Stress-induced cracking performance of hard basalt in a large underground cavern based on multi-information observation

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Abstract: Overcoming the brittle cracking and the corresponding hard rock has become the key bottleneck challenge in the excavation of underground engineering with high geostress. To further understand the onsite cracking's characteristics and the basic mechanism of hard rock, we carried out a detailed field monitoring action for basalt breaking behaviors in a large underground powerhouse by in situ investigation, digital borehole camera, multi-point deformation measurement, and real-time microseismic monitoring. On the basis of our observations, the inner cracking performances of surrounding rock embodied as discontinuous appearance and open of cracks during excavation, and these fractures were often parallel to the outline of the cavern and extended to the inner side because of the subsequent excavation disturbance. Corresponding numerical simulation indicated that the redistribution of rock stress induced local stress concentration and would result in the splitting break of basalt. Field complicated proof indicated that this stress-induced cracking of basalt belonged to the tensile break, and the macroscopic deformation of the surrounding was the result of the accumulation of abundant open deformation of discontinued cracks. This observed achievement can enrich our understanding of the cracking mechanism of hard rock and provide some key cures for optimization design for underground engineering construction under high geostress conditions.

1. Introduction

During the construction of large underground caverns or tunnels under high geostress, the brittle failure of hard rock often happened, such as cracking, spalling, and rockburst [1-4]. Current excavation practice in deep underground engineering with hard rock indicated that the stress-induced cracking failure and resultant engineering disasters have become the key bottleneck challenge in underground space construction [5-9]. In deep gold mining of South Africa, the observed break velocity of rockburst was more than 2.5 m/s [10, 11]. The maximum cracking depth of surrounding rock in the Jinping underground powerhouse was nearly 13 m, which resulted in a long-time reinforcement more than a half year [12]. Serious stress-induced slab breaking-off and collapse also had led to an obvious increase of safety risk and supporting cost in Chinese Jinping deep laboratory [13]. Thus, it is essential to have a
deep understanding of the stress-induced cracking of hard rock in large underground engineering for supporting design and disaster prevention in deep engineering construction.

Back analysis of engineering practice has indicated that brittle stability accidents are often related to the redistribution of the rock stress during excavation [14, 15]. Considerable efforts have been carried out to elucidate the stress evolution and failure mechanisms of hard rock in underground caverns under high geostress conditions, including laboratory experimentation [16-21], in situ investigation and monitoring [22-26], and theoretical and numerical analysis [27-30]. These studies have indicated that the stress change (i.e., loading and unloading) of the surrounding rock plays a critical role in its brittle failure and that this redistribution of rock stress causes the migration, concentration, and release of the strain energy within the rock mass [31-34]. A multi-observation method, including in situ investigation, visual digital borehole camera, deformation measurement, and micro-seismic (MS) monitoring, may be a more reasonable way for deeply understanding the brittle cracking mechanism of surrounding rock.

On the basis of the onsite investigation in an underground powerhouse with the largest size in the world, we first analyzed the stress-induced crack characteristics of hard basalt. We carried out an appropriate field monitoring analysis for basalt’s cracking behaviors, including digital borehole camera, multi-point deformation monitoring, and real-time MS monitoring. To expose the mechanical mechanism of basalt’s break performance, we also used the numerical back simulation and true triaxial experiment. In this study, we indicated that the redistribution of rock stress induced local stress concentration, which resulted in the brittle break of basalt and embodied as discontinuous cracks inside the surrounding rock.

2. Background

The second-largest water-power engineering in China is the Baihetan hydropower station, which is located at the boundary of the Sichuan and Yunan provinces. This hydroelectric project is composed of many elements, including a double-curvature arch concrete dam, flood discharge tunnels, diversion tunnels, underground powerhouses, main transformer caverns, and tailrace tunnels (Fig. 1). The Baihetan hydropower station has two underground powerhouses, with a combined electrical capacity of $16 \times 10^6$ kW, located on the respective banks of the Jinshang valley, that is, the right underground caverns and the left underground caverns. Each underground powerhouse has a size of 438 m (length), 88.7 m (height), and 34 m (width), indicating these two powerhouses to be the widest underground hydroelectric caverns in the world.

![Fig. 1 Position and general layout of the Baihetan underground powerhouse](image)

The underground powerhouse cavern inside the right bank is surrounded by stratigraphic rock, which is a basaltic formation originating from magmatic and volcanic eruptions and belongs to the Emei
mountain group of the Permian system \( (P_2\beta) \). These basaltic flowing layers are inclined with an attitude of 40°–50° NE in trend and 15°–25° SE in dip angle. The actual rocks exposed at the underground cavern are mainly cryptocrystal basalt, devonite basalt, fragmentary breccia lava, and columnar jointed basalt. The underground cavern on the right bank is buried under the rock mass at 480–800 m (vertical depth) and 420–540 m (horizontal depth). The direction of the maximum principle at the site, whose measured value is approximately 26 MPa in general and 30 MPa in geographical position, is nearly parallel to the axis of the main powerhouse \[35, 36\]. There appeared core disking phenomena in exploratory boreholes at the site. According to the Chinese standard for engineering classification of rock mass \[38\], the rock mass quality is ranked as II and III, which is acceptable for the construction of underground tunnels or caverns. According to Barton's Q system and GSI classifications \[39-40\], the quality indices of rock mass are 20–50 and 70–80, respectively.

3. Observation for basalt's cracking failure by multi ways

3.1 Visual observation of macroscopic cracking by a digital borehole camera

To visually observe the inner cracks of surrounding rock induced by the excavation, we applied the digital borehole camera to scan the cracks around the surface of the borehole. In this way, the discontinuous distribution of cracks inside the basalt had been detected in the roof and the sidewall of the powerhouse, and the temporal evolution of the basalt cracking had been observed. By pre-drilling the borehole on the roof of the underground powerhouse, we proved that the excavation induced these cracks. Taking the observed result at K0 + 133 as an example, the first observation before excavation exposed no cracks at the 7.5 m position (Fig. 2a); however, the broken face had been observed at the 7.5 m depth from the surface of the sidewall during the excavation of the third layer of the underground powerhouse (Fig. 2b), and this crack multiplied during the subsequent excavation, that is, from layers 4–8 (Fig. 2c).

On the sidewall of the underground powerhouse, observation of the digital borehole camera also indicated that the main cracked zones were in the range of 2 m to the surface. In this fractured zone, we can find that the largest depth of the cracking position was different between different boreholes, and the width of cracks in the same borehole was also different in the same borehole. It was common that almost all the exposed cracks were performed as open cracks induced by the tensile failure and were approximately parallel to the surface of the sidewall.

For real-time observing the fracturing process of basalt, we drilled a borehole at the top of the left powerhouse’s upstream spandrel before its opening. On the basis of the observations using a digital borehole camera, the stress-induced break of basalt was a typical dynamic fracturing process with its initiation, extension, and coalescence (Fig. 3).
Fig. 2 Observed distribution of cracks inside the roof of the underground powerhouse (a) before excavation and (b) after excavation as well as the (c) long-time state

Fig. 3 Fracturing process of basalt at the powerhouse’s upstream spandrel observed by a digital borehole camera

3.2 Estimation of basalt’s inner cracking depth by multi-point meters

During the excavation of the caverns, many multi-point meters had been set for monitoring the temporal deformation of the surrounding rock. In general, the deformation values of rock at the shallow position were larger than the deformation values of rock at the deep position, which is also proved by many monitoring dates [41-43]. However, in the Baihetan underground powerhouse, there were many monitored time-deformation curves with special mode: that is, two points had the similar
deformational values and development mode (Fig. 4). This is because there was an obvious crack whose opening deformation led to the total displacement of the surrounding rock outside this crack. In addition, the monitored macro deformation proved that the excavation induced many discontinuous inner cracks of surrounding rock under a high geostress condition, which was following the visual results obtained by the borehole camera.

![Fig. 4](image)

**Fig. 4** Monitored deformation of the surrounding rock by the multi-point meters during excavation (a) at the arch, (b) at the skewback, and (c) at the sidewall.

### 3.3 Spatial mesoscopic break analysis by MS monitoring

To monitor the fracture process of rock masses in the roof and sidewalls during the excavations of the underground powerhouse, we selected the drainage tunnels Nos. 5-1 and 5-2, located at the upstream and downstream of the powerhouse, respectively, to install the MS sensors. Three monitoring sections were placed in the drainage tunnel No. 5-1, each consisting of three or four MS sensors, and were arranged at intervals of 30 m from chainage K0 + 70 to K0 + 130. Five monitoring sections were placed in the drainage tunnel No. 5-1, each consisting of two MS sensors, and were arranged at intervals of 30 m from chainage K0 + 50 to K0 + 170 (Fig. 5).

From January 1 to June 16, 2017, the spatial distribution of cumulative MS events induced by the excavation of the main powerhouse was shown in Figs. 6a and b, in which the sphere in the figure represents the MS event. The radiated MS energy determined the radius of the sphere, and the moment magnitude determined the color of the sphere. When the radius of the sphere was larger, the MS energy was greater, and when the color was brighter, the moment magnitude was greater. The front view of the MS event (Fig. 6a) showed that the MS events were unevenly distributed along the outline of the cavern, clustered in the upstream spandrel and downstream foot of the main powerhouse. The cluster of MS events had a certain correlation with the maximum principal stress; that is, the cluster of MS events was distributed in the stress concentration region. Thus, the monitored results meant that the spatial distribution of the MS events could indirectly reflect the distribution of the excavation-disturbed stress field. In addition, a large number of MS events were clustered near the sidewall of the main powerhouse. The cluster of MS events indicated internal damage and deterioration of the rock mass to a certain extent and that the risk of large deformation or failure increased. The top view of the MS event (Fig. 6b) revealed that the chainage from the K0 + 90 to K0 + 145 region had a higher risk of failure in the study area. Figs. 6c and d show the corresponding event count clouds of MS events, which visually revealed the micro cracks’ spatial distribution inside the rock mass.
3.4 Surface spalling performances of the surrounding rock

Because of the cracking of the basalt on the sidewall and roof, a series of prominent failures of basalt were encountered during the excavation of the underground powerhouse, mainly including the stress-induced spalling and stress-structure controlled collapse.
In stress-induced spalling, the spalling is by flaky or platy exfoliation of rock and can be produced in intact rock mass under low-confining conditions, including the stress-induced process of crack initiation, propagation, and fracture. During the layer-by-layer excavation of underground powerhouse in the Baihetan, the most common failure type was the spalling of surrounding basalt (Fig. 7).
Fig. 7Photos of typical spalling of basalt in the Baihetan underground powerhouse (a) at the sidewall and (b) on the arch foot. (c) Statistical result of spalling thickness.

Stress–structure-induced collapse was a failure type of surrounding rock that was driven not only by the stress but also by the rock mass structure. Under the influence of stress concentration, the existed structure plane would gradually propagate the basalt’s fracturing process, and the surrounding rock would be cut through almost to form a potentially unstable rock block. Then, a collapse with almost hundreds of cubic meters of collapsed rock would finally occur (Fig. 8a). Contrasting to the stress-induced spalling, the failure depth and range of stress–structure-controlled collapse were larger. Field statistical investigation illustrated that the failure depths of most of the collapse were within 1 m, but a few collapse depths exceeded 1 m (Fig. 8b). This kind of failure also occurred near the opening face during excavation.

Fig. 8 (a) Photos of typical stress–structure-controlled collapse in the Baihetan underground powerhouse. (b) Statistical result of collapse depth

4. Numerical back analysis

4.1 Numerical model

To expose the stress-induced failure mechanism, we applied the numerical back analysis. The numerical model, which included the general hill and the underground caverns also, had been built to analyze the evolution of redistributed stress and the fractured zone around the powerhouse (Fig. 9). An elasto-brittle constitutive model (rock deterioration model), which can simulate the brittle break of basalt and its strength soften after a break, was applied in the numerical simulation. Here, the rock failure degree (RFD) also defined the fractured zone \(^{[44]}\). The initial geostress condition and basic mechanical parameters were decided on the basis of the onsite test data \(^{[25, 35]}\).
4.2 Evolution of stress distribution and failure zone

The simulated numerical results indicated that the concentrated stress $\sigma_1$ at the upstream spandrel of the powerhouse, not only its value but also its high-stress zone's area, increased with layer-by-layer excavation from top to down (Fig. 10). At the concentrated stress zone of the left roof, the low-angle dip of the compressive $\sigma_1$ vector (as shown in Fig. 10) would lead to the tensile splitting of the hard basalt. Thus, the fractured zone also increased from the surface to the inner rock during the stress concentration process of the upstream spandrel. It was clear that the depth of the fractured zone increased with the layer-by-layer excavation until in the fifth layer. Finally, the numerical simulation indicated that the maximum depth of the fractured zone was more than 8 m (Fig. 11).
Fig. 11 Evolution of the failure zone (RFD ≥ 1.0) during the layer-by-layer excavation of the powerhouse

5. Discussion
To understand the onsite failure of surrounding in the Baihetan powerhouse, we conducted a compressive true triaxial test for the Baihetan devonite basalt, which was finished in the Northeastern University of China [45]. The specimens were rectangular solid with 50 mm × 50 mm × 100 mm in size. The results showed that the basalt maintained the linear elastic behavior before peak strength and performed abrupt stress drop after peak strength, which means that the basalt was typically elastoplastic rocks, and its strength would lose after breakage (Fig. 12).

In general, the analysis indicated that the broken face of the failed specimens was rough and parallel to the plan of \(\sigma_1-\sigma_2\). The statistical analysis showed that the intersection angle between the broken face and the \(\sigma_1\) direction was in the range of 73–85, which met the onsite results performed by the digital borehole camera, indicating that the cracking face was approximately parallel to the outline of the caverns (Fig. 3). Further micro-analysis for the onsite spalling surface by a scanning electron microscope indicated that the broken model of basalt could be regarded as a tensile break (Fig. 13).

Fig. 12 Typical stress–strain curves of basalt under true triaxial compression condition with different stress levels

Fig. 13 Micro-surface images of onsite spalling slice observed by a scanning electron microscope

6. Conclusions
To overcome the stress-induced disaster challenge in the excavation of underground rock engineering with high geostress condition, we conducted a detailed field monitoring action, including in situ investigation, capturing images using a digital borehole camera, multi-point deformation measurement, and real-time MS monitoring in a large underground powerhouse for exposing the basalt’s onsite cracking characteristics and corresponding mechanical mechanism.

The onsite observation showed that the inner cracking performances of surrounding rock embodied as discontinuous appearance and opened during excavation. These fractures were often parallel to the outline of the cavern and extended to the inner side because of the subsequent excavation disturbance. These stress-induced cracks belonged to the tensile break mode, and the macroscopic deformation
surrounding rock was the result of the accumulation of open deformation of abundant and discontinuous cracks inside rock mass. Further, the 3D numerical simulation analyzed the evolution of stress concentration and fractured zone. This simulation exposed that the redistribution of rock stress induced local stress concentration, which actuated in the brittle tensile break of basalt. This study can enrich our understanding of the cracking mechanism of hard rock and provide some key cures for supporting design for underground engineering construction under high geostress conditions.

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