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In situ experimental investigation of basalt spalling in a large underground powerhouse cavern

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ABSTRACT

Rock spalling is one of the most frequent break modes and a serious stability challenge for the supporting design during engineering excavation under high geo-stress and hard rock conditions. The primary objective of this work was the field investigation and experimental testing of basalt spalling in more than 50 cases in a large underground cavern in China. The field characteristics of basalt spalling, including the spatial distribution of events, its micro-surface morphology, the joint effect, the time-dependent relation to the excavation, the spatial distance to the opening face, and the supporting condition, are first presented via detailed statistical investigation. An *in situ* study of the full spalling process, including the surface development of rock slabbing and inner cracking extension of the surrounding rock, was recorded in a time series via a borehole camera, displacement measurement, and *in situ* photos. These experimental results exposed the time-dependent development of surface spalling performance and the inner cracking evolution of rock mass ahead of spalling. All of these actual spalling cases in a large underground cavern and the corresponding statistical analysis provided meaningful evidence for the tensile failure mechanism and prevention measures for rock spalling.

1. Introduction

In deep excavations of hard rock, stress-induced brittle fracture of the surrounding rock produces a strong possibility of failure, embodied as slabbing, spalling, or even rockburst, which have brought about great safety risks (Fairhurst and Cook, 1966; Hoek, 1968; Ortlepp and Stacey, 1994; Martin et al., 1997; Harrison and Hudson, 2010; Jiang et al., 2010). In general, designing an optimal support for the surrounding rock under high geo-stress conditions and the brittle failure mechanism of hard rock have been discussed in many ways. Not only the properties of the rock related to brittle spalling have been tested in the laboratory (Eberhardt et al., 1999; Haimson, 2006; Zhao et al., 2013; Xue et al., 2014; Kaiser and Kim, 2015) but also many theoretical demonstrations and field studies have been carried out (Hajiabdolmajid and Kaiser, 2003; Rojat et al., 2009; Cho et al., 2010; Edelbro, 2010; Siren et al., 2015). Especially, two research projects, i.e., Mine-by tunnel of AECL's Underground Research Laboratory and SKB's Äspö Hard Rock Laboratory, have produced rich knowledge regarding brittle failure and rock spalling (Martin, 1993; Biickblom et al., 1997; Siren et al., 2011).

Rock spalling, embodied as parallel fractures close to the free surface, is a tensional and brittle splitting failure process with no obvious ejection performance (Ortlepp and Stacey, 1994; Zhu et al., 2014; Ma et al., 2015; Chen et al., 2015; Xiao et al., 2016). Currently, a widely accepted prediction method for brittle spalling depth in boreholes has been summarized, which is commonly formulated in Eq. (1) (Andersson et al., 2009; Martin and Christiansson, 2009; Lee et al., 2012; Hoek and Martin, 2014). In practice, the actual threshold stress and critical depth of spalling is affected by many environmental factors, such as grain size, surface tunnel dimension, irregularity of the excavation boundary, loading path, and load/unloading rate (Read et al., 1998; Laigle, 2006; Pinto and Fonseca, 2013; Cai and Kaiser, 2014). Yet, more detailed field investigation of rock spalling in large tunnels or caverns is still needed.

$$D_f/a = 0.48 \pm 0.1 + 0.5\frac{\sigma_{\theta\theta}}{\sigma_{sm}} \quad (1)$$

whereD_f is the depth of failure, a is the tunnel radius, $\sigma_{\theta\theta}$ is the maximum tangential stress, andσ_{sm} is the UCS of intact rock.

Detailed laboratory experiments have indicated that rock spalling manifests as splitting slices, which are generally parallel to the loading planes of σ_1 and σ_2 (Papamichos et al., 1994; Rojat et al., 2009; Pinto

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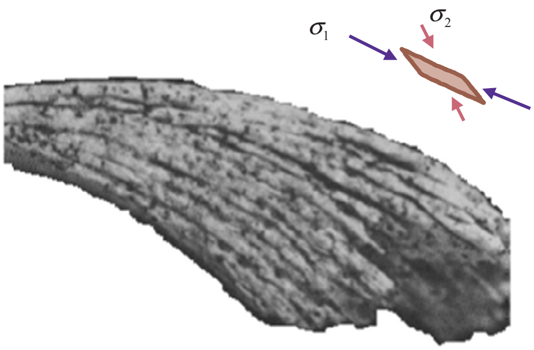

Fig. 1. Typical spalling slices of hard rock (Martin et al., 1997).

and Fonseca, 2013), as shown in Fig. 1. Its micro failure mechanism is related to the tensile and extensional failure of cracks in rock and rock mass (Cho et al., 2010; Kaiser and Kim, 2015), and the shear mode only occurs after the tensile cracks have reached a sufficiently high density such that coalescence can create near-surface parallel slabs (Kaiser et al., 2000; Nicksiar and Martin, 2014). In the field openings for a large cavern, the surrounding hard rock generally undergoes complicated unloading and stress redistribution. Thus, an understanding of the crack-tensile failure mode for rock spalling stills need additional *in situ* observational data, which include the crack's initiation, extension, coalescence, and final spalling failure. Furthermore, a detailed micro investigation of the spalling slices' surface will be helpful in explaining the tension failure of hard rock spalling.

In addition to *in situ* stress directly influencing the cracking of hard rock, field observation has indicated that time effect also plays an important role during the development of rock spalling (Brace et al., 1966; Atkinson and Meredith, 1987; Li et al., 2014b; Schoenball et al., 2014). Various mechanisms have been identified as the cause for this time effect of spalling. For example, stress corrosion is a time-dependent cracking phenomenon in rock that depends on the load, temperature, and moisture (Okui and Horii, 1997; Potyondy and Cundall, 1998; Li et al., 2014a). The reduction of the mobilized strength *in situ* is also a reasonable interpretation for time-dependent spalling (Lajtai and Schmidtke, 1986; Hajiabdolmajid and Kaiser, 2003; Li and Konietzky, 2014). If visual observation and measurement of breeding cracks in surrounding rock can be obtained ahead of rock spalling, deep knowledge and prediction of rock spalling are possible.

Thus, this paper presents a detailed investigation of basalt spalling in more than 50 cases during the excavation of a large Chinese underground hydroelectric power house. The statistical field characteristics of basalt spalling, including the spatial distribution of event occurrence, its micro-surface morphology, the joint effect of the surrounding rock, its time-dependent relation to the excavation, the spatial distance to the opening face, and the supporting condition of the surrounding rock, are first investigated. An entire time-dependent spalling process, including the surface development of rock slabbing and inner cracking extension of rock mass, is exposed via a digital borehole camera, displacement measurement, and *in situ* observation during excavation. This visual observation and analysis of actual spalling cases not only can enrich the understanding of rock spalling mechanisms but also can improve the supporting design for underground engineering with obvious spalling or brittle failure risk.

2. Basic information of project and rock mass

2.1. Background of the Baihetan (BHT) project

The Baihetan hydropower station, located at the boundary of Sichuan and Yunnan provinces, is the second largest water-power engineering project in China. This hydroelectric project is composed of many elements, including a double-curvature arch concrete dam, flood discharge tunnels, diversion tunnels, underground powerhouses,

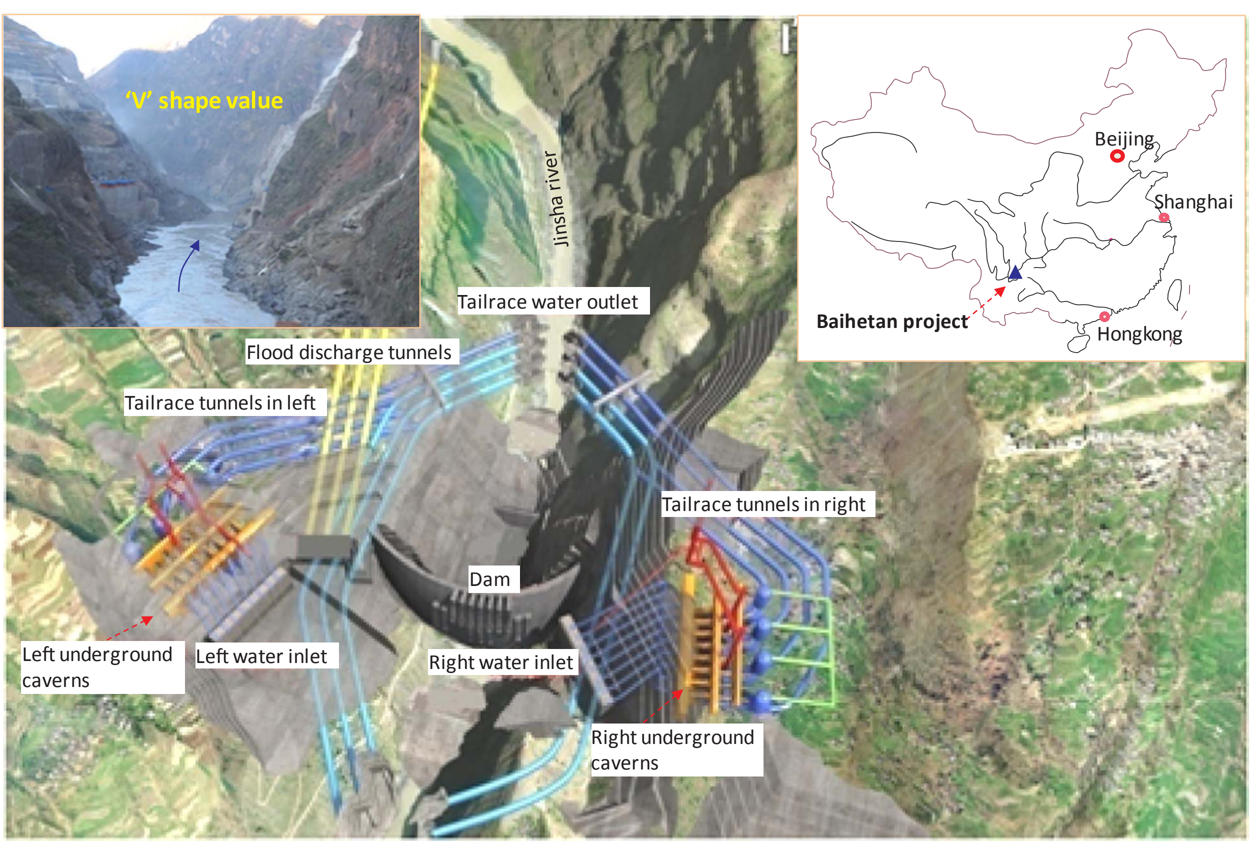

Fig. 2. Position and general layout of the Baihetan hydropower station.