

Technical Note

Estimating *in-situ* rock stress from spalling veins: A case studyQuan Jiang^{a,*}, Xia-ting Feng^a, Jing Chen^a, Ke Huang^b, Ya-li Jiang^b^a State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 43007, China^b East China Investigation and Design Institute, China Hydropower Electric Consultant Corporation, Hangzhou 310014, China

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ABSTRACT

Stress-induced failures have typically been considered as engineering disasters in deep underground excavations. This paper highlights the importance of stress-driven rock failures as a means to estimate the *in-situ* rock stress at the depth. The method, which is based on the observation and documentation of a failure mode referred to here as “spalling” in deep tunnels or caverns, is put forward and presented to estimate the macro-scale rock stress. Using the proposed method, the orientation of the principal stresses *in-situ* can be deduced by the spalling intensity and associated stress-induced spalling veins in the rock mass surrounding the opening, and the magnitude of the principal stresses can be estimated by the assumed crack initiation stress required to generate spalling in the given rock by careful documentation of spalling failure characteristic in the field. A real case study at Baihetan powerhouse site has been carried out and indicates that the proposed method is an available way to enriching recognition of *in-situ* rock stress and a helpful supplement to traditional methods of stress measurements after strictly numerical verification. Analysis of the regional tectonic setting as well as measurements of *in-situ* stress supports the results by the suggested approach.

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1. Introduction

When designing or opening deep underground tunnels or caverns, the characteristics of the *in-situ* rock stress have always been assessed, principally for avoiding or decreasing troublesome stress-induced failures, such as slab breaks, rock outbursts, and cave-ins (Cook, 1965; Exadaktylos and Tsoutrelis, 1995; Rajmeny et al., 2002; Diederichs et al., 2004; Phillipson, 2008). In general, rock stress is estimated by means of *in-situ* measurements such as hydraulic fracturing (Bjarnason, 1986), HTPF (Haimson and Cornet, 2003), overcoring method (Kim and Franklin, 1987; Sjöberga et al., 2003), etc. With the aid of special instruments and mechanical theory, these methods can provide a good estimation of the geo-stress tensor acting in the rock mass of interest. Yet, plentiful practical experiences have suggested that there exist a number of factors that may disturb the testing results and cast some doubt as for their actual representativeness, particularly the small scale of the testing procedures and the overall effect of the local rock mass structure which is ignored. Finite measured data of rock stress is commonly scattered in both magnitude and orientation per a given site. For example, Amadei and Stephansson (1997) supposed the expected imprecision of geo-stress by the overcoring method to be at least 10–20%, even under ideal rock conditions. This viewpoint coincides with other studies (Leijon, 1989; Kang et al., 2000; Hakala et al., 2003; Sjöberga et al.,

2003). Indeed, Hudson and Cornet (2003) emphasized: “It is not always easy to establish precise values for the components of the *in-situ* rock stress state.”

When the *in-situ* measured data of rock stress were either lacking or not sufficiently reliable due to practical difficulties, some alternative methods had been proposed. Leeman (1964) reported early the usage of borehole breakouts for original rock stress determination. Li and Nordlund (1993) summarized the relationship between historical rock stress and Kaiser effect. Martin et al. (1990) suggested seismic and micro-seismic methods for estimating initial rock stress. Hakala (1999) had suggested a methodology for deducing *in-situ* stresses from core discing. Vallejo and Hijazo (2008) described a new procedure for assessing the ratio between *in-situ* current stresses and far-field tectonic stresses in the rock mass, and so on. Obviously, the community keeps on encouraging the development of new methods for the estimation of rock stresses in addition to traditional measurement.

In the course of constructing underground engineering structures in hard rock masses, many stress-induced failure events, such as spalling and abrupt rockburst, are common. Currently, stress-induced failures of surrounding rock are deemed engineering disasters and much attention has been paid to the prevention of such catastrophic and dangerous rock failure modes. Naturally, the beneficial aspects of these failure modes to rock engineering have been ignored. In essence, such failure modes can provide useful information in exhibiting some characteristics of the *in-situ* rock stress. Given the inevitable corresponding relationship between stress-induced failure

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near the excavation and the far field stress conditions in the hard rock mass, the rock stresses can be estimated by application of the plentiful stress-induced rock failures in different tunnels and caverns at a given site. In fact, each tunnel and cavern in each observed zone can be regarded as a large-scale *in-situ* rock stress testing chamber whose representation and reliability can be considered superior to that of several small-scale measurements of rock stress.

In this paper, we highlight the usefulness of rock failures triggered by excavation induced rock stresses and try to develop a method to estimate the *in-situ* stress based on spalling veins observed in deep underground excavations. We hope this method will provide helpful means for recognizing *in-situ* rock stress and for supplementing traditional geo-stress measurement techniques performed underground. The case of Baihetan basalt is provided to illustrate the proposed method by which both the orientation and magnitude of *in-situ* rock stresses can be deduced through observation and documentation of rock spalling. Corresponding analyses meant to validate the inferred results are also performed, specifically with regard to the tectonic setting and contrasting measurements of *in-situ* stresses at the same site.

2. Spalling characters of Baihetan basalt

2.1. Background of Baihetan hydropower station

The Baihetan hydropower station, located in the downriver region of Jinsha River, will be another vast hydraulic station similar to the Three Gorges (Fig. 1). This hydraulic station has been designed as a fully underground powerhouse system: all caverns and tunnels related to generating electricity will be inside the bank side. The Baihetan basalt can be regarded as quasi-isotropic rock in the aspect of strength and failure model (Zhang et al., 2010). For the purpose of understanding the engineering geology and rock stress conditions of the underground caverns at the right slope site, five horizontal

exploratory tunnels were excavated inside the basalt rock with little joints and minor weathering at a depth of 400 m by careful drill and smooth blasting (see Fig. 1). *In-situ* investigations revealed a great deal of basalt spalling and flaking, with thickness ranging from 0.5 to 3 cm in the exploratory tunnels (Figure 2). Here, we commonly refer to this kind of brittle basalt failure as “spalling”. Widespread spalling failure observed in tunnels indicates that the right slope selected as a site for the hydraulic caverns is a typical high-stress zone. The stress-induced failure of surrounding rock could challenge the design and excavation of underground multi caverns. Understanding the rock stress at the right slope site is a key issue not only for the support design of surrounding rock but also for the safe cavern excavation.

Two kinds of *in-situ* stress measurement techniques, hydraulic fracturing with three boreholes intersection and over-coring, were carried out in different exploration tunnels. However, these two different methods did not produce the same horizontal major principle stress direction, i.e. the hydraulic fracturing result indicated the dominant orientation of the major principal stress is trending NNE but the over-coring result indicated the regnant orientation of the major principal stress is in NE direction. The complicated rock stress at the underground hinge site leads to a dilemma on how to choose the optimal axis orientation of the large underground powerhouse for the purpose of increasing its stability margins and reducing the intensity of the applied rock support. To resolve this puzzle, a new way to assess the characteristics of rock stress at the right powerhouse site, especially the trend and magnitude of horizontal major principal stress, is needed.

2.2. General characteristics of spalling in exploratory tunnels

To provide first-hand information on spalling in Baihetan's exploratory tunnels, an associated team, comprised of geological, structural,

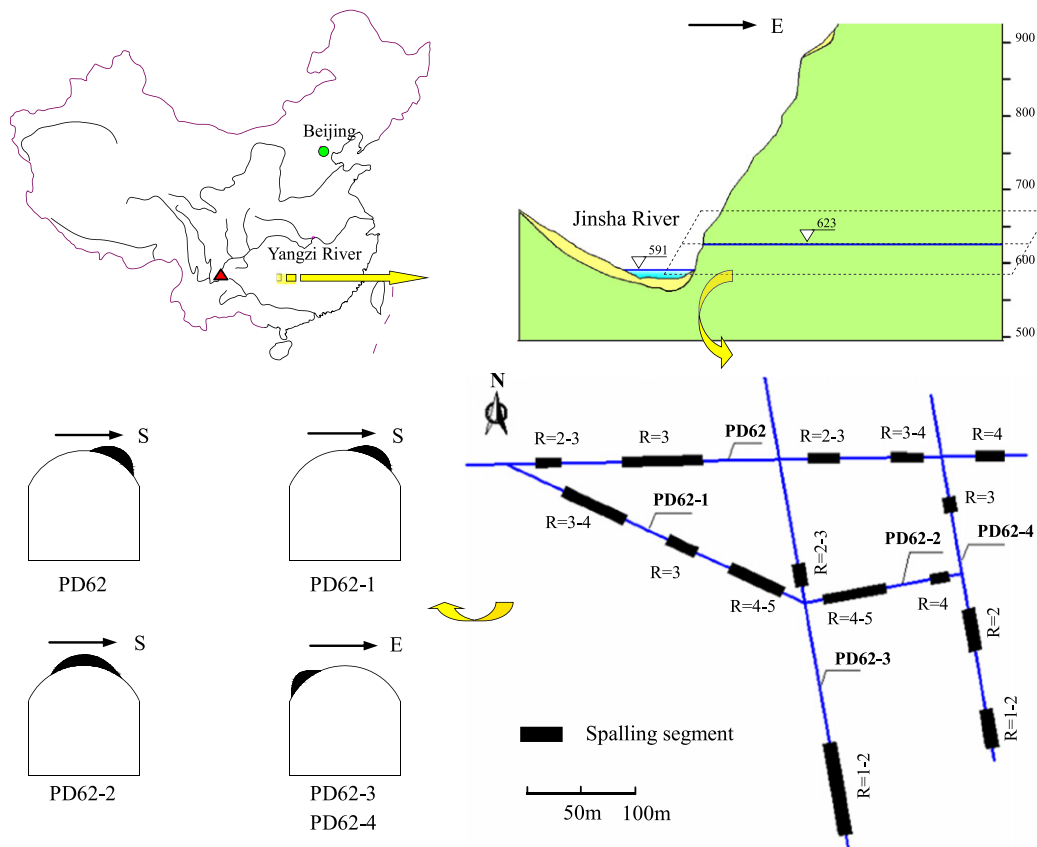


Fig. 1. Position of Baihetan hydropower station and rock spalling in its exploratory tunnels of right bank site.

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