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Field evaluation of the hydromechanical behavior of flat-lying fractures during slug tests

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Summary Slug tests were conducted at depths of 20–50 m in a fractured gneiss and axial displacements were measured along the borehole with a portable extensometer in order to evaluate the feasibility of combining pressure and displacement measurements to improve the characterization of fractured rock. Displacements on the order of microns occurred during slug tests when maximum head changes were on the order of meters. Maximum displacement lagged behind the maximum head, and the signals at a given location were repeatable to within reasonable tolerances. Tests were conducted at 12 packed-off depth intervals in a borehole and the signals from each interval were distinctly different from those at other depths. Parameter estimation techniques were used with a hydromechanical model to interpret the field results, and the findings show that there are three transmissive zones in the borehole and the compliance of the fractures generally decreases with depth. The inversion also highlights the importance of considering heterogeneities in the vicinity of the well bore when interpreting hydromechanical tests. Zones of leakage and blockage in the fractures were predicted in the vicinity of the well bore, and their presence had a significant effect on the displacement signals.

Introduction

Slug tests can provide important information during aquifer characterization, but they are by no means a panacea. The transient pressure signal from slug tests is weakly sensitive to storativity (Butler, 1998), so characterization of this parameter will always be uncertain when relying on pressure measurements from slug tests. Furthermore, interpreting features of fracture networks from a slug test can also be challenging because a variety of distributions of parameters can produce similar pressure signals (Karasaki et al., 1988; Shapiro and Hsieh, 1998).

Issues of non-uniqueness are common to aquifer testing methods, and a promising way to address this problem is to increase the amount and/or the type of data used in

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the inversion (McKenna and Poeter, 1995). A variety of geophysical data are being considered to improve the interpretation of aquifer tests (Moysey et al., 2006; Day-Lewis et al., 2006; Hubbard and Rubin, 2000; Hyndman and Gorelick, 1996; Kowalsky et al., 2005; Paillet, 1995), and displacements of the aquifer material are one possibility (Schweisinger and Murdoch, 2002). The idea is that the pressure change during a slug test produces displacements that depend on the distribution of aquifer properties, so measuring and interpreting both the transient displacements and the heads improve the ability to infer properties of the aquifer.

In a companion paper to this one (Svenson et al., 2007), we describe a theoretical analysis of a hydromechanical slug test in fractured rock that considers both pressures and displacements. That paper presents some simple methods for interpreting field data, and it shows how the forms of transient pressure and displacement signals are sensitive to properties of the fractures and the basic configuration of the fracture network.

The purpose of this paper is to present field results from a suite of hydromechanical well tests conducted near Clemson, South Carolina, and to apply the theoretical analyses described in the companion paper to the interpretation of the field results. This type of measurement is by no means new. Gale (1975) simultaneously measured displacements and fluid pressures during a well test. Gale's work was followed by field research typically intended for applications where coupling between hydrology and rock mechanics was important (Thompson and Kozak, 1991; Martin et al., 1990; Hesler et al., 1990; Cornet et al., 2003; Cappa, 2005; Cappa et al., 2005, 2006a). That body of work demonstrated the feasibility of hydromechanical well testing, but the use of this technique has been limited. Previous applications have required equipment that was tedious to mobilize and deploy, and the interpretation of the field data has either been limited to simple methods or has required the use of sophisticated commercial codes (Guglielmi et al., 2003; Cappa, 2005; Cappa et al., 2006b).

In an effort to make hydromechanical well tests more accessible, we developed a removable borehole extensometer that can be used to measure small displacements during well tests. The device is relatively simple, can be deployed between packers, and it can readily be moved to make measurements along the length of a borehole (Schweisinger et al., 2007; Murdoch et al., 2005). Simple methods for analyzing the resulting data are given in Svenson et al. (2007), and that paper also describes the use of a more detailed numerical model (Murdoch and Germanovich, 2006) for predicting and interpreting the response from slug tests.

Field setting

The field site for this study is in western South Carolina at an experimental and teaching well field near the Geology Museum on the southern end of the Clemson University campus (Fig. 1). The site is in the Inner Piedmont terrane of the Piedmont physiographic province, a band of northeast-trending igneous and metamorphic rocks bounded to the northwest by the Blue Ridge Mountains and to the southeast by the Atlantic Coastal Plain.

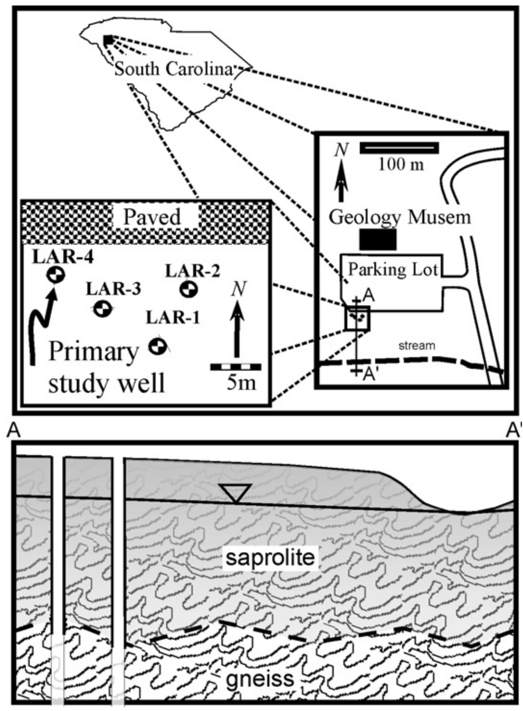

Figure 1 Location of field site near Clemson, South Carolina (top), and idealized cross-section of the field area (bottom).

The field site is underlain by biotite gneiss mantled by saprolite derived from the gneiss. The contact between the saprolite and the underlying gneiss occurs at roughly 20 m depth, so no fresh gneiss is exposed at the ground surface. The gneiss is medium-grained with variable strength of banding that strikes northeast and dips between 40° and 80° to the southeast. This unit is designated on the regional map by Nelson et al. (1998) as ''CZbs'', which is biotite–plagioclase–quartz gneiss. Petrographic analysis of a representative sample of core from the site indicates the rock consists of quartz (0.4 volume fraction), plagioclase (0.35), and biotite mica (0.11), with lesser amounts of hornblende (0.07), epidote (0.03), garnet (0.03), and chlorite (0.01). Bands rich in biotite are common, as are pods and veins of pegmatite. Tests elsewhere on similar rocks indicate the porosity of unweathered gneiss is roughly 0.01 and the hydraulic conductivity is on the order of 10^{-10} m/s (Randall et al., 1966).

Saprolite overlying the gneiss is a porous, relatively weak material composed of quartz, clay, mica, and iron oxides. Tests elsewhere on similar material give porosity values of 0.4–0.5, and hydraulic conductivity values of 10^{-6} to 10^{-8} m/s (Sowers and Richardson, 1982).

The gneiss is cut by several dozen fractures, which were identified in core and in video images of the walls of the borings. Some fractures appear to be roughly flat-lying and open 0.5 mm or more, whereas others dip more steeply and have a narrower aperture. Iron oxides are present on fracture surfaces in the core, and reddish brown selvages envelop some fractures exposed in the boreholes. Other fractures exposed in the boreholes lack signs of alteration.

The well field includes four wells penetrating the gneiss to depths of 60–120 m (Fig. 1). The wells are cased through the saprolite, and they are open holes 15 cm in diameter through the rock. Testing for this project was conducted