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ORIGINAL PAPER

Excavation unloading destruction phenomena in rock dam foundations

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Abstract Excavation unloading destruction (EUD) is a common phenomenon in the large-scale construction sites in Southwest China, where intense horizontal tectonic stresses are present in the rock mass. The paper discusses the Xiaowan hydropower dam where stresses of 23–35 MPa were measured in the strata in the valley sides and 44–57 MPa in the floor of the valley. It describes the characteristics of EUD, discussing the laminar, arched and imbricate fractures which occurred when the near surface strata were excavated for the dam construction. The EUD fractures were largely restricted to the upper 6 m below the excavation and were particularly pronounced in the top 2 m. It is concluded that the typical Mohr Coulomb formula is not applicable where a rock mass near its critical stress is rapidly unloaded. A better understanding of EUD is important for the prediction of rock bursts etc. and hence safety in large engineering constructions in highly stressed strata.

Keywords Excavation unloading destruction (EUD) · High geo-stress · Rock burst · Dam foundations

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Introduction

When constructing large dams, the weathered and fractured near-surface rocks need to be removed. This results in unloading of the underlying strata and a consequential rebound deformation as the excavation proceeds; referred to as the "excavation unloading destruction" (EUD) phenomenon (Cai and Kaiser 2005; Sheng et al. 2002; Malmgren et al. 2007; Blümling et al. 2007; Schuster et al. 2001). The rapid excavation of the engineering works creates a sudden release in stress, with the unloading being almost immediate compared with that associated with down-cutting of rivers. Further, in regions with high crustal stresses, the effect may be exacerbated and may be very intense. A number of authors have referred to the excessive deformation created by EUD and the significance of this for safety in large dam projects (Jubien and Abbott 1989; Kalkani 1977; Bossart et al. 2004; Sabine and Ugur 2004; Xie and He 2004).

The paper discusses the EUD phenomena at the Xiaowan hydroelectric power station on the Lancang River in Southwest China. This double-curvature arch dam has a designed height of 292 m—the highest in the world at the time of writing. The rocks at the dam site are Triassic granitic gneiss and amphibolite gneiss which are massive and dense. Uniaxial compressive strength testing indicated strengths of 127–172 MPa. Geo-stress testing using discs from the drill cores taken from 85 m depth in a borehole at the dam site indicated the maximum principal stresses in the horizontal plane vary from 22 to 35 MPa. This would imply a maximum of 44 to 57 MPa at the stress concentration zone in the valley floor. Such high stresses are commonly encountered in the very strong rocks of the tectonically active regions of Southwest China where there are high mountains and gorges.

Figure 1 shows the zone of excavated material is up to 40 m thick on the right bank of the Xiaowan dam, while on the left bank it reaches a maximum of 90 m such that an unloading equivalent to 70 m of material is likely. Such a thickness of excavation would result in an unloading of the rock mass equivalent to a pressure of some 1–2.3 MPa (2,600 kg/m^3 × 9.8 N/kg × (40–90)m). The relatively sudden unloading has resulted in the development of intense fracturing even in the very strong rocks with UCS values exceeding 100 MPa.

EUD and its spatio-temporal distribution

The EUD of the rock mass at the dam site includes not only dilation of existing discontinuities but also new stress release fracturing of the intact rock below the surface of the excavation and near the valley floor (Cerrolaza and Garcia 1997). The types of fracture created by the rapid unloading can be divided into three groups:

Laminar fractures

These occur near the valley floor and parallel with the excavated surface (Fig. 2). The lamellae vary in thickness from several centimetres to more than a metre with widths and lengths tens to hundreds of times the thickness of the lamellae. These lamellae are generally flat, but with a rough and fresh surface indicating they are fresh breaks/fractures. As seen in Fig. 2, the lamellae usually have downslope displacements of several centimetres, suggesting that they experience a shear movement due to the low confining pressures.

Arched fractures

These fractures usually develop very quickly, sometimes within hours of the excavation. With a release of downward vertical stress whilst there is still lateral confinement, the surface layer of the rock rises suddenly and breaks off in an "arch" form, frequently accompanied by a blasting sound (similar to gunshot). As seen in Fig. 3, the laminae may be centimetres to decimetres thick, with sharp (knife-edge shaped) borders.

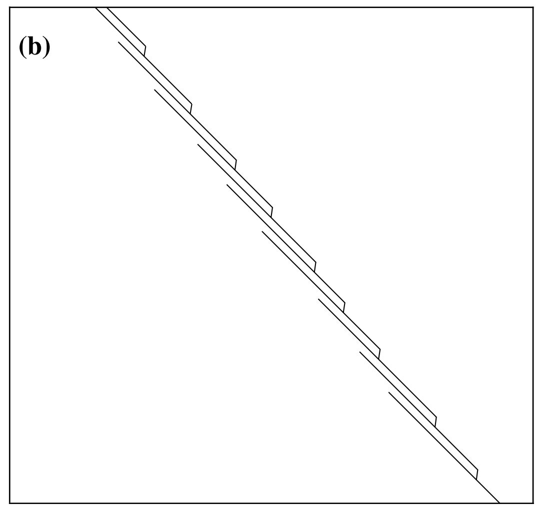

Fig. 2 Laminar fractures. **a** Photo of the laminar fractures. **b** Section sketch of the laminar fractures

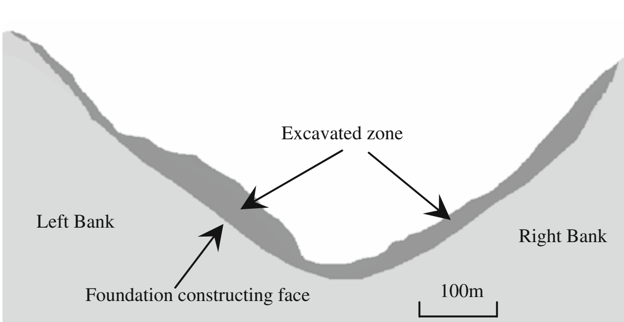

Fig. 1 Sketch map of the dam foundation section. The *dark grey* part, which has been excavated, is about 70 m thick at most. *Scale bar*, 100 m

Imbricate fractures

In order to create a smooth excavation surface in the lower part of the dam site, the rocks were pre-split with blast holes at a very low angle (Fig. 4a). When the pre-split holes are detonated simultaneously, many imbricate fractures develop between neighbouring blast holes—named "onion-skin" phenomena according to their shape. Again, imbricate fractures vary in thickness from centimetres to decimetres and have a dip angle about 10° smaller than that of the excavation surface, such that they intersect the excavation surface at a low angle (Fig. 4). A consistent explanation of this phenomenon has not yet been formed; however, it may be related to the high geo-stress in Southwest China, the metamorphic structure of the rocks,

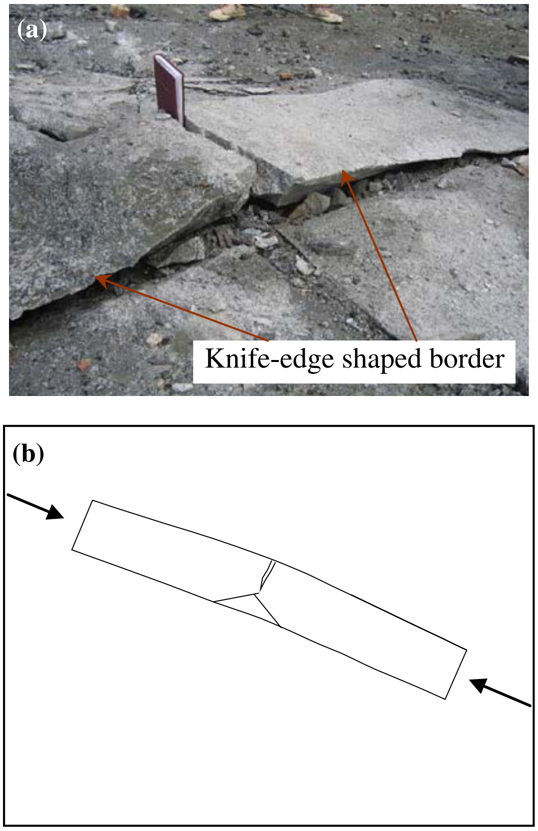

Fig. 3 Arched fractures. **a** Photo of the arched fractures. **b** Sketch map of the arched fractures

the incipient stress release fractures which are developing as the overburden load is removed, or to the fact that the surface rock above the pre-split blasting provides insufficient confining pressure hence the highly stressed rock fractures form an imbricate structure. The relationship between the incipient unloading fractures and the angle of the pre-split is manifest as the imbricate structure seen in the dam location.

Spatial distribution of unloading fractures

It is of note that the angle of the unloading fractures becomes gentler into the valley and generally is nearly parallel to the excavated surface (Fig. 2). Figure 5 shows that the unloading fractures caused by stream downcutting in the geological past also formed parallel to the morphology of the valley, i.e. the long term (geological) unloading compared with the rapid EUD. The consistency of this unloading phenomenon with the geological formation of stress-release fractures suggests it is necessary to incorporate this process in engineering design considerations. Interpreting downhole photography indicates that the EUD fractures are principally distributed within the

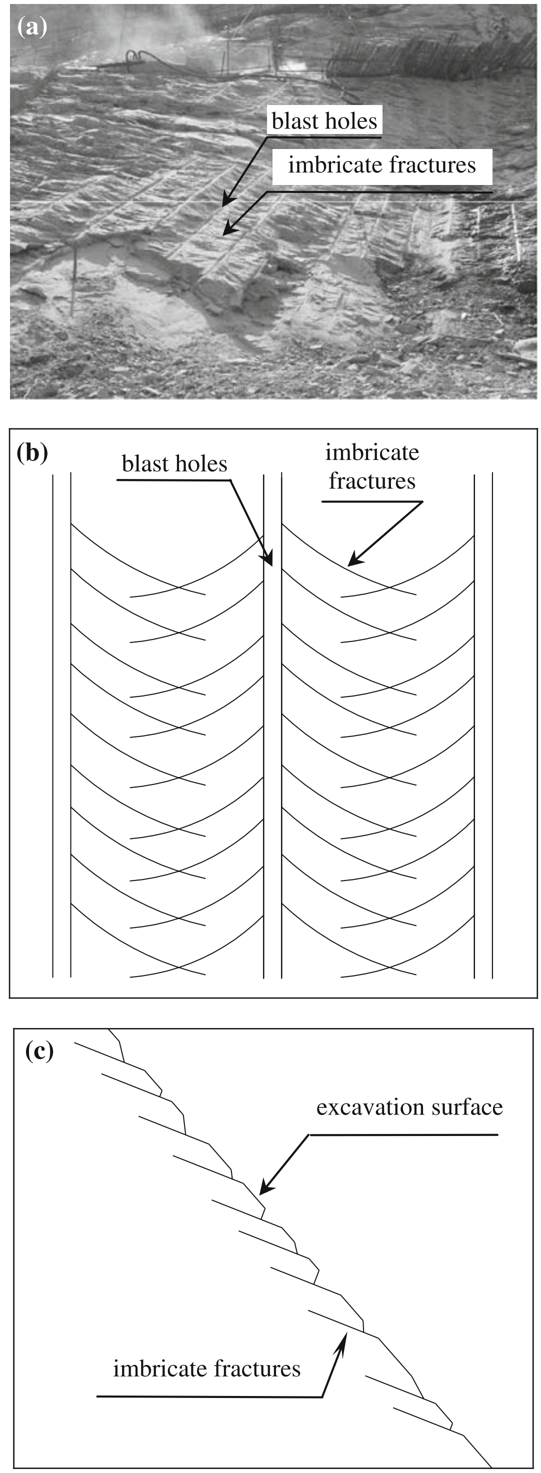

Fig. 4 Imbricate fractures. **a** Photo of the imbricate fractures. **b** Plan sketch of the imbricate fractures **c** Section sketch of the imbricate fractures (along direction of the blast boles)

depth range of 5–6 m and reduce in intensity with depth (Fig. 6a). Figure 6b shows the opening of the fractures also varies with depth, the dilation being greater at shallow depths. This is an important consideration hence the intensity of EUD has been divided into two zones—heavy and slight (A–E and E–F respectively in Fig. 6b) (Wu et al. 2008; Sato et al. 2000).

Characteristics of EUD

The influence of EUD on the integrity of the rock mass has been investigated by acoustic velocity monitoring. Figure 7 shows the acoustic wave velocity (Vp) vs depth in the borehole before excavation and 30 days and 90 days after the excavation. It can be seen from the curve (1) that the acoustic velocity of the rock mass does not vary much with depth before excavation. However, as seen in Fig. 7, after 30 and 90 days (curves 2 and 3) there is a significant change in the acoustic wave velocity in the upper 7 m compared with that prior to the stress release (curve 1). Between 2 and 4 m below the depth of the excavation there is still a noticeable difference between the 30 and 90 day readings compared with that prior to the excavation, while below 7 m depth there is only a slight change in velocity. These results confirm that EUD is concentrated over a short time range after excavation and in the upper shallow part, about 7 m deep for example.

Discussion and conclusions

Stress variation in the unloading fracture process

Figure 8 shows the process of stress variation at a point in the rock mass at the dam foundation. The stress state before excavation is shown as a solid black circle, where σ_1 is the principal stress parallel with the slope surface and σ_3 is the confining stress. It can be seen that σ_1 hardly varies while σ_3 decreases due to the excavation. However, when σ_1 decreases to a certain threshold (i.e. the dashed circle reaches the Mohr-Coulomb failure envelope), the rock mass unit will fail suddenly, leading to a rapid decrease in σ_1. Figure 8 implies that with a relatively limited further unloading, there can be an intense fracturing of the rock

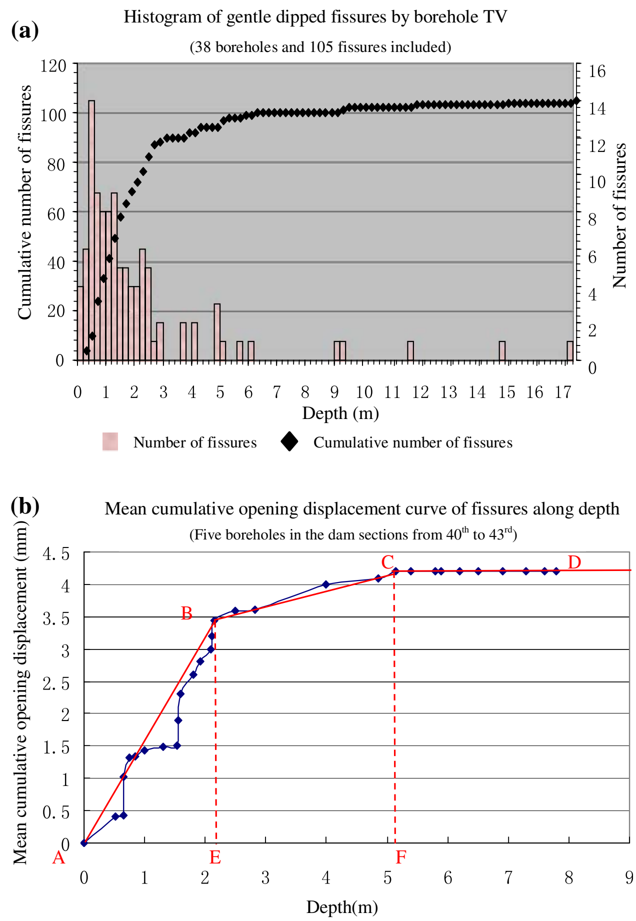

Fig. 6 Statistical graphs of fissures in the boreholes. **a** The dam foundation is divided into 43 dam sections. Two sections were selected at random, i.e. 22nd and 23rd sections. They include 38 boreholes. 105 fissures were found in these boreholes by borehole televiewer. **b** A mean cumulative opening displacement curve was drawn based on fissures found in the boreholes in the 40th to 43rd dam sections

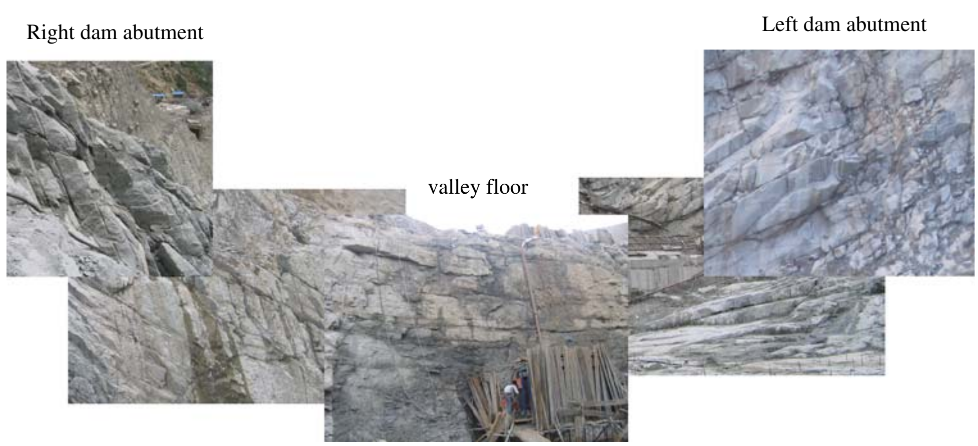

Fig. 5 Unloading fractures caused by stream downcutting in the geological past formed parallel to the morphology of the valley

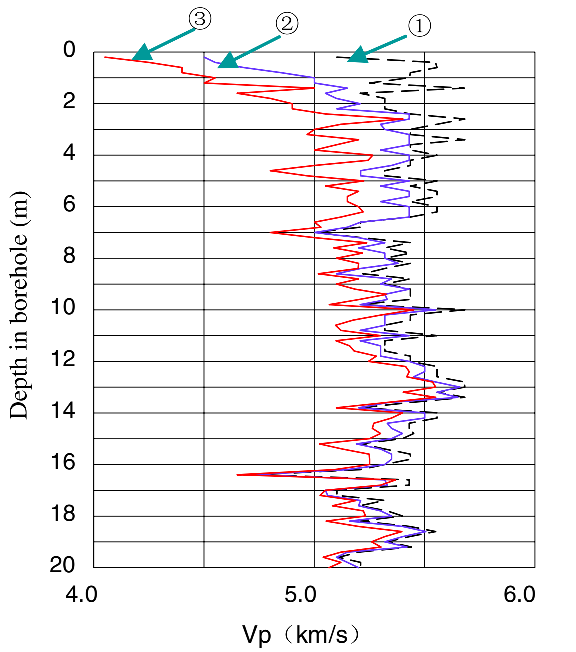

Fig. 7 Evolution of acoustic wave velocity versus depth in borehole. Curve ①in the figure is wave velocity measured before excavation, curve ② measured 30 days later after excavation, and curve ③ measured 90 days later

mass as the new stress state approaches the critical stress level. This is referred to as the non-linear mechanical behaviour of the rock mass (Wu 1993; Wu and Wang 2001; Cai et al. 2004).

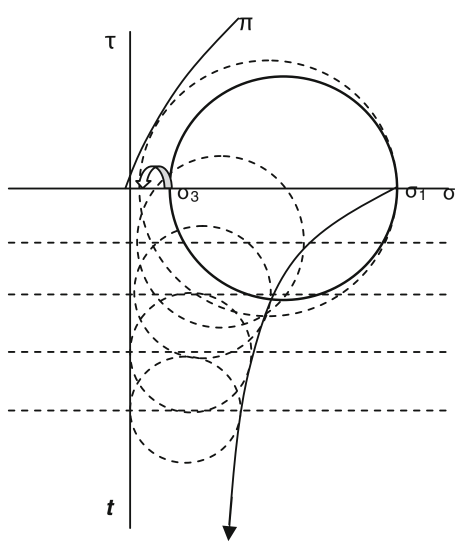

Fig. 8 Change of stress circles due to unloading and failure of rock mass. Horizontal axis of the figure is principal stress of a point in the rock mass of dam foundation, the upper part of vertical axis is shear stress, and the lower part is a time axis starting from excavation. The line π is the Mohr-Coulomb failure envelope

From the above, it can be seen that there is a high distortion energy caused by the change in the stress relationship (σ_1–σ_3) in the rock mass. Although the unloading caused by the excavation is relatively small, it is sufficient to pass the critical state threshold such that there is an intense release of energy. It is known that rocks with a high imposed strain energy, approaching its critical state, are very sensitive to changes in the boundary conditions. Because of this intense sensitivity, brittle fracture problems such as rock bursts and earthquakes are difficult to forecast. For this reason, rock burst and earthquake prediction should be based on non-linear critical state theory.

Mechanical analysis

Laminar fractures

According to the Mohr Coulomb theory, the angle between the maximum principal stress and the shear fracture surface is expressed as $\alpha = 45^\circ - \frac{\varphi}{2}$. In this study, the internal friction angle measured by triaxial tests varied between $\varnothing = 50.40 \sim 56.65^\circ$ hence $\alpha = 24.8 \sim 16.62^\circ$. However, field observations indicated that the laminar fractures develop at a much lower angle to σ_1 and considerably less than the theoretical value of α. This suggests that in these tectonically stressed rocks, the imposed σ_1 direction does not change while the fractures develop at progressively lower angles as the centre of the valley is reached (see Fig. 5). A high σ_1–σ_3 stress condition and its relationship with the excavation governs the fracture angle. When σ_3 is relatively high the rock may fracture in the shear mode. However, when σ_3 is very low (atmospheric), it fractures in the axial mode and hence the rock surface splits away in tabular sheets.

Arched fractures

Arched fractures are often bilaterally symmetrical features, created when the "horizontal" maximum principal stress causes a compression of the strata where there is little overburden stress. The surface squeezes at right angles to the imposed stress and the arching and cracks develop when the tensile stress of the rock is unable to allow further arching. Stress readings on rock bolts have confirmed these tensile stresses in the rocks at the study site.

Imbricate fractures

When two parallel blast holes are detonated, the impact results in the creation of radiating incipient fractures. Where these intersect parallel with the blast holes, imbricate fractures will be formed. However, the fact that the dip angle of the imbricate fractures is about 10° smaller than that of excavation surface indicates that they are due to a combination of the blasting effect and the high geo-stresses.

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