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Mesoscale characterization of coupled hydromechanical behavior of a fractured-porous slope in response to free water-surface movement

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Abstract

To better understand the role of groundwater-level changes on rock-slope deformation and damage, a carbonate rock slope ($30\,\text{m} \times 30\,\text{m} \times 15\,\text{m}$) was extensively instrumented for mesoscale hydraulic and mechanical measurements during water-level changes. The slope is naturally drained by a spring that can be artificially closed or opened by a water gate. In this study, a 2-h slope-dewatering experiment was analyzed. Changes in fluid pressure and deformation were simultaneously monitored, both at discontinuities and in the intact rock, using short-base extensometers and pressure gauges as well as tiltmeters fixed at the slope surface. Field data were analyzed with different coupled hydromechanical (HM) codes (ROCMAS, FLAC^{3D}, and UDEC).

Field data indicate that, in the faults, a 40 kPa pressure fall occurs in 2 min and induces a $0.5–31 \times 10^{-6}$ m normal closure. Pressure fall is slower in the bedding-planes, lasting 120 min, with no normal deformation. No pressure change or deformation is observed in the intact rock. The slope surface displays a complex tilt towards the interior of the slope, with magnitudes ranging from 0.6 to 15×10^{-6} rad.

Close agreement with model for both slope surface and internal measurements is obtained when a high variability in slope-element properties is introduced into the models, with normal stiffnesses of $k_{\text{n\_faults}} = 10^{-3} \times k_{\text{n\_bedding-planes}}$ and permeabilities of $k_{\text{h\_faults}} = 10^{3} \times k_{\text{h\_bedding-planes}}$. A nonlinear correlation between hydraulic and mechanical discontinuity properties is proposed and related to discontinuity damage. A parametric study shows that 90% of slope deformation depends on HM effects in a few highly permeable and highly deformable discontinuities located in the basal, saturated part of the slope while the remaining 10% is related to elasto-plastic deformations in the low-permeability discontinuities induced by complex stress/strain transfers from the high-permeability zones. The periodicity and magnitude of free water-surface movements cause 10–20% variations in those local stress/strain accumulations related to the contrasting HM behavior for high- and low-permeability elements of the slope. Finally, surface-tilt monitoring coupled with internal localized pressure/deformation measurements appears to be a promising method for characterizing the HM properties and behavior of a slope, and for detecting its progressive destabilization.
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1. Introduction

Understanding coupled groundwater and mechanical processes in complex fractured-porous rocks is essential for the safety and efficiency of subsurface and slope-stability engineering, and thus for the security and economic well-being of the general public. Although poorly documented, water is often mentioned as a triggering mechanism for failure of rocks with well-developed pre-existing fracture networks and thus the cause for rockslides [1]. Sartori et al. [2] observed that "explosion-like failure of rock slabs and sprays of water under pressure" characterized the events preceding the 1991 Randa rockslide ($22 \times 10^{6}\,\text{m}^{3}$) in Switzerland. Similar observations have been made in other cases in which events have been triggered close to and above the main spring draining the aquifer contained in a slope. Groundwater can also play a role in accelerating

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rock-slope movements. For example, Cappa et al. [3] found clear correlations between periods of seasonal water infiltration and accelerations of the La Clapière rockslide ($60 \times 10^6\,m^3$) in the southern French Alps. Such observations indicate that groundwater flow and mechanical deformations are intimately coupled and cannot in general be analyzed independently of each other.

These coupled effects are especially prevalent in fractured rock, where the groundwater flow concentrates along pre-existing discontinuities or along discontinuities induced by progressive failure occurring in the massif. Such coupled effects have been studied primarily through laboratory specimens on single fractures, and, secondarily in the field, within the deep saturated zone of large fractured rock masses [4–7]. Usually, intact rock has relatively low permeability. Numerous laboratory tests on single fractures show that fracture permeability is quite sensitive to changes in fracture aperture, which in turn depend on the state of stress acting on the fracture [8–11]. Under normal stress loading, fracture permeability depends on effective stress variation, as a function of the amount and spatial distribution of void spaces between the fracture surfaces [12]. A decrease in fracture voids under increasing stress leads to a decrease in fracture permeability. Under shear stress, induced fracture-slip permeability first increases because of dilatancy. Then, gouge production linked to fracture asperity damage may induce a clogging of the void spaces and a lowering of fracture permeability [13,14].

In fractured rock masses, within a complex fracture-network geometry, hydromechanical (HM) processes depend on the coupled effects within fractures and their hydraulic and mechanical connections with other fractures as well as the orientation and magnitude of the effective stress state [15,16]. In addition, scale effects and sampling disturbances indicate that hydraulic and mechanical properties derived from a small-scale laboratory sample might be significantly different from that in the field [7,17,18]. Hydraulic well testing applied to investigate *in situ* coupled HM effects in fractured rock [17–21] showed that the *in situ* behavior of a single fracture strongly depends on the HM behavior of the surrounding fractured rock mass. Experiments that carried out simultaneous measurements at different locations within an *in situ* fracture network [9,22] showed that the time-dependent response of the fracture network is being characterized by a delayed response, with a time lag of a few minutes to a few hours at some points [22], and reversed pressure–deformation variations that were linked to stress transfers effects from one point to another. For example, pressure increased in some fractures located at a distance from an experimental well, where an induced pressure drawdown caused an effective stress variation affecting a larger volume of the reservoir [23].

The coupled HM behavior of fractured rock has been extensively studied in rock mechanics over the past 30 years, in research programs concerned with flow in fractures at great depths, under high stresses, and with a relatively small hydraulic aperture and high stiffness [24]. Coupled processes in rock slopes or at shallow depths are seldom studied because those effects are difficult to quantify, are often three-dimensional, and involve highly permeable fractured media under a very low stress state, which can be modified at different time scales with the development of slope destabilization [25–27].

The stability of a rock slope depends on the rock mass mechanical strength and on the state of stress inside and at the boundaries of the slope [28]. Slope strength depends on the fracture-network geometry, individual fracture strength, and intact rock strength. The state of stress in a slope is complex, with zones of low stress close to the middle and upper part of the slope, and zones of high stress at the toe and deep within the slope [29,30]. It is commonly acknowledged that tensile stresses develop from the middle to the top of the slope and may induce traction opening of existing fractures. Deeper within the slope and at the slope toe, all principal stresses are compressive and may induce sliding on fractures (depending on their orientation). Assuming this initial highly heterogeneous state of stresses inside a highly discontinuous rock mass, failure may develop in a variety of modes, through a single fracture plane (plane failure) to a combination of several discontinuities connected together (step path and step wedge failure). Moreover, failure occurs both along pre-existing discontinuities and within rock bridges made of intact rock between the discontinuities.

Groundwater seasonal flow is one major trigger that governs the stability of rock slopes [31,32]. The hydrogeology of a rock slope depends on land-surface topography, hydrogeological properties, and the infiltration of rainfall and melting snow. Furthermore, winter ice can prevent outflows and increase water pressures in the slope [33]. An unconfined aquifer is drained through seepage points located at the foot of the slope. Depending on the hydrologic conditions, the free water-surface elevation changes with time, being relatively high during heavy precipitation periods and relatively low during dry periods. In the basal, saturated zone of the slope, interstitial pressures (P_f) act to reduce effective normal stress in discontinuities [34–36]. Compressive effective normal stresses ($\sigma_n' - P_f$) press the opposing discontinuity walls together and resist sliding motion along the discontinuity surface, which can be induced by shear stresses (τ) acting parallel to the discontinuity plane. A reduction in the effective normal stress state leads to the normal opening of discontinuities, inducing a reduction of the internal shear strength of discontinuities or of the failure surface [37]. Deep in the slope and at the slope toe, where principal stresses are all compressive, an interstitial pressure increase can then induce slip on favorably oriented discontinuities. In zones close to the surface and in the upper part of the slope where tensile stresses develop, a traction induced opening of discontinuities can occur. In both locations, coupling between groundwater pressure and deformation is a major factor in slope elastic and inelastic deformation.

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