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Unloading-induced instability of a simulated granular fault and implications for excavation-induced seismicity

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ABSTRACT

Deep excavation in rock masses has the potential to break the frictional equilibrium of nearby faults, resulting in induced seismicity. We conducted the experimental and numerical studies on a simulated granular fault to uncover the mechanism of excavation-induced seismicity. A series of laboratory experiments were used to investigate the effects of initial shear stress, initial normal stress and its unloading rate on the frictional instability of the fault, and a numerical simulation was carried out to interpret stress variation and particle evolution during the unloading process. Our results show that both normal and shear stresses sharply drop when the fault is approaching a critical stress state. The stress reduction is due to interparticle force decrease and particle contact breakage. The evolution of fault state depends on the initial stress condition and excavation process. A greater initial normal stress and a lower initial shear stress provide a favorable environment to accumulate higher strain energy in adjacent rock, leading to larger slip displacement. A larger normal stress unloading rate can also cause higher strain energy and larger slip displacement. Understanding unloading-induced instability of a simulated fault allows us to interpret the seismic events occurred during the excavation of the Gotthard Base Tunnel in Switzerland. The reduction of normal and shear stresses associated with the excavation work decreases the differential stress applied to a natural fault zone, and subsequently results in the occurrence of induced earthquakes.

1. Introduction

Induced seismicity occurs when human activities perturb the frictional equilibrium of preexisting faults in the Earth's crust. Underground excavation creates usable space, but makes nearby faults reach or close to a critical stress state. For example, during the excavation of the Gotthard Base Tunnel in Switzerland, a seismic network recorded a series of seismic events, among which a magnitude 2.4 earthquake with a focal depth of 1–1.5 km drew extensive attention in nearby residents and caused severe damage in the excavated tunnel (Husen et al., 2013). The occurrence of induced seismicity was due to stress redistribution in hard rock in the vicinity of the tunnel and a fault zone striking at a small angle to the tunnel axis (Hagedore and Stadelmann, 2010). Nevertheless, the mechanism driving unloading-induced fault instability still eludes explanation. Particularly, the process of fault instability related to stress redistribution remains unclear.

Fault instability depends on a range of coupled factors, including the mechanical response and mineral composition of fault gouges, the hydraulic pressure in fault zones, and the state of stress. Extensive research has focused on the mechanical response of fault gouges, demonstrating that fault behaviors are associated with gouge dilation, compaction, movement and breakage (Morrow and Byerlee, 1989; Segall and Rice, 1995; Fan and Wong, 2013; Zhao, 2013; Wu et al., 2015). In shale reservoir rocks, the clay and organic contents can make fault slip rate transit from velocity weakening to velocity strengthening (Kohli and Zoback, 2013). The hydraulic pressure in fault zones has attracted wide attention in recent years, as injection-induced seismicity frequently occurs during the production of geothermal energy and unconventional hydrocarbon (Ellsworth, 2013; Guglielmi et al., 2015). Many other studies vary stress conditions in order to examine fault behaviors in response to static and dynamic disturbances (Marone, 1998; Cai and Kaiser, 2005; Savage and Marone, 2008; Li et al., 2011; Johnson et al., 2012; Wu, 2015; Zhang et al., 2017). In nature, the occurrence of fault instability is essentially related to the combination of these factors. For example, fault gouges likely exhibit shear dilation and permeability enhancement under a low normal stress, and gouge particles may roll with moving rock walls and have limited damage on particle surfaces. In contrast, fault gouges can be compacted under a high normal stress, and

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crushed particles may fill interparticle voids and lead to permeability reduction. Therefore, the coupled interaction between fault characteristics and stress conditions mainly influences the frictional instability of preexisting faults during underground excavation.

Although many studies have examined fault instability under a broad range of intrinsic and extrinsic conditions, few attempts have been made to assess the occurrence of fault instability induced by underground excavation. The objective of this study is to uncover the mechanism of excavation-induced seismicity that can improve our understanding of excavation-induced earthquakes and our ability of optimizing underground excavation strategies. We first conduct friction experiments using an unload-induced direct-shear (UIDS) model, and consider the parameters that may primarily affect fault instability, such as an initial shear stress, an initial normal stress and its unloading rate. Second, we employ a two-dimentional Particle Flow Code (PFC-2D) to study the relation between stress reduction and particle evolution and to verify our experimental observations. Finally, based on the experimental and numerical studies, we assess the implication of the seismic events occurred during the excavation of the Gotthard Base Tunnel.

2. Experimental study of unloading-induced fault instability

In the experimental part, we briefly reviewed the UIDS model (Wu et al., 2014), and specially considered the effects of initial shear stress, initial normal stress and its unloading rate on the frictional instability of a simulated granular fault. A natural fault can be viewed as a granular framework, which is discrete and strongly heterogeneous (Ben-Zion and Sammis, 2004). The laboratory investigation could help us uncover the mechanism underlying excavation-induced seismicity.

2.1. Experimental procedure

A suite of friction experiments was conducted on a simulated granular fault using the UIDS model. In each experiment, a 2-mm-thick layer of quartz sand ranging in size from 1 mm to 2 mm was sandwiched between two norite plates, as shown in Fig. 1. A servo-controlled normal load was applied on a fixed plate, and a steady shear load provided by a hydraulic jack was exerted on a driving plate. The driving and fixed plates were able to move along x and y axes, respectively, allowing us to consider the frictional instability of the fault in the x-y plane. We used a Philtec fiberoptic sensor to record the relative displacement of two plates, a group of strain gauges connected in the full shear bridge to assess the local deformation of adjacent rock, and two load cells to measure the normal and shear stresses, respectively. The displacement sensor, the strain gauge group and load cells were simultaneously controlled by a LabVIEW data acquisition unit at a sampling rate of 1000 Hz. More details regarding the experimental setup can be found in Wu et al. (2014) and Wu and Zhao (2014).

Fig. 2 shows a high normal stress and a low shear stress are applied on the fixed and driving plates, respectively. A simulated fault was initially in a state of frictional equilibrium. During the experiment, the shear stress was kept constant, and the normal stress was decreased at a constant unloading rate until the frictional instability of the fault occurred.

2.2. Experimental results

Our results show that both normal and shear stresses sharply dropped when a simulated granular fault was at a critical or near-critical stress state (Figs. 3–5). During the unloading process, a decreasing normal stress disturbed the frictional equilibrium of the fault, and the initial shear stress was subsequently approaching

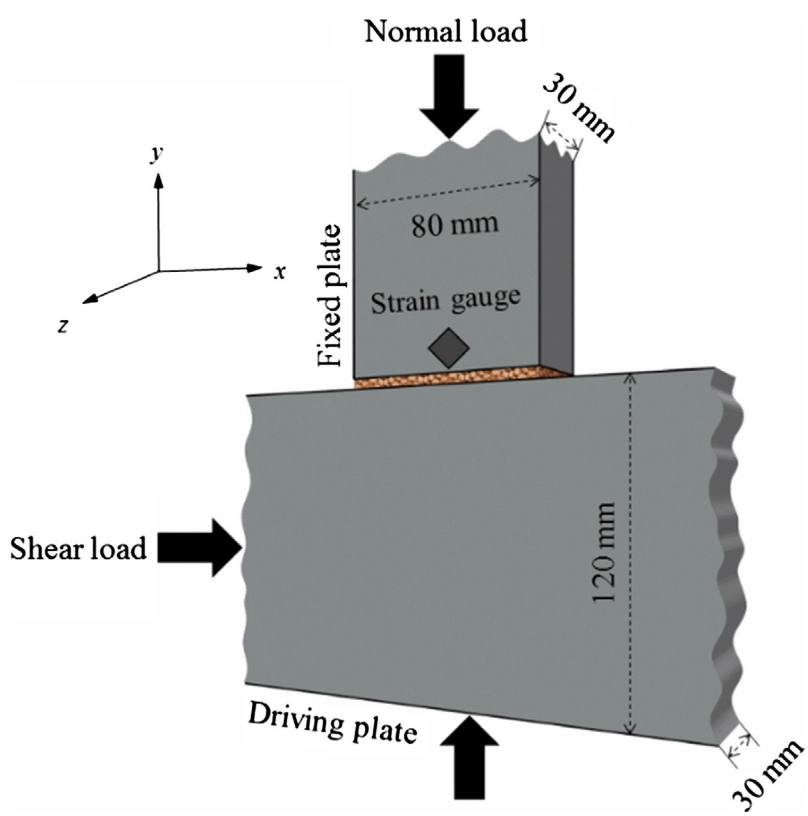

Fig. 1. Schematic view of an unload-induced direct-shear model. A granular fault was simulated between the fixed and driving plates. Normal and shear loads were applied on the fixed and driving plates, respectively.