TRANSIENT CHANGES IN FRACTURE APERTURE DURING HYDRAULIC WELL TESTS IN FRACTURED GNEISS

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Abstract. The influence of deformable fractures on aquifer tests is studied by the development of a technique to measure and analyze in-situ changes in fracture aperture. A high-resolution borehole extensometer is used to measure the axial displacement of a borehole during packed-off hydraulic well tests in fractured rock. The extensometer yields repeatable displacements ranging from less than 0.5 microns/(meter of head) to 5 microns/meter depending on the testing location. The field measurements are interpreted using a theoretical analysis that couples elastic deformation and fluid flow in the fracture. Basic measurements from a single well can be interpreted to estimate transmissivity and storativity as functions of depth.

INTRODUCTION

Fractures are the primary conduits of groundwater in crystalline rock aquifers (Legrand, 1948). The flow occurs primarily within a discrete network and is strongly influenced by the location, shape, size and connectedness of the individual fractures. These geometrical characteristics provide useful insight into local flow patterns for tracking contaminant migration or siting wells, but they are challenging to obtain. One possibility is to infer these characteristics from changes in apertures of fractures.

The aperture of a fracture changes when subjected to a change in applied stress (Gale, 1977). Changes in stress occur by modifying either the external load or the internal fluid pressure. This physical interaction between the mechanical and hydraulic processes is known as “hydromechanical (HM) coupling” (Rutqvist, 2003).

We have developed a technique to measure and interpret aperture changes during hydraulic well tests that is intended to add insight into the HM coupling of in-situ fractured rock. It also provides additional information about the geometry and characteristics of individual fractures within a crystalline rock aquifer.

CONCEPTUAL BEHAVIOR

Fractures may either dilate or contract in response to head changes during hydraulic well tests. Opposing fracture surfaces are typically in contact with one another; however, surfaces that are irregular and unmated create void spaces for fluid flow within the fracture. The void spaces are held open by both fluid pressure within the fracture, and by adjacent asperities.

Increasing fluid pressure in the voids causes the fracture to dilate. As pressure increases, the fluid supports more of the confining stress on the fracture, and the effective stress on the asperities diminishes. Significant increases in pressure during injection may cause the fracture walls to separate completely and no longer be supported by asperities. Conversely, decreasing the fluid pressure compresses the fracture as the asperities deform under increasing effective stress.

It is our hypothesis that analyzing the deformation of fractures will improve the interpretation of hydraulic well tests in fractured rock aquifers. In addition, information unavailable from conventional hydraulic well tests can be extracted by experimentally measuring the deformations that occur in-situ and analyzing the results.

THEORETICAL ANALYSIS

The theoretical model used for this work simulates the deformation of a single, horizontal fracture subjected to a change in fluid pressure. The analysis assumes an idealized, circular fracture, located in a porous, linearly elastic matrix under far-field compressive stress with a vertical well intersecting the center of the fracture. Conservation of mass and momentum govern 1-D radial fluid flow within the fracture and 2-D flow in the matrix. The aperture of the fracture is calculated by coupling the elastic displacement from an arbitrary radial pressure distribution with an empirical relationship for asperity deformation.

Pumping tests and slug tests are simulated in the model to induce a fluid pressure change in the fracture. Values representative of typical fracture dimensions and mechanical properties were used to obtain illustrative displacement and head curves.

Model Results

The model predicts that a fracture dilates in response to increases in head. During slug tests, for example, the change in fracture aperture, or displacement, is roughly proportional to the change in head (Figure 1a). Model results indicate peak displacements of a few microns can result from head changes of meters. The peak displacement of the fracture lags behind the peak head.

Simple estimates of transmissivity, T, can be derived from type curves of slug tests data to give

$$T \approx \frac{d_c^2}{t_{0.37}}$$

where d_c is the diameter of the well casing, and $t_{0.37}$ is the time when the head returns to within 37% of the initial value (Figure 1a).

Plotting displacement as a function of head shows hysteresis in the theoretical response of the fracture (Figure 1b); the displacement at a particular drawdown is less during increasing head, than it is during diminishing head. The geometry of the fracture influences the magnitude of the displacements as well as the hysteresis and general shape of the curve.

The fracture compliance, χ_f, used in the model is proportional to the slope of the displacement-head curve at late time (Figure 1b). The late-time data is used in compliance calculations because the inverse slope at this time is similar to the normal fracture stiffness used in the model.

The fracture compliance can be used to estimate

$$S^f = \rho_f g \chi_f$$

fracture storativity, $\boldsymbol{S^f}$, where $\boldsymbol{\rho_f}$ is the density of the fluid in the fracture and $\boldsymbol{g}$ is the gravitational acceleration (Rutqvist, 1998), assuming that all the water released from storage is due to the change in volume of the fracture.

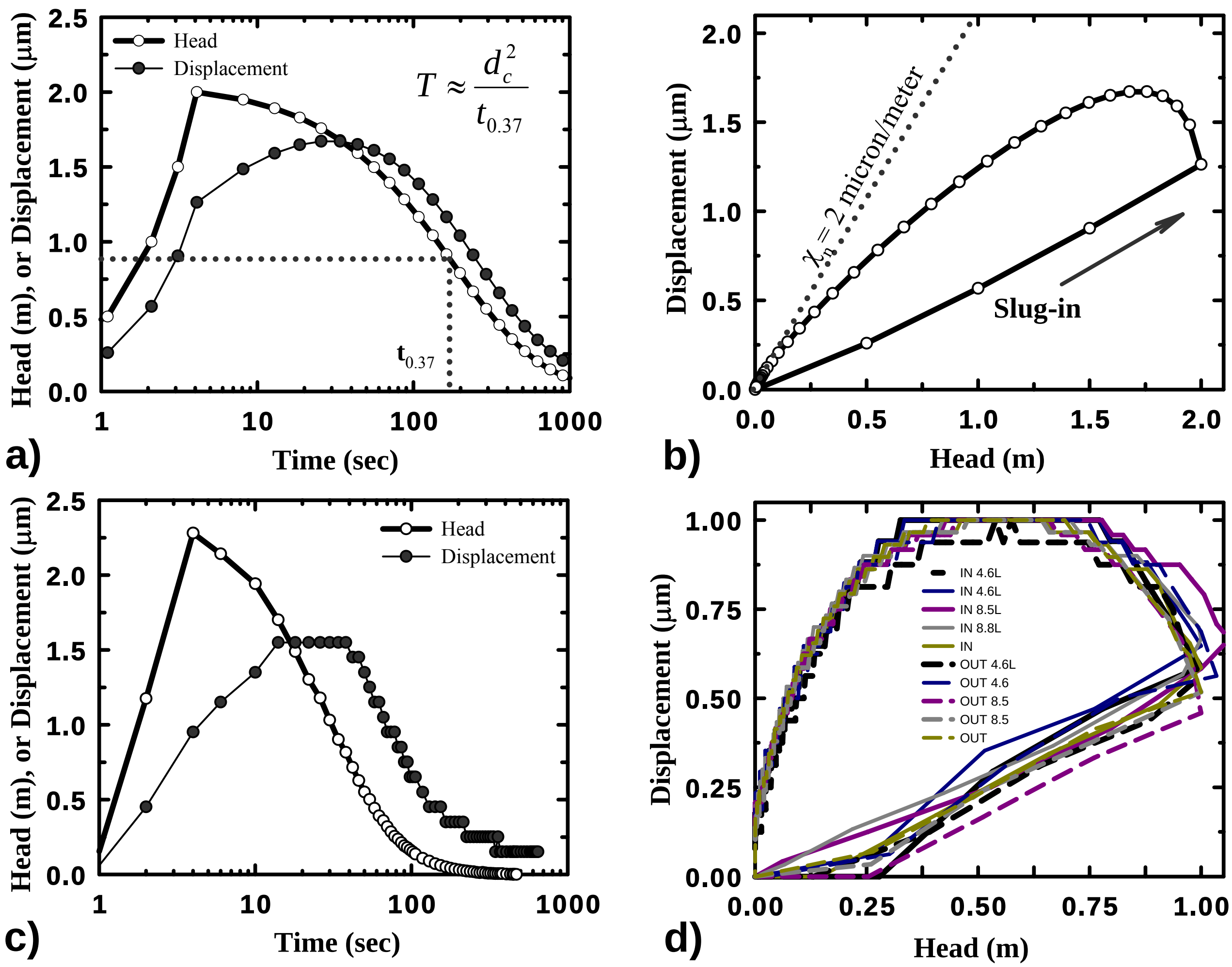

Figure 1. a) Theoretical transient data for slug test b) Theoretical displacement as a function of head c) Field data from slug test d) Normalized field data from 10 slug tests

FIELD TESTS

Fracture deformation is monitored during pumping tests and slug tests in intervals isolated by straddle packers. Axial displacement of the wellbore is measured with a portable, high-resolution borehole extensometer (Figure 2). The packers and extensometer can be readily deployed at one interval and then moved to another interval along the borehole to provide detailed spatial resolution.

Extensometer Functionality

The extensometer is mounted between the packers and lowered to depth in a wellbore. Pneumatic cylinders extend two carbide anchor points, two meters apart, into the face of the borehole. The extensometer is disengaged from the frame, so it only responds to rock displacement. A registration system sets the extensometer within the range of the measurement device prior to testing, then it is released so the anchor points are independent of one another during testing. A high-resolution Linear Variable Differential Transformer (LVDT) measures the displacement of the anchor points. Invar is used in critical components of the extensometer to minimize the influence of temperature variation. Current field data suggests that the device is capable of detecting displacements on the order of 0.1 microns at depths of 100 meters.

Measurement Results

A suite of packed-off air-slug tests was conducted at Clemson University in wellbores intersecting fractured gneiss. Deformations were simultaneously measured using the borehole extensometer.

A typical test at 25 meters deep shows approximately 2 microns of displacement for a 2 meter increase in head (Figure 1c). The peak displacement lags the peak head by approximately 30 seconds. As the head equilibrates, the displacement curve returns to its approximate starting value. The transmissivity of the straddled interval is estimated as 0.73 cm^2/s.

Ten tests were conducted at 25 meters deep using three different slug volumes ranging from 4L to 9L to evaluate repeatability. The normalized data shows the peak magnitude and trend of the displacements are repeatable within 5% (Figure 1d). The results also indicate the fracture compliance is independent of slug volume. A Storativity of 10^{-5} is estimated by assuming the compressibility of water and the unfractured rock are negligible compared to the compressibility of the fractures.

Dozens of similar tests were performed in the same well at varying depths. The displacement-drawdown curves at each depth are different, which suggests the technique may be used to extract

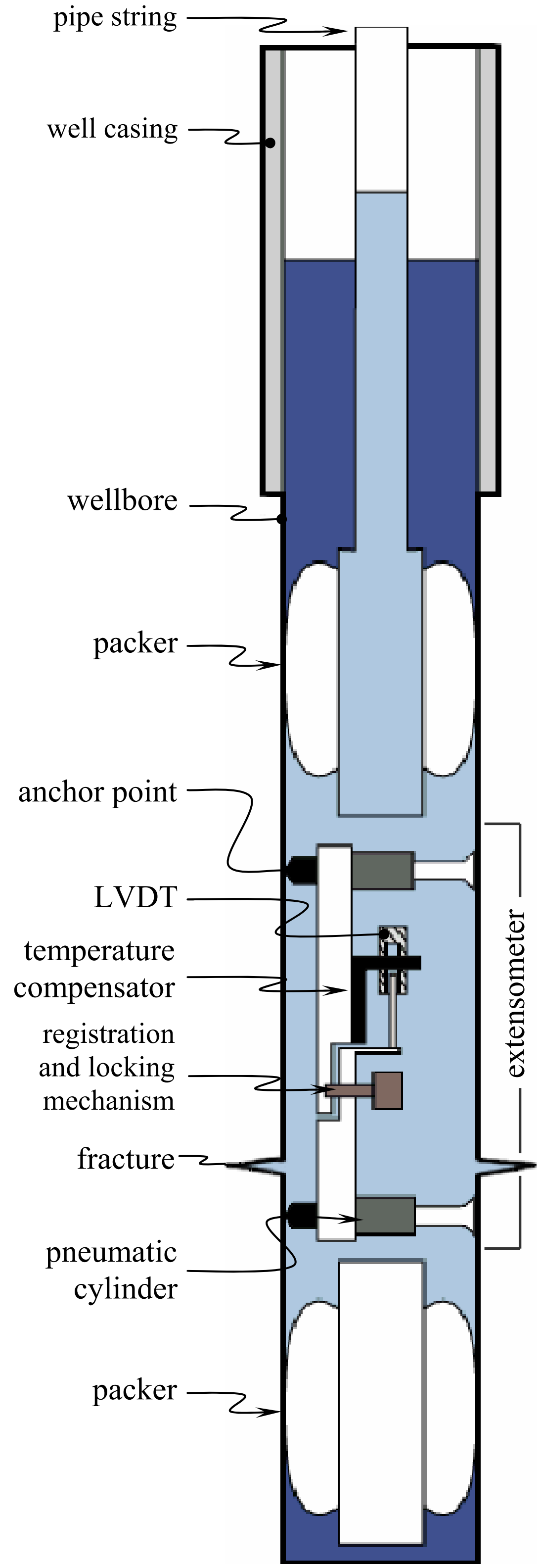

Figure 2. Borehole extensometer straddling a fracture isolated by packers. LVDT measures relative displacement of anchor points as fracture aperture changes.

information about the distribution of hydromechanical properties within the aquifer. The distribution of T and S as a function of depth can be estimated from tests at multiple depths along the wellbore.

The compliance of each test interval varies with depth but typically ranges from less than 0.5 micron/meter to 5 micron/(meter of drawdown). Current analyses suggest that details of the displacement and drawdown records are affected by heterogeneities in the formation, suggesting that the technique can improve the interpretation of hydraulic well tests compared to current methods. The presence of heterogeneities can be determined by inverting the analysis with transient field data.

CONCLUSIONS

It is possible to measure transient, micron-scale changes in aperture during pumping and slug tests. Measurements are repeatable to within 5% at one location, although temporal variations occur at other depths. The measured displacements can be interpreted to obtain estimates of transmissivity and storativity from a single interval, and repeated measurements provide spatial distributions of these parameters along the borehole. Preliminary analyses suggest that the tests can also provide information about the transmissivity distribution away from the borehole.

ACKNOWLDEGEMENTS

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