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Hydromechanical interactions in a fractured carbonate reservoir inferred from hydraulic and mechanical measurements

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Abstract

Hydromechanical coupled processes in a shallow fractured carbonate reservoir rock were investigated through field experiments coupled with analytical and numerical analyses. The experiments consist of hydraulic loading/unloading of a water reservoir in which fluid flow occurs mainly inside a heterogeneous fracture network made up of vertical faults and bedding planes. Hydromechanical response of the reservoir was measured using six pressure–normal displacement sensors located on discontinuities and two surface tiltmeters. A dual hydraulic behavior was characterized for low-permeability bedding planes well connected to high-permeability faults. Displacement responses show high-variability, nonlinear changes, sometimes with high-frequency oscillations, and a large scattering of magnitudes. Initial normal stiffnesses and effective normal stresses along fault planes were estimated in the field by interpreting pressure–normal displacement relations with a nonlinear function between effective normal stress and normal displacement. Two-dimensional discontinuum modeling with transient fluid flow was performed to fit measurements during hydraulic loading tests. Results show that the hydromechanical behavior of the reservoir is restored if a high stiffness contrast is allocated between low- and high-permeability discontinuities. Thus, a dual-permeability network of discontinuities will likely also be a contrasting stiffness network, in which the deformation of major flow-conducting discontinuities is significantly influenced by the stiffness of the surrounding less-permeable discontinuities.

Keywords: Hydromechanical coupling; Fractured rocks; Mechanical; Permeability; In situ measurements

1. Introduction

In fractured rock with a low-permeability porous matrix, the main hydromechanical processes occur in the fracture network system. Coupled hydromechanical processes in such fractured rock are particularly difficult to characterize, mainly because of the lack of knowledge related to the discontinuity network geometry, and the great variability of hydromechanical properties in both intact rock matrix and fractures. Many previous works have studied the hydromechanical behavior of fractured rock through laboratory experiments on a single deformable natural fracture [1–12], and some constitutive models including hydromechanical interactions have been proposed [4,7,13–19]. However, because of scale effects, laboratory data can hardly be used for deriving the in situ hydromechanical properties of a fractured rock mass [20]. In situ field measurements appear to be essential determining the hydromechanical features of fractured rock [20–24]. Commonly, these in situ measurements are based on hydraulic-well-testing methods [21,25] on single deformable discontinuities. Coupled with a back-calculation numerical analysis, these hydraulic tests can provide useful estimations of

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hydromechanical properties, but they do not allow a complete and accurate description of hydromechanical effects. To improve accuracy in estimating the hydromechanical properties of discontinuities, Rutqvist et al. [22] recommend combining hydraulic tests and mechanical displacement measurements. However, in situ tests on discontinuities that measure both hydraulic and mechanical responses are rare [3,24,26–29], and very few simultaneous in situ hydromechanical measurements of a discontinuous network have been carried out [29].

To improve our knowledge of hydromechanical couplings in shallow fractured reservoir rock, a medium-scale field experiment consisting of a hydraulic loading and unloading was performed in a water reservoir, to obtain values for some experimental parameters. Measured hydromechanical effects were analyzed through 2D coupled hydromechanical discontinuum modeling, using the distinct element code UDEC.

This paper first presents a detailed description of the experimental site. Second, results are presented of simultaneous hydraulic and mechanical measurements obtained during hydraulic well tests on single discontinuities, and from hydraulic loading and unloading of the rock mass. Then, a first attempt to analyze the experimental data was carried out, using an analytical solution based on the nonlinear Cundall and Hart joint model [15]. Thereafter, hydromechanical modeling is performed to fit experimental results, considering a relation between the changes in hydraulic aperture, normal stress, hydraulic pressure, and normal stiffness of the discontinuities. Finally, results are discussed both at the single discontinuity scale and at the entire reservoir scale.

2. Experimental set up and hydrogeological context

2.1. Hydrogeological context

The Coaraze Laboratory Site is located in the French Southern Alps (Fig. 1). This site corresponds to a natural reservoir (30×30 m) made up of a 15 m thick pile of fractured limestone limited at the top and bottom by an impervious glauconious marl layer (Fig. 1). The fractured calcareous rock mass is drained by a spring (average annual yield of $12\,\mathrm{l\,s^{-1}}$) that appears directly on a vertical impervious fault contact between permeable limestone and impervious glauconious marls. This fault serves as a natural dam for the water stored in the reservoir. The spring is artificially closed with a water-gate; the piezometric level can be controlled in the reservoir by opening or closing the gate. Water from a fault, located 30 m upstream from the water-gate, continuously flows into the reservoir. The topographic surface was waterproofed with concrete to a 10 m height, to avoid water leakage from the discontinuities when water pressure increases. When the water-gate is closed, no more discharge occurs at the spring, and the pressure increases and stabilizes up to 10 m above the water-gate. When pressure stabilizes, two temporary springs (T1 and T2) overflow at the reservoir boundaries (Fig. 1). When the water-gate is opened, water stored in the reservoir flows out. The hydraulic boundaries of the reservoir are thus fully known and can be summarized as follows:

- Four impervious boundaries corresponding to the top and bottom geologic layers, the downstream fault zone, and the topographic surface covered with concrete
- One permeable boundary corresponding to the upstream fault. During the experiments, small changes in pressure head along this fault (less than 5×10^3 Pa) suggest that the fault can be assumed to be a constant-pressure-head boundary.

2.2. Discontinuity network geometry

Carbonate rocks at the Coaraze site present a regular stratification inherited from sedimentary processes, with two sets of orthogonal near-vertical brittle faults generated by a polyphased tectonic evolution during the Alpine orogeneses. From surface and boring scan-line data, the network can be characterized by 26 decametric discontinuities that extend over the boundaries of the reservoir and forming three sets (Figs. 2a, b and c):

- Three faults with a N50/N70 trend dipping 70°–90° NW (F_{11}, F_{12}, and F_{13}). These faults have a 2–3 m spacing.
- Eleven faults with a N120/N140 trend dipping 75°–90° NE (F_1 to F_{10} and F_{14}) and with a 2 m spacing.
- Twelve bedding planes with a N40 trend dipping 45° SE (S_1 to S_{12}) and with a 0.5–1 m spacing.

Metric and below-metric discontinuities are sparse. Minor bedding planes appear parallel to the major bedding planes. Near-vertical faults correspond to a small brittle zone (0.001–0.01 m thick) with reverse kinematic.

At the single discontinuity scale, amplitude distribution of surface asperity was studied statistically on 61 profiles measured with CLA rating method, after Tse and Curden, and Fénart [32,33]. The surface roughness of major fault planes is larger than that of bedding planes with average values of asperity heights (CLA) being $1.4 \pm 0.3 \times 10^{-3}$ and $0.5 \pm 0.2 \times 10^{-3}$ m.

2.3. Experimental set up

Simultaneous in situ measurements of fluid pressures, rock matrix, and discontinuity strains are automatically