slope instabilities (Terzaghi, 1962; Hermanns and Strecker, 1999; Sartori et al., 1999; Agliardi et al., 2001; Ambrosi and Crosta, 2006; Jaboyedoff et al., 2009; Berhane and Walraevens, 2013). Due to the spatial variance of the discontinuities, it is difficult to evaluate the stability of abutment slopes containing faults and intercalations using theoretical methods. However, numerical methods, such as finite element and finite difference methods, are powerful tools that can be used to solve such a complex problem (Chen et al., 2007; Gurocak et al., 2008; Kalenchuk et al., 2010; Li et al., 2011; Lu et al., 2012). Numerical methods can help people investigate static problems, such as the failure mechanism or structural control of unstable rock slopes (Eberhardt et al., 2004; Böhme et al., 2013), as well as dynamic problems, such as the response of weak rock planes under dynamic action (Fan et al., 2013; Zhu et al., 2013). The shear strength reduction method (SSRM) has been used to quantitatively assess the safety of jointed rock slopes (Dawson et al., 1999; Zheng et al., 2003; Hammah et al., 2004). However, most numerical simulations for the unstable rock slopes are two-dimensional (2D). The interaction between the abutments and a dam is a three-dimensional (3D) problem. As a result, 3D numerical simulation is more suitable than 2D numerical simulation for hydropower engineering (Jiang et al., 2005; Yu and Ren, 2007; Ning et al., 2008). To understand the long-term behavior of rock slopes, establishing a monitoring system is necessary for hydropower engineering, which will work up to one hundred years (Barla et al., 2010).

The Shimenzi hydropower engineering is a typical case of a dam built in a region with poor geological and geotechnical conditions. The left and right abutments are divided by faults and intercalations into several potential sliding wedges. Twenty million RMB, which was a large budget in the 1990s in China, is spent on the stabilizing structures

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to increase the factor of safety (FOS) of the abutments. The right abutment is artificially divided into upstream and downstream parst by the dam when making the stabilizing plan. The upstream part is considered a general slope, which requires that the FOS should be larger than 1.25 after being stabilized. The downstream part is stabilized according to the standard for abutments, which requires that the FOS should be larger than 3.25 after being stabilized (The Ministry of Water Resources of The People's Republic of China, 1985). This stabilizing plan ignores the interaction between the upstream and downstream parts and results in a significant amount of controversy. Its rationale needs to be proved.

In this paper, the geological and geotechnical conditions based on in situ surveys and laboratory experiments are presented. The stabilizing measures and monitoring systems of the abutments and the dam are also described in detail. The long-term stability of the abutments is analyzed based on the data gathered in the last 13 years. A 3D finite difference model, in which the dam, the abutments and the stabilizing structures are considered, is established to understand the monitoring data and the behavior of the abutments. SSRM is introduced to discuss the rationale of the stabilizing plan for the right abutments.

2. Geological and geotechnical conditions

The Shimen valley is located on the Taxi River in Manas County, Sinkiang, China. The valley is 350 m in length and 70 to 80 m in width at the bottom. The right flank (western side) and the left flank (eastern side) of the valley are 140 m and 100 m in height, respectively. The slopes of both flanks are between 60° and 80°. The Shimenzi reservoir is constructed in the Shimen valley. Roller-compacted concrete (RCC) technology is used to build the dam. The elevations of the dam bottom and crest are 1289 m and 1394 m, respectively. The dam crest is 169 m in length, and the design water level of the Shimenzi reservoir is at an elevation of 1390 m with a total storage of 5×10^7 m^3.

Fig. 1 shows the geological map of the Shimenzi RCC arch dam project. Three formations of Late Jurassic, early Cretaceous and Quaternary sedimentary rocks crop out in the study area. The Late Jurassic formation is divided into the lower part (Ja 3hl) and the upper part (Jb 3hl), according to lithological features, as shown in Fig. 3. The lower part of the Late Jurassic formation is composed of brown conglomerate formed by the cementation of mud and autunite. The upper part of the Late Jurassic formation is composed of gray conglomerate formed by the cementation of autunite. Three major intercalations, which are denoted as I_1, I_2 and I_3, are developed within the Late Jurassic formation. The intercalations are composed of broken rocks and mud. The attitudes of the three soft intercalations are NE90°/N30°. Intercalation I_3 crops out on both flanks of the valley. Intercalations I_1 and I_2 partially crop out within the upper part of the right flank of the valley. The Early Cretaceous formation (Ka 1tg), which crops out on the top of the left flank, is composed of grayish sandstone, arenaceous mudstone and siltstone. The Quaternary formation, which is mainly distributed in the river valley and the ancient riverbed on the left flank, is composed of alluvial sand gravel, diluvial loess and diluvial gravel-containing soils.

In addition to intercalations I_1, I_2 and I_3, the stability of the two abutments is mainly affected by three faults, which are close to the dam and are denoted as F_3, F_5 and f_6. The lengths of the three faults are no more than 1 km. The fault f_6 with an attitude of NE10°/SE90° shows the

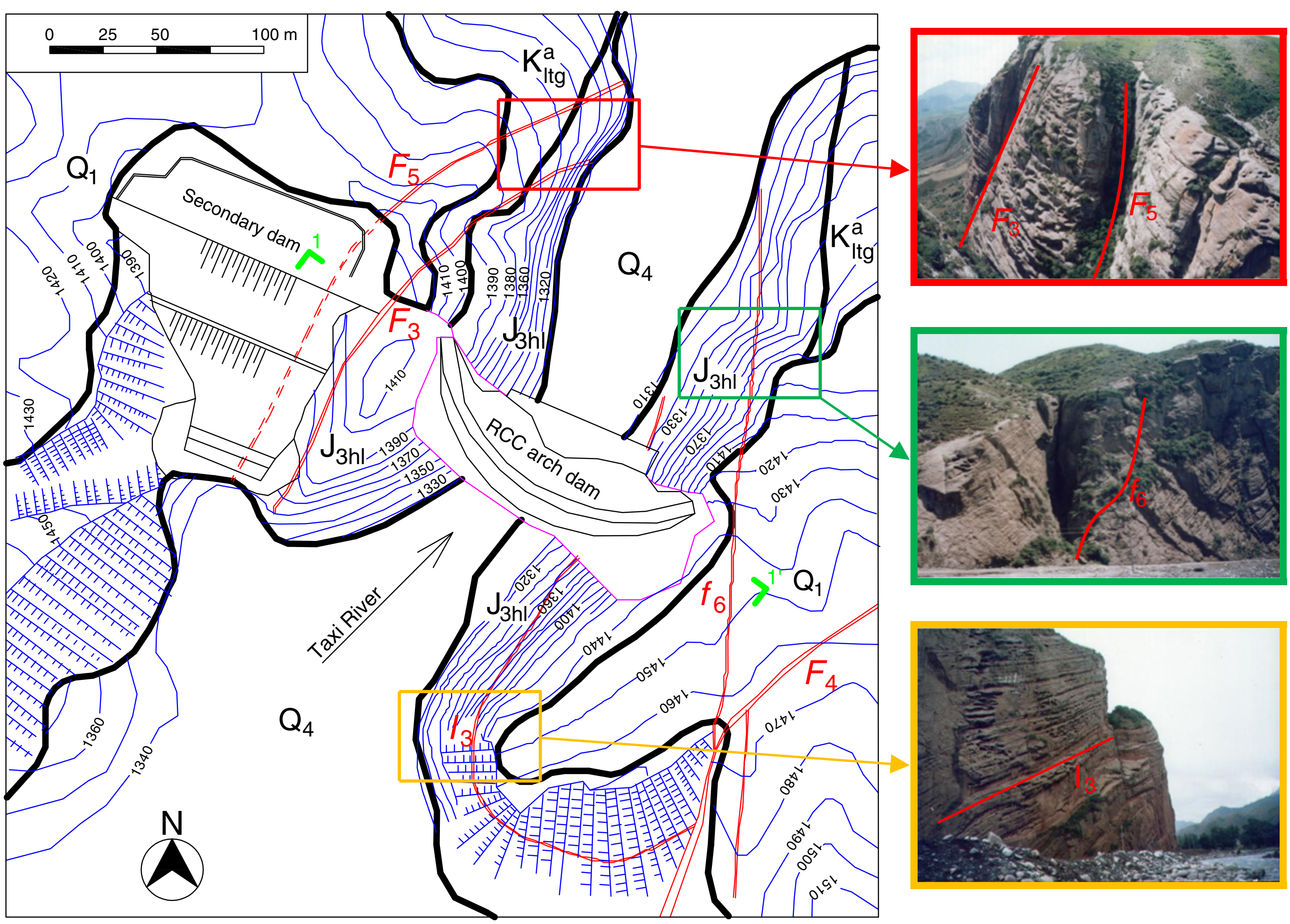

Fig. 1. Geological map of Shimenzi RCC arch dam project. The pictures show outcrops of faults F_3, F_5 and f_6 and intercalation I_3.