Field and Laboratory coupled Fracture Deformation—Pore Pressure-Permeability Experiments that provide Insight for Depressurization of Fractured Rock Slopes

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Abstract Slope failures in fractured rocks occur along fracture planes and through rock bridges. Pore-water pressures within fracture planes, with a critical orientation relative to the driving and resisting forces, can trigger slope failures. For 500 to 1000 m high mine slopes the need for pore pressure control is extremely important, especially in low-permeability fractured rocks. Predicting the rate and effectiveness of depressurization of slopes requires that models incorporate fracture characteristics and coupled behaviour for the full range of stresses. Model calibration against sparse data without comparison of blind predictions to well controlled experimental data is no substitute for model validation.

Keywords Fracture deformation, slope depressurization, model validation.

Introduction

Most argillaceous and crystalline rock masses consist of rock blocks bounded by discrete fracture planes. The blocks may be porous and permeable rock, such as sandstone, or may have low porosity and very low permeability, such as granite. It is the ratio of the permeability of the rock blocks to the permeability of the fractures that determines the significance of the fractures in a given flow system. In metamorphic and granitic rocks, it is generally accepted that the hydraulic conductivity of rock blocks is $<10^{-9}$ cm/s and thus significant flows can occur only through the fracture system. Very little data are available on the effect of fractures on flow in shales and other low-permeability argillaceous rocks. In the more permeable argillaceous rocks, there have been almost no systematic attempts at distinguishing the contributions to flow from the rock blocks and from the fracture system. Groundwater studies in these rocks have assumed that the rock block-fracture system is a porous medium. Thus the most significant data base in fracture hydrology is primarily for metamorphic and crystalline rocks. In addition, extensive literature exists on fluid movement through fractured carbonate rocks in which solution channels are the primary conduits but these systems are generally considered to act as open channel flow systems.

Considerable effort has been and will be devoted to understanding how pore water pressures in fractured and fractured–porous rock slopes can be managed to reduce the risk of slope failures, especially in open pits where the slopes can and will range up to hundreds of metres in height. Fractures open and close due to changes in pore pressure within the fracture planes as well as changes in the applied normal and shear stress. The original fracture permeability is controlled by the properties of the fracture plane and the overall fracture geometry. Fluids moving through a fracture plane over long periods of time create a network of open pore space and contact points or asperities (Fig. 1) that are in meta-stable equilibrium under the applied stresses. (The pore structure map in Fig. 1 was created by resin impregnation under the applied load, followed by sectioning the fracture plane on 5 mm grids and digitizing the images (Seok

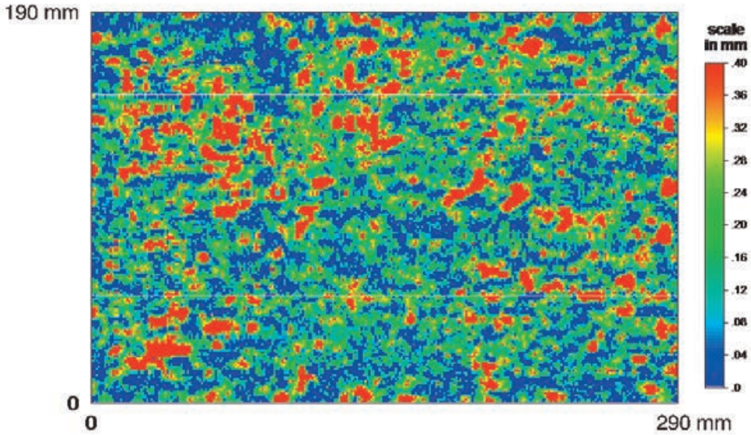

Fig. 1 *Fracture apertures from resin injection experiments (Seok 2012)*

2012)). Decreases in the applied stress and increases in the pore pressures will cause the fractures to open with a corresponding increase in permeability, while increases in the applied stress and decreases in the pore pressures will cause the fractures to close with a resulting decrease in permeability and crushing of the asperities producing a permanent change in the fracture permeability and hence the pore pressure distribution within the fracture planes and within the fractured rock slope.

Clearly, the ratio of the permeability of the fracture plane relative to the permeability and porosity of the bounding rock blocks will determine if fluid pressures that are either induced by mechanical loading, infiltration or thermal loading will dissipate along the fracture plane or into the adjacent rock block. Goren and Aharonov (2008) presented finite difference numerical simulations of a simple block model bounding a shear zone with two types of boundary conditions. One boundary condition shows pore pressure evolution within a shear zone for conditions where the initial velocity of the bounding block is zero but where the non-dimensional pore pressure is greater than zero which corresponds to fluid pressurization within a shear zone by either fluid addition by rain, deformation or thermal loading. The second boundary condition is the case where the bounding block is given an initial velocity while fluid is neither added to the shear zone nor initially pressurized within the shear zone. Fig. 2 represents the second set of boundary conditions and shows how the dissipation of the generated pore water pressure depends on the permeability of the fracture relative to the permeability of the rock that is bounding the shear plane. For the simulations with the lower permeability, the pore pressures cannot dissipate faster than they are generated and the block slides in an uncontrolled fashion. With the higher permeability, the generated pore pressures are dissipated and the movement of the block is arrested.

In-Situ Measurements of Fracture Deformation

Direct evidence of fracture deformation due to changes of fluid pressure in the fracture system is limited. One of the first direct measurements of fracture deformation was performed by Davis and Moore (1965). They placed deformation gauges across a fracture at approximately 25 m below the ground surface in a cave and were able to measure relative movements of the fracture walls of a few microns due to earth tides but with no obvious changes in water pressure. Snow (1968) described a 24 m deep water supply well at the Cecil H. Green Geophysical Observatory, Bergen Park, Colorado. This well, drilled in metamorphic rock, produced radial and tangential surface ground

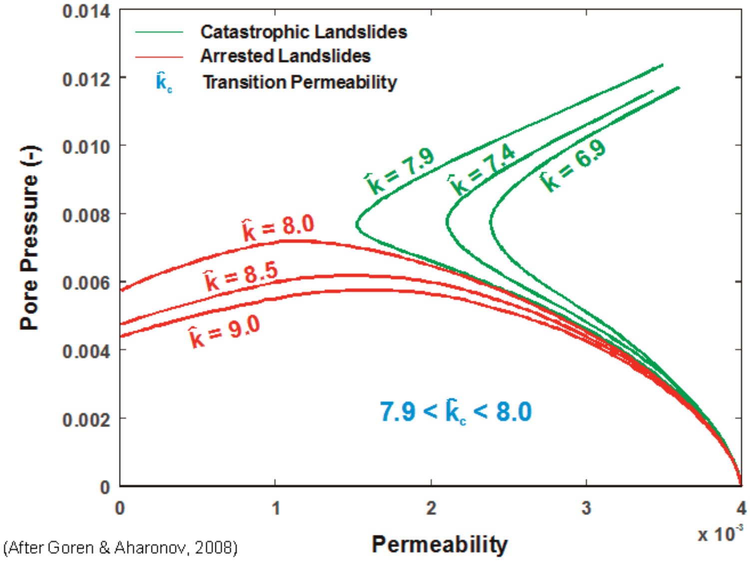

Fig. 2 *Effects of permeability ratios on pore pressure dissipation and shear movements (Goren and Aharonov 2008).*

strains of 10^{-7} to 10^{-8} up to 75 to 95 m from the well for a drawdown of 10 m. In addition, a two hour time lag was observed on the strain records every time the well was pumped. The measuring devices in this case were 24 m long quartz rod strain meters. More indirect evidence of fracture deformation was the difference between pumping into and pumping out of a well (Evans 1966) and the nonlinear relationship between fluid pressure and flow rate during injection tests (Louis and Maini 1970; Louis 1976).

Gale 1975, used a specially designed borehole deformation gauge to measure aperture changes for two different shallow sub-horizontal fractures in granite, one fracture at approximately 6.75 m of depth and a second fracture at approximately 9.75 m of depth. For each fracture, an inflatable packer was placed in the borehole immediately above the borehole fracture deformation gauge and water was injected into the isolated borehole interval. Fluid pressures were measured both in the injection borehole and in a second borehole at a radial distance of approximately 1 m where the test fracture was isolated using a double packer system. In this field experiment, both the changes in fluid pressure (changes in effective stress during injection and withdrawal) and the change in fracture aperture (fracture deformation) were measured in the borehole (Fig. 3), obtaining an *in situ* measure of the fracture normal stiffness. The measured fracture opening and closure are consistent. The three line segments in Fig. 3 demonstrate the non-linear change in the fracture normal stiffness for these shallow fractures. The measured changes in fracture apertures due to changes in fluid pressure represent a significant change in the permeability of this isolated fracture.

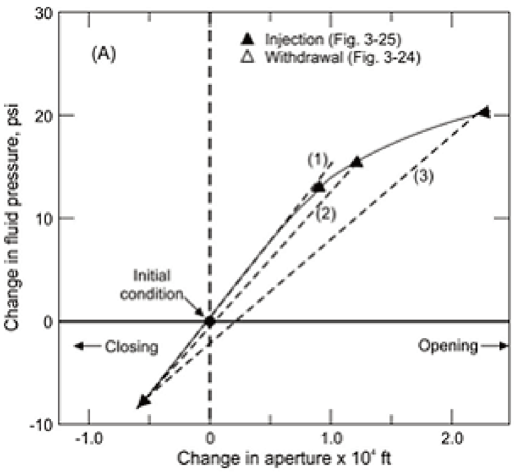

Fig 3 *Changes in fracture aperture due to changes in borehole packer injection pressures.*

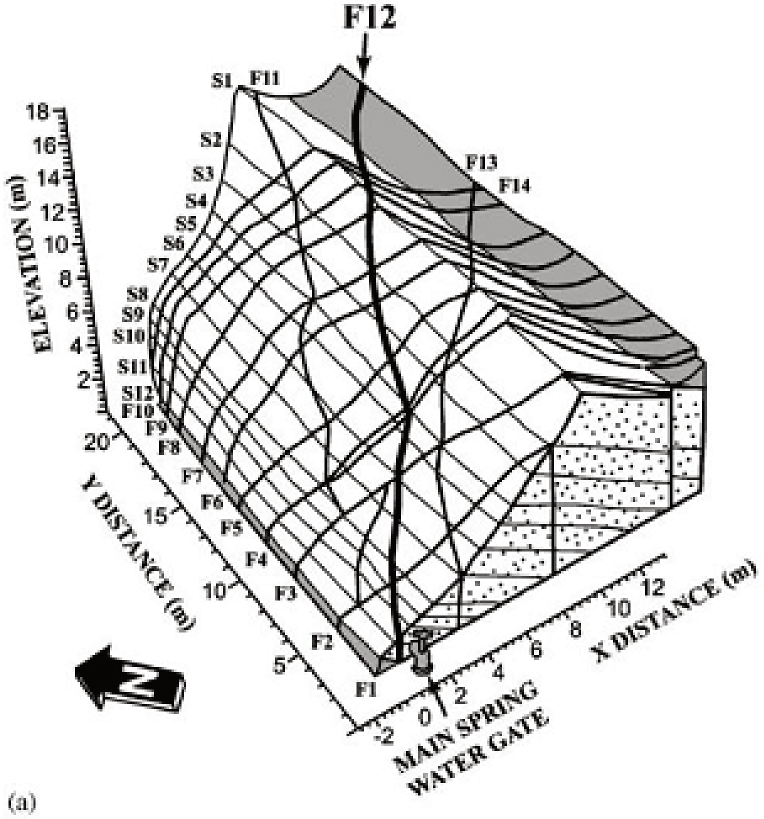

Fig. 4 *The Coaraze Laboratory site (from Cappa et al. 2005)*

Schweisinger *et al.* (2009) reported on a borehole tool that was used to measure changes in fracture aperture during packer injection tests and these authors demonstrated that significant changes in aperture were produced at moderate increases in pore pressure. On a large block scale, the hydro-mechanical coupled processes in a shallow fractured rock mass were investigated *in situ* through field experiments at the Coaraze Laboratory Site (France; Cappa *et al.* 2005). This carbonate rock slope (30 m × 30 m × 15 m; Fig. 4) was extensively instrumented for meso-scale hydraulic and mechanical measurements during water-level changes. The slope is naturally drained by a spring that can be closed or opened by a water gate. The experimental approach consists of performing simultaneous and frequent measurements of fluid pressures and displacements at different points on the surface and in boreholes and on different fracture types within this carbonate block. The observed changes in fracture aperture for a corresponding large increase in pore water pressures were not as large as one would expect. However, the fractures in the rock block at this site have been subjected to a very large number of loading and unloading cycles due to the repeated opening and closing of the gate that controlled the fluid pressures in the rock block. It is reasonable to assume that these repeated loading cycles have crushed the asperities on the fracture plane removing the non-linear stress-displacement that would be characteristic of fractures in more brittle rocks.

Hydro-Mechanical Characteristics from Laboratory Experiments

Laboratory tests on natural and induced fractures collected from the same brittle rock mass show that the permeability versus stress relationship and the overall hysteresis or permanent fracture closure for natural and induced fractures are very different. However, data from a series of coupled hydraulic-mechanical experiments on samples from the same natural fracture plane (Fig. 5) show a similar coupled non-linear response under normal and shear loading with similar dilatant and contractant behavior (Gale *et al.* 2001). Small shear displacements tend to produce large changes in fracture permeability (Fig. 6) in brittle rocks even at high normal stress (Esaki *et al.* 1999).

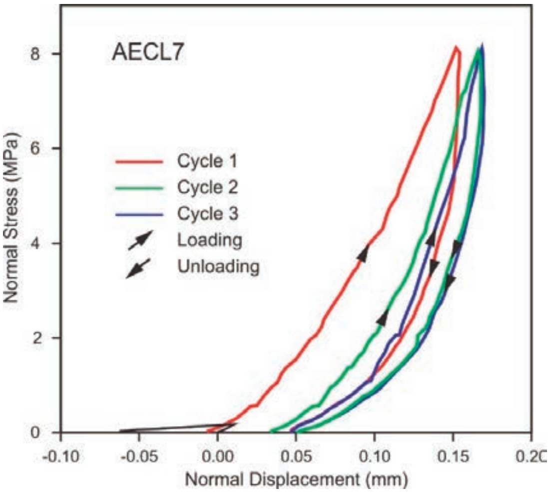

Fig. 5 *Measured fracture closure as a function of normal stress showing decrease in hysteresis and permanent deformation with repeated loading cycles (After Gale et al. 2001).*

Validation of Model Predictions of Slope Depressurization

Field and laboratory data show that fracture apertures open and close with increase and decrease in pore water pressures. Depending on the relative permeability of the fracture planes versus the adjacent rock blocks, increases in pore pressures that are generated by mining activities will either dissipate or produce shear movements that will combine to form failure planes in rock slopes. In any fractured rock slope, the fracture system will form a complex pattern of fracture orientations and interconnections in which fracture planes will both open and close under changes in normal and shear stress producing a range of pore pressure changes. Applying numerical models with confidence to such complex systems, requires that the models replicate the coupled hydro-mechanical characteristics that have been documented for discrete fractures that exist in all rock slopes. Literature reviews demonstrate that neither large scale laboratory experiments nor large scale field experiments have been conducted that are well suited to both slope depressurization model calibration and model validation. Model validation requires that the characteristics or parameters of the sample or area be used to predict the experimental outcome before the experiment is conducted or the area is stressed. Validation ex-

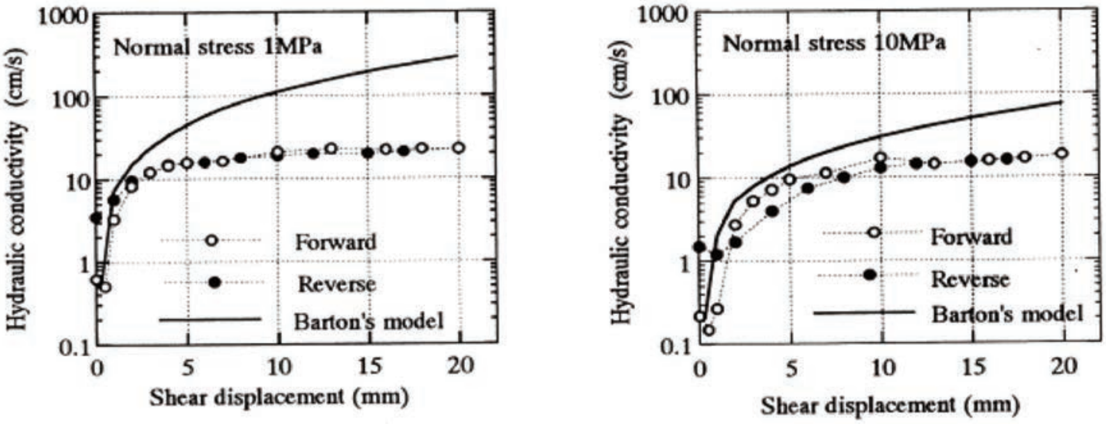

Fig. 6 *Hydraulic conductivity of a granitic joint as a function of shear displacement under a normal stress of (a) 1 MPa and (b) 10MPa, Esaki et al. (1999).*

periments need to be completed using either metre scale centrifuge samples or actual fractured rock slopes that are at least 30 to 40 times higher than the average fracture spacing in the slope. Predicting the failure of a well characterized slope within well-defined limits in an inactive mine setting and then failing the slope by increasing the water pressure in the fracture network would constitute a credible validation experiment.

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