Measuring and Analyzing Transient Changes in Fracture Aperture During Hydraulic Well Tests: Preliminary Results

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Fractures either dilate or contract in response to head changes during hydraulic well tests. Dropping the hydraulic head will increase effective stress, compressing asperities on fracture surfaces and causing aperture to diminish. Increasing hydraulic heads during an injection test, or during the recovery following pumping, will relieve the effective stress on asperities and dilate fracture aperture. Significant increases in head during injection into a well may cause the fracture walls to separate completely and no longer be supported by asperities. Continued injection may elevate the stress intensity enough to cause propagation and the creation of new fracture surface by hydraulic fracturing. Termination of injection will cause the fracture to close once again and rest on asperities (Rutqvist, 1995; NRC, 1996).

The qualitative behavior of fractures during a well test outlined above is widely recognized, but published field data describing transient changes in aperture is limited (e.g. Gale, 1975; Thompson and Kozak, 1991; Martin and others, 1990; Hesler and others, 1990). We are measuring the changes in aperture in an effort to increase the information obtained from hydraulic well tests. The measurements are made with a borehole extensometer that can be temporarily anchored to the walls of an open borehole. Current investigations have focused on isolated, flat-lying fractures, so axial displacements are assumed to equal changes in aperture. Field data are interpreted using a model that couples fluid flow and deformation of a flat-lying, circular fracture.

Equipment

The borehole extensometer was designed to be a robust tool that can be used routinely during short-term tests, but that will also remain stable during longer term tests. Related devices are described by Thompson and Kozak, 1991; Hesler and others, 1990; and Martin and others, 1990. Remotely actuated, mechanical anchors that remain passively locked in place without requiring power were developed to promote long-term stability. The anchors can be deactivated to recover, or move the device. An LVDT is used to measure axial displacement between pairs of anchors, and those measurements are recorded along with pressure and temperature during a well test. The LVDT can resolve displacements of approximately 0.1 micron, but accuracy appears to be several times greater than the resolution, on the order of 0.3 to 0.5 micron using the current device. Spacing between the anchors is currently 1.1 m.

Limiting sensitivity of the device to changes in temperature has been an important aspect of ensuring accuracy during transient tests. Rods connecting the anchors are made of invar, a material with an exceptionally low coefficient of thermal expansion. The LVDT itself exhibits small displacements during temperature changes, and this effect was considered in the design. The device is configured so the thermal expansion of the LVDT is equal in magnitude and opposite in sign to the thermal expansion of the invar connector rods and anchors. The effective thermal expansion of the device is calculated to be less than 0.2 micron per ^{o}C.

Field tests

Preliminary tests have made use of boreholes cutting fractures in biotite gneiss in western South Carolina. The wells are cased through saprolite to depths of approximately 21 m, and they are open to total depths of 60 m to 120 m. Fractures were identified on the walls of boreholes using a video camera, and those results were supplemented with caliper logs and data from slug tests using overlapping straddle packers. The packer tests indicate that three intervals a few meters thick at depths of 26 m, 35 m, and 50 m are several orders of magnitude more transmissive than elsewhere in the borehole. The video survey and correlation among neighboring wells indicates the presence of three, roughly flat-lying fractures or fracture zones at those depths. The borehole extensometer was deployed across intervals where significant fractures are evident, and across intervals that appear to be free of fractures. Constant-rate pumping tests followed by recovery were conducted and displacements, which are assumed to correspond to changes in aperture, were monitored along with changes in pressure and temperature. The initial suite of tests was conducted by pumping from open boreholes while measuring displacements at selected depths.

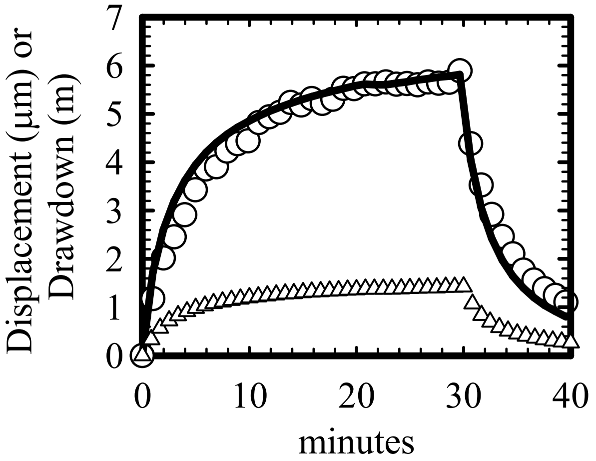

Figure 1. Observed displacement (circle) and drawdown (triangle) during constant rate pumping test. Heavy line is the displacement predicted using parameters determined by IFFCO.

The results show that displacements accompany changes in hydraulic head during and following pumping tests. Displacements of up to 10 microns were observed accompanying drawdowns of up to several meters, and in general the displacement as a function of time resembles drawdown (Fig. 1). The ratio of displacement to drawdown is assumed to be equivalent to an effective normal compliance of the fracture (inverse of normal stiffness). The current results show that the normal compliance ranges from 5 micron/(m of drawdown) to less than 0.5 micron/m. Similar compliance values were measured in the field by Martin and others (1990).

Normal compliance can be used to estimate an effective uniaxial specific storage, suggesting that this approach could measure storativity using data from a single well. Dividing the compliance by the spacing between the anchors and converting to pressure gives the specific storage (assuming the displacement causes an equivalent change in fluid storage volume per unit area). The current results give values for specific storage ranging from 0.5 x 10^{-4} $MPa^{-1}$to 5 x 10^{-4} MPa^{-1}. These results are consistent with Schwartz and Zhang (2003), who give a range of 3 x 10^{-4} MPa^{-1} to 7 x 10^{-4} MPa^{-1} for the specific storage of fractured rock, and they claim that the specific storage of intact rock is less than 3 x 10^{-4} MPa^{-1}. It is possible to use the borehole extensometer to determine specific storage as a function of depth. Integrating these values along the length of the bore could provide a means for estimating aquifer storativity using data from a pumping well alone.

Model

Transient changes of aperture and head during well tests are being analyzed using a model that considers fluid flow along a flat-lying, circular deformable fracture embedded in a porous material. The fracture is assumed to be initially supported by asperities, but the fracture walls can separate and the fracture can even propagate if the driving pressure becomes high enough. The model treats the fracture as a circular cavity embedded in an elastic medium and loaded by an arbitrary, axisymmetric pressure. This approach is attractive because the displacements can be determined quickly by superimposing analytical solutions. The model uses a new analytical solution to the displacements caused by a uniform pressure applied over a narrow ring for this purpose. The effect of propping by asperities is included by assuming the fracture is partly supported by an effective stress, in addition to the fluid pressure. The effective stress distribution is assumed to occur so that the aperture determined by the elastic cavity solution is equal to the aperture determined using a hyperbolic model of displacements similar to Goodman (1976) and Bandis et al. (1983). Fluid flow through the fracture, and 2D partially saturated flow in the matrix are fully coupled to the displacements.

The model has been used with parameter estimation schemes with acceptable results. PEST and an implicit-filtering algorithm called IFFCO (Choi et. al., 2001) have been used to calibrate the model to displacement data obtained during constant-rate pumping tests. The parameter estimation techniques are capable of fitting data as in Figure 1 using 40 to 60 model runs (Fig. 1). This takes roughly an hour on a desktop computer using reasonable grids and time discretization. The results of this effort indicate that it is feasible to include transient displacement data in a parameter estimation analysis, just as transient drawdown data are used in conventional analyses of well tests.

The model also predicts that changes in fracture aperture could cause significant errors during well tests where pressure changes are relatively large. Changes in head of tens of meters could result in changes in fracture aperture of tens of microns or more, for example. This could markedly change the apparent transmissivity of a fracture and cause significant errors where tests are intended to determine transmissivity under ambient conditions. Including measurements of aperture change during a well test provides a mechanism for avoiding this potential problem.

Conclusions

Axial displacements of a borehole are roughly proportional to drawdown during transient wells tests and appear to be due to changes in fracture aperture. Observations in a borehole in biotite gneiss give normal compliance values that vary from 0.5 microns/(m of drawdown) to 5 microns/m. Larger values of compliance occur where flat-lying fractures cut the well and smaller values are in relatively unfractured intervals. Compliance values can be used to estimate specific storage, and specific storages obtained using this approach are typical of fractured rock. A theoretical analysis of a deformable fracture has been developed to simulate the well tests and predict aperture changes. The analyses can be inverted to predict in situ hydromechanical properties of fractures.

Both the theoretical and field results suggest that the aperture, and therefore the transmissivity, of a fractured aquifer will change with pressure. Well tests that make use of large changes in pressure (to induce flow in tight rocks, for example) may significantly change the transmissivity of the fractures they are seeking to measure. Measuring changes in aperture is one approach to addressing this potential problem.

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