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

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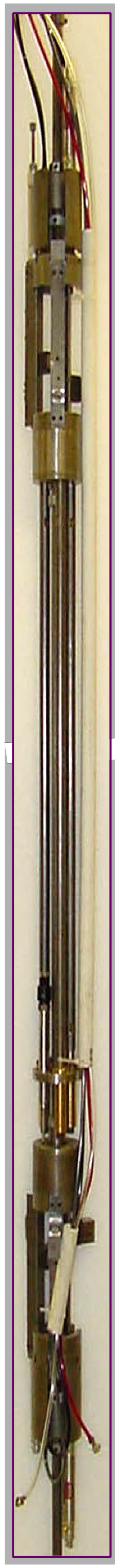


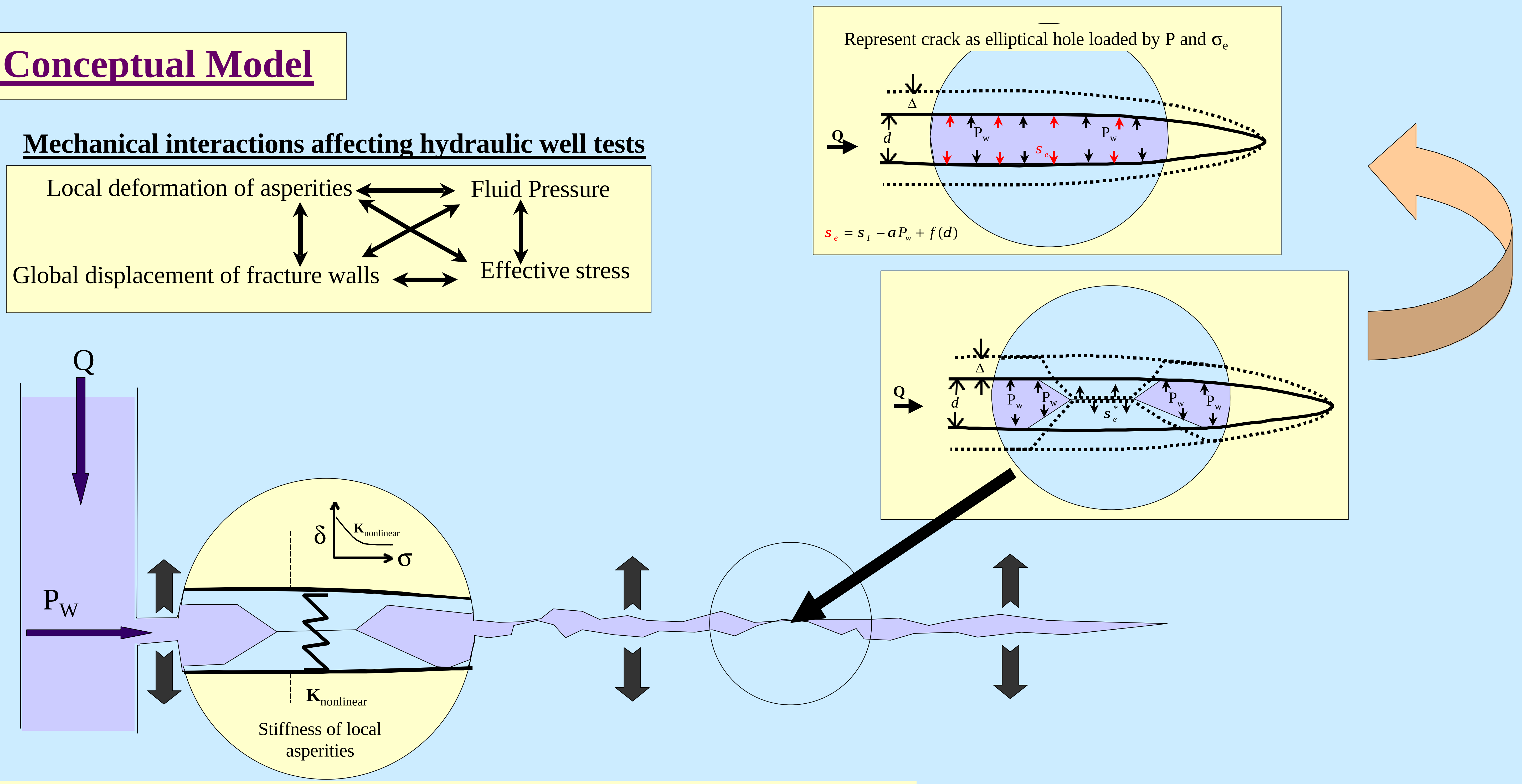
1. Abstract

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.

2. Conceptual Model

Mechanical interactions affecting hydraulic well tests



Local deformation of asperities

Fluid Pressure

Global displacement of fracture walls

Effective stress

Represent crack as elliptical hole loaded by P and σ_e

$s_e = s_T - aP_w + f(d)$

Stiffness of local asperities

Approach: Invert pressure and displacement records to estimate *fracture*: aperture, stiffness, asperity area (Biot alpha), interaction with other frx and matrix. Determine aquifer parameters: effective conductivity. specific storage.

3. Methods

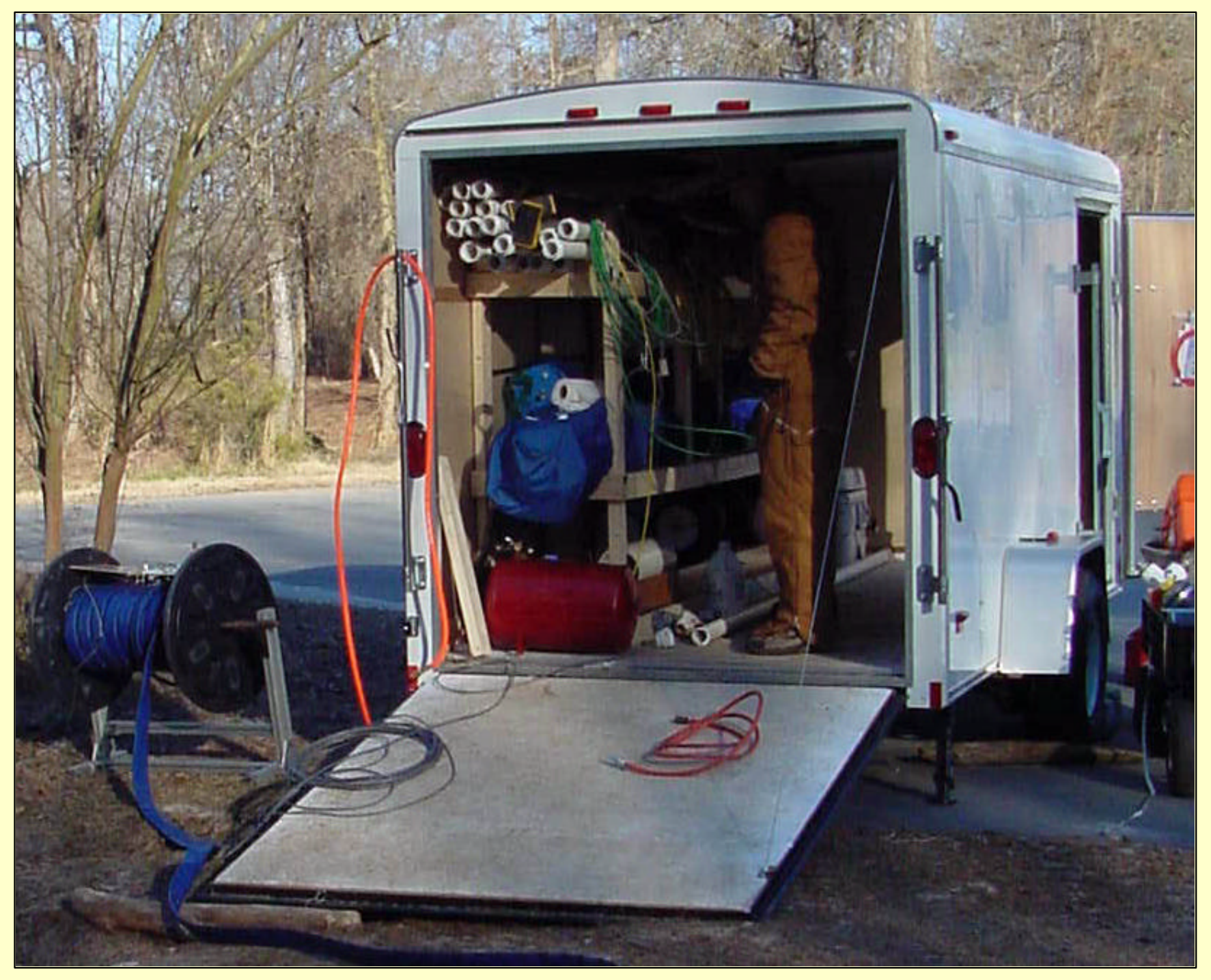
Two anchors are lowered to straddle a fractured zone. The anchors are locked in place until actively retracted. An LVDT records the change in distance between the two anchors in response to injection or withdrawal. We've performed two types of well tests: constant rate pumping tests and slug tests.

Pumping Test: Pump water out of packed interval of well, fractures close as asperities deform.

Slug Test: Inject air slug, fractures dilate in response to pressure change.

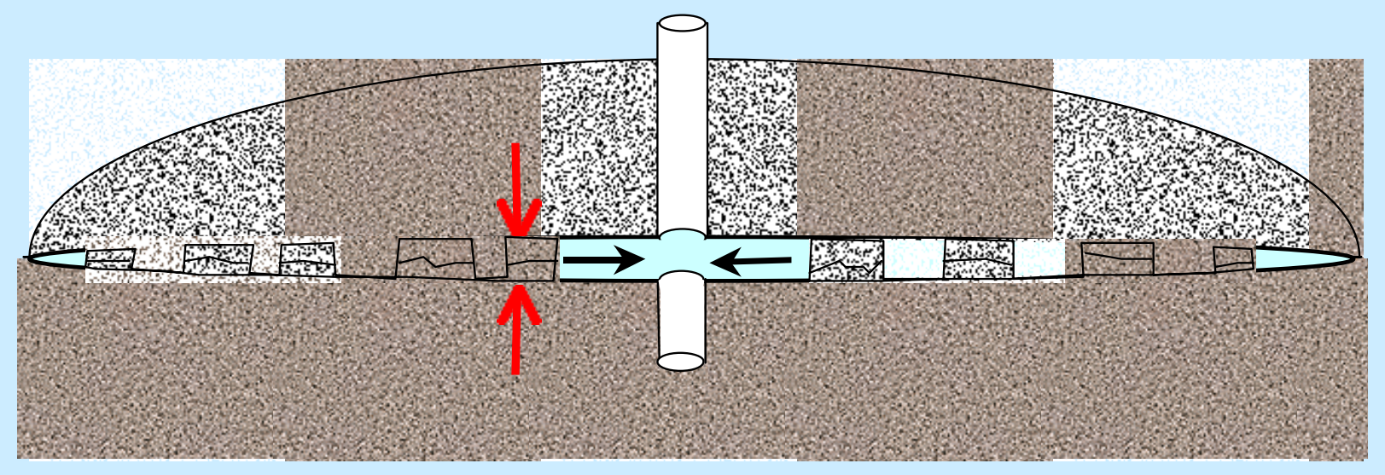
Above: Erik opens the valve on the well head to inject the air slug into the packed region.

Left: Displacement of a fractured zone is measured during hydraulic well tests using a removable borehole extensometer positioned between packers. The extensometer and upper packer are shown suspended over the well casing by a hand winch on the tripod. The lower portion of the extensometer is hidden by the well casing. The blue hose protects the control hoses and electrical conductors that communicate downhole with the instrument.



The mobile laboratory is set up on-site, and contains all the equipment necessary to conduct the well tests. The operator inside the mobile lab controls the operation of the packers, extensometer, and data acquisition system during a well test.

4. Theoretical Analysis



The analysis considers radial fluid flow in a circular, deformable fracture of finite radius. The flow problem is treated in 1-D radial coordinates, and it is coupled to a solution from elasticity theory that gives the aperture of a circular crack loaded by an arbitrary pressure.

Continuity

$$\frac{\partial(qdr)}{\partial r} + \frac{qdr}{r} + rq_L + \frac{\partial rd}{\partial t} = 0$$

The continuity equation is written for mass flow within a deformable fracture that can exchange flow with enveloping matrix (left). Continuity is also assumed to hold during multi-phase flow in the matrix. This provides a versatile and accurate assessment of leakoff.

Elastic Displacements

$$u_z = \frac{4c}{Ep}\int_r^1 \frac{m\,dm}{(m^2 - r^2)^{1/2}}\int_0^1 \frac{xp\,(xmc)\,dx}{(1 - x^2)^{1/2}}$$

Sneddon's integral (left) for the displacement of the walls of a circular crack loaded by a pressure with an arbitrary radial pressure distribution *p*(r) is solved to give a closed form expression for the displacement due to a load uniformly distributed over a short radial distance, which corresponds to the dimensions of the grid blocks used in the finite difference analysis.

Asperity Deformation

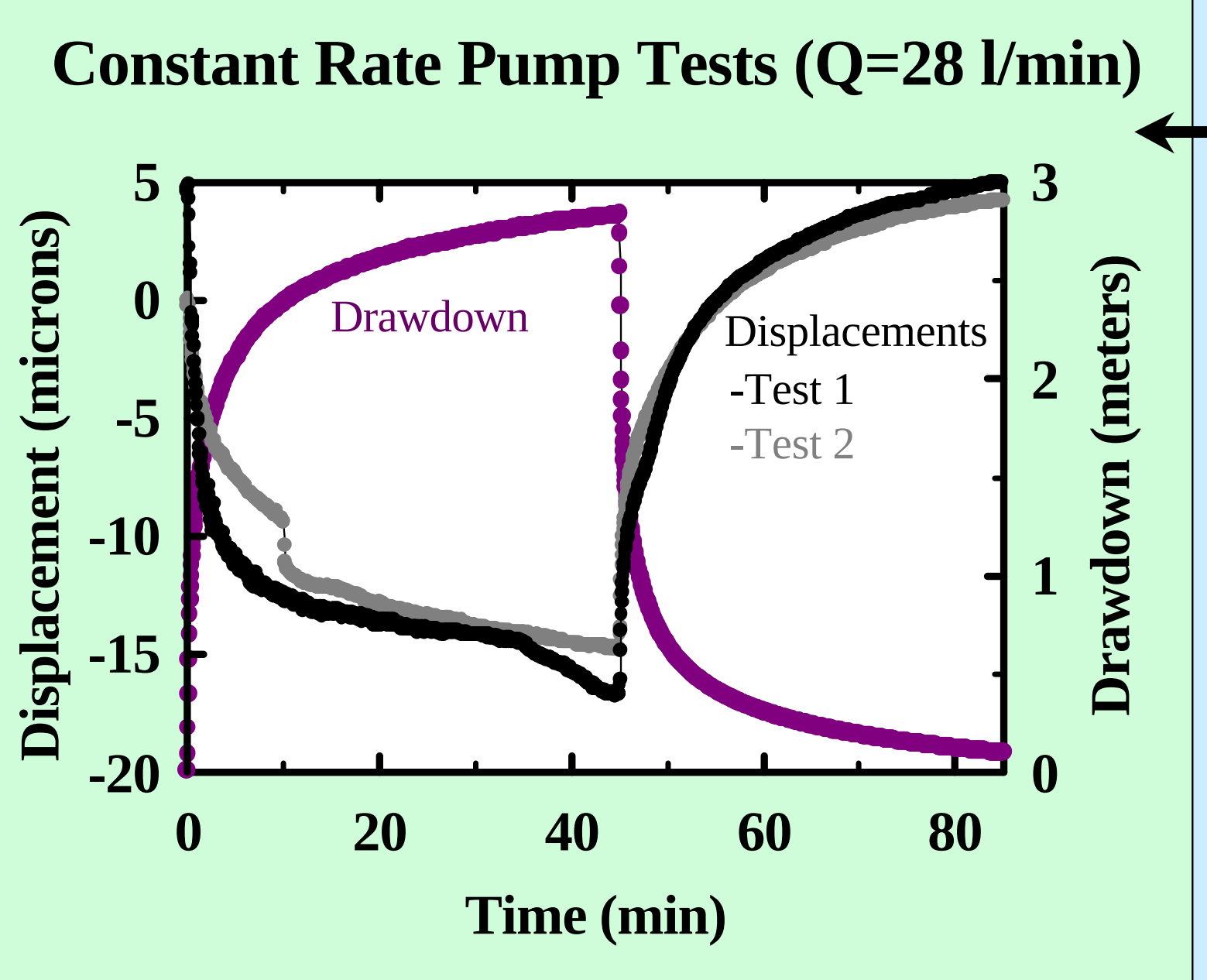
The fracture is assumed to be propped open on asperities that deform elastically due to small changes in effective stress, according to empirical relations described by Bandis et al. (1983). Effective stress is adjusted so that displacements due to asperity deformation equal elastic displacement of the crack walls.

Solution Method

The coupled problem is formulated using a continuity equation for each block along the fracture and for each grid block in the matrix. An expression for local deformation of asperities due to effective stress is set equal to global displacements calculated for the entire fracture. The system of non-linear equations is solved using Powell's method and marched through time to yield a transient solution for fluid pressure, effective stress, and displacement of the fracture walls. The closed form expression for the displacements makes this method remarkably fast.

5. Results

Field results from packed off extensometer well tests at the Clemson University hydrogeology well field.

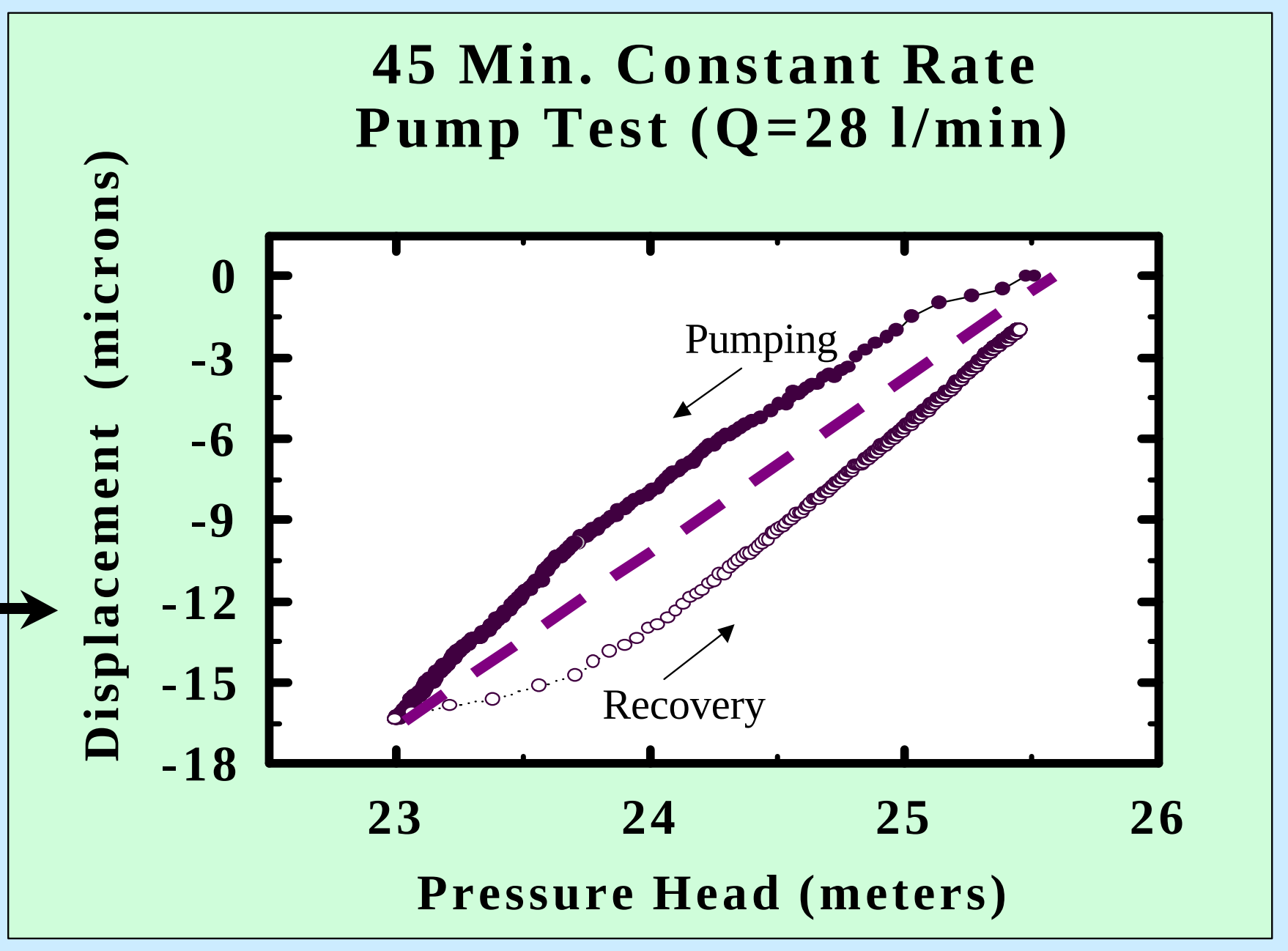

Constant Rate Pump Tests (Q=28 l/min)

Constant Rate Tests

Displacement and head measured over a 1.2-meter-wide zone during two constant rate withdrawal test. Drawdown was 2.9 meters and displacement was more than 15 microns.

45 Min. Constant Rate Test

We pumped from a fractured zone located 25.5 meters below the water table. The head in the zone decreased approximately 2.5 meters and resulted in a net compression of the zone of 17 microns. Displacements during opening differ from those during closure. Ave slope=Fracture compressibility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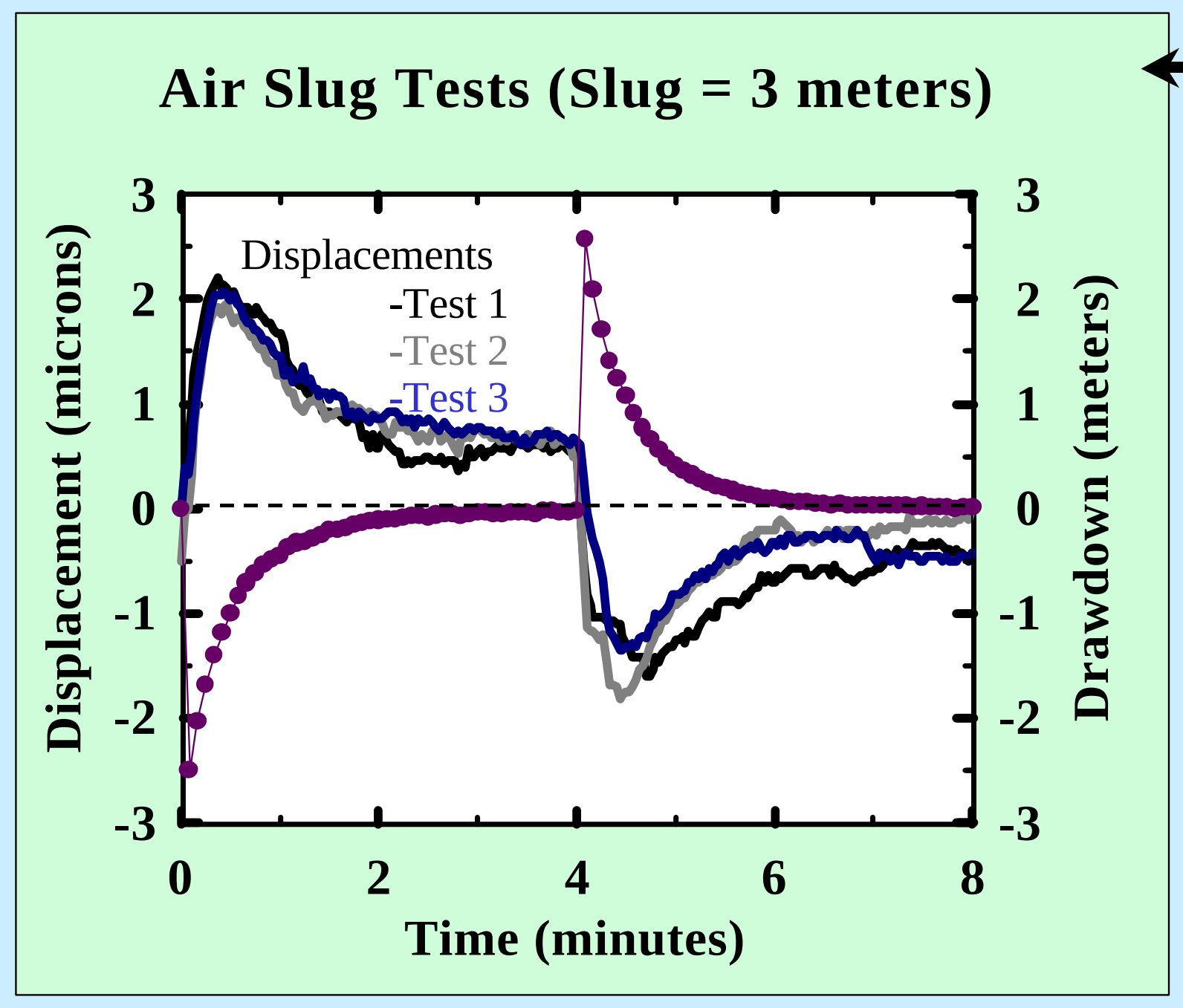
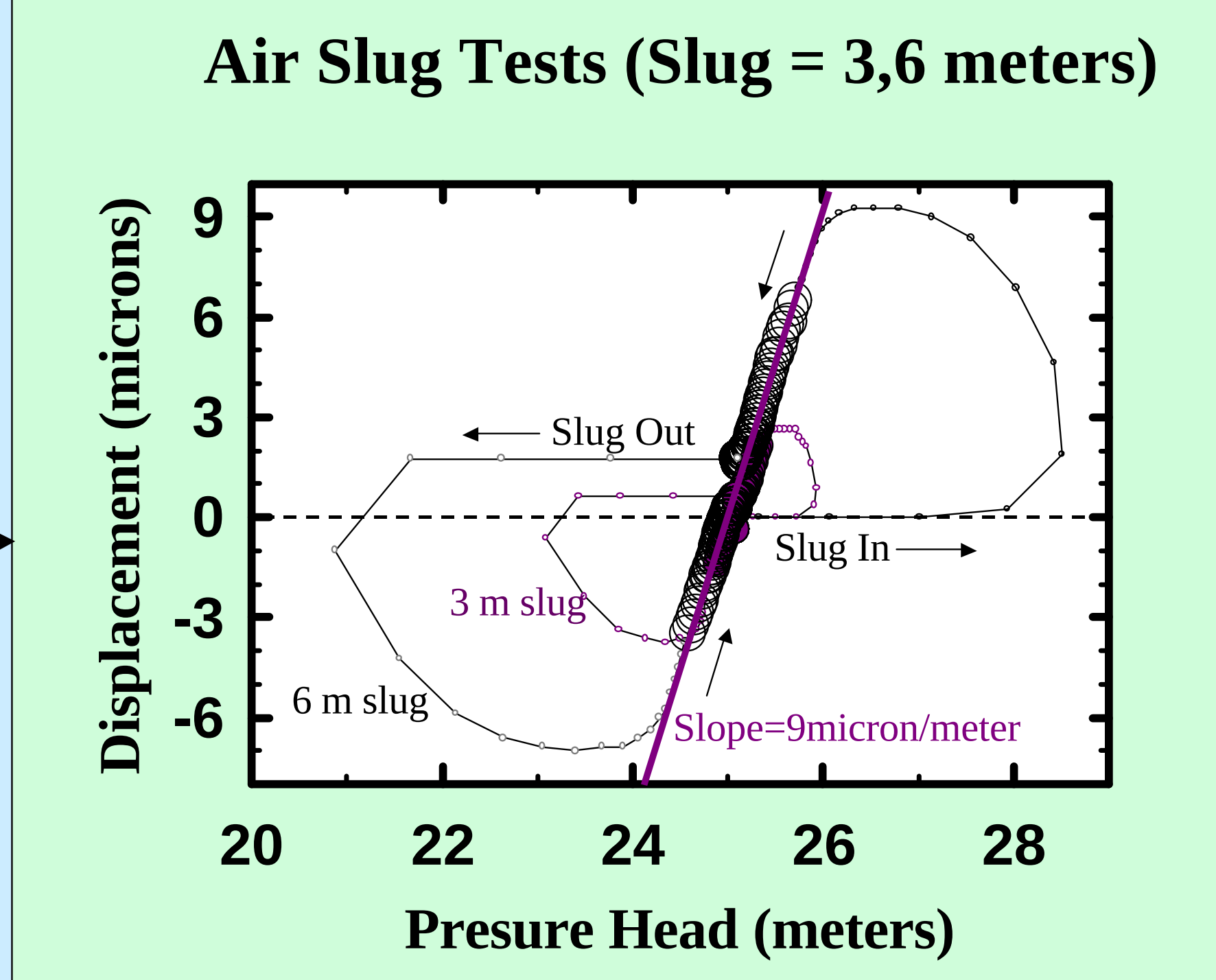

Air Slug Tests (Slug = 3 meters)

Air Slug Tests

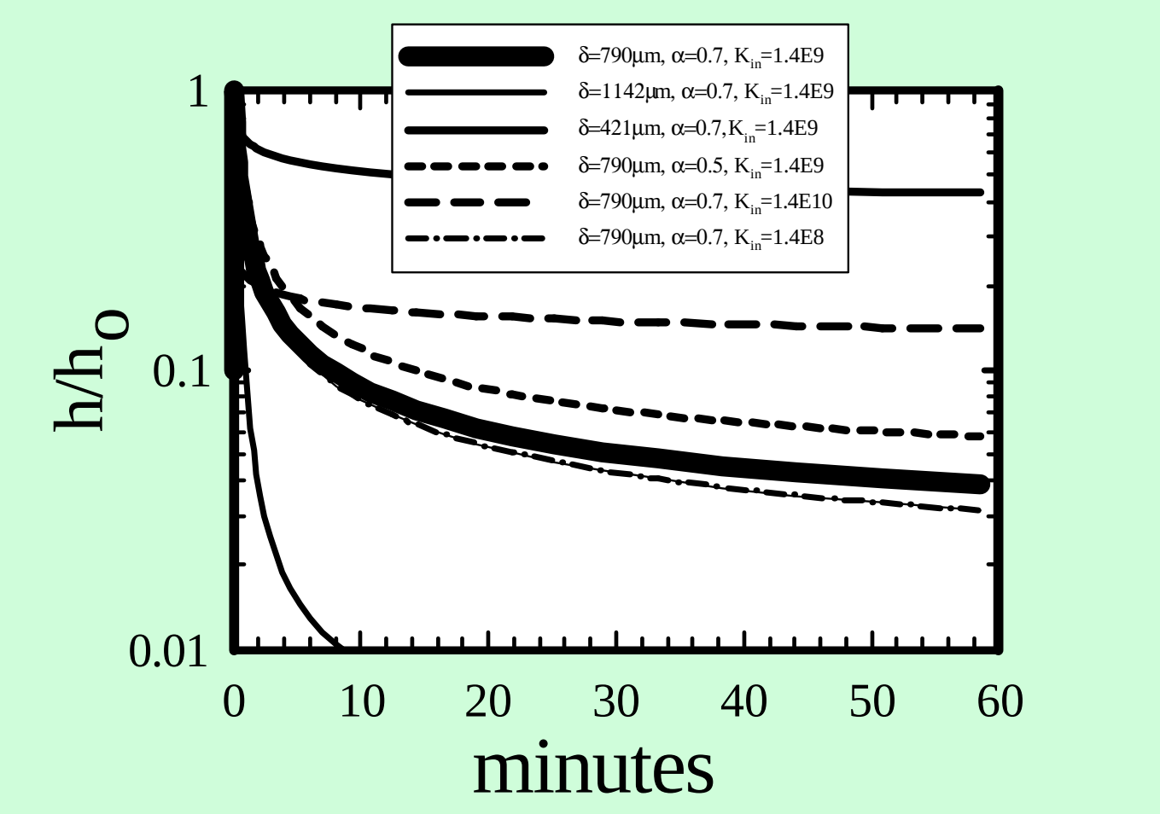
Three consecutive packed-off slug tests with a 3 meter air slug. The net displacement in each of the three tests was approximately 2 microns. The packed region returned to equilibrium within 4 minutes of slug injection.

Air Slug Tests (3,6 meter Slug)

Two slug tests in the same zone 25 meters below the water table: a 3 meter air slug test, and a 6 meter air slug test. The slope of the linear portion of the late time data from the slug in and slug out indicates fracture compressibility. Compressibility = 9e-6 m^{-1}.

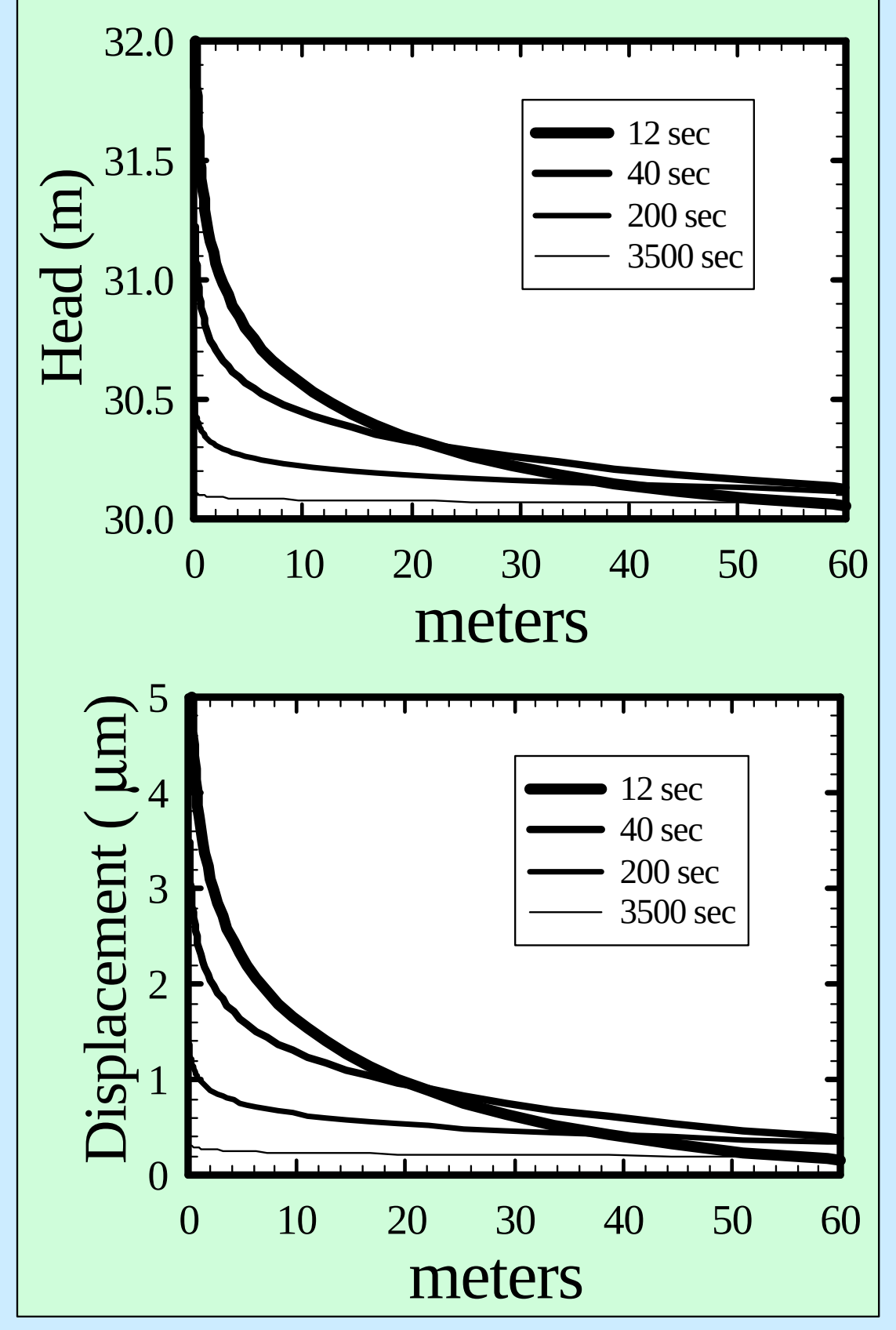

Air Slug Tests (Slug = 3,6 meters)

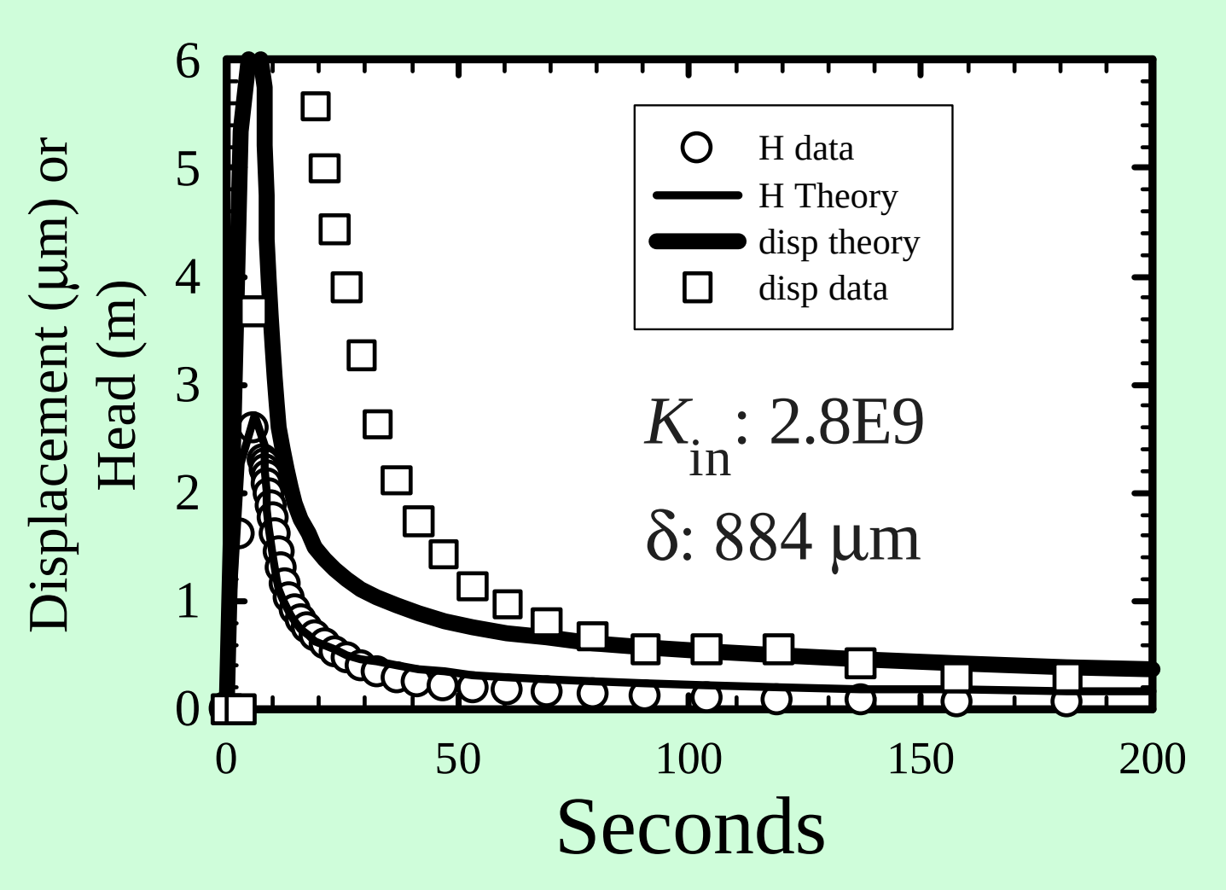
Results from theoretical analyses



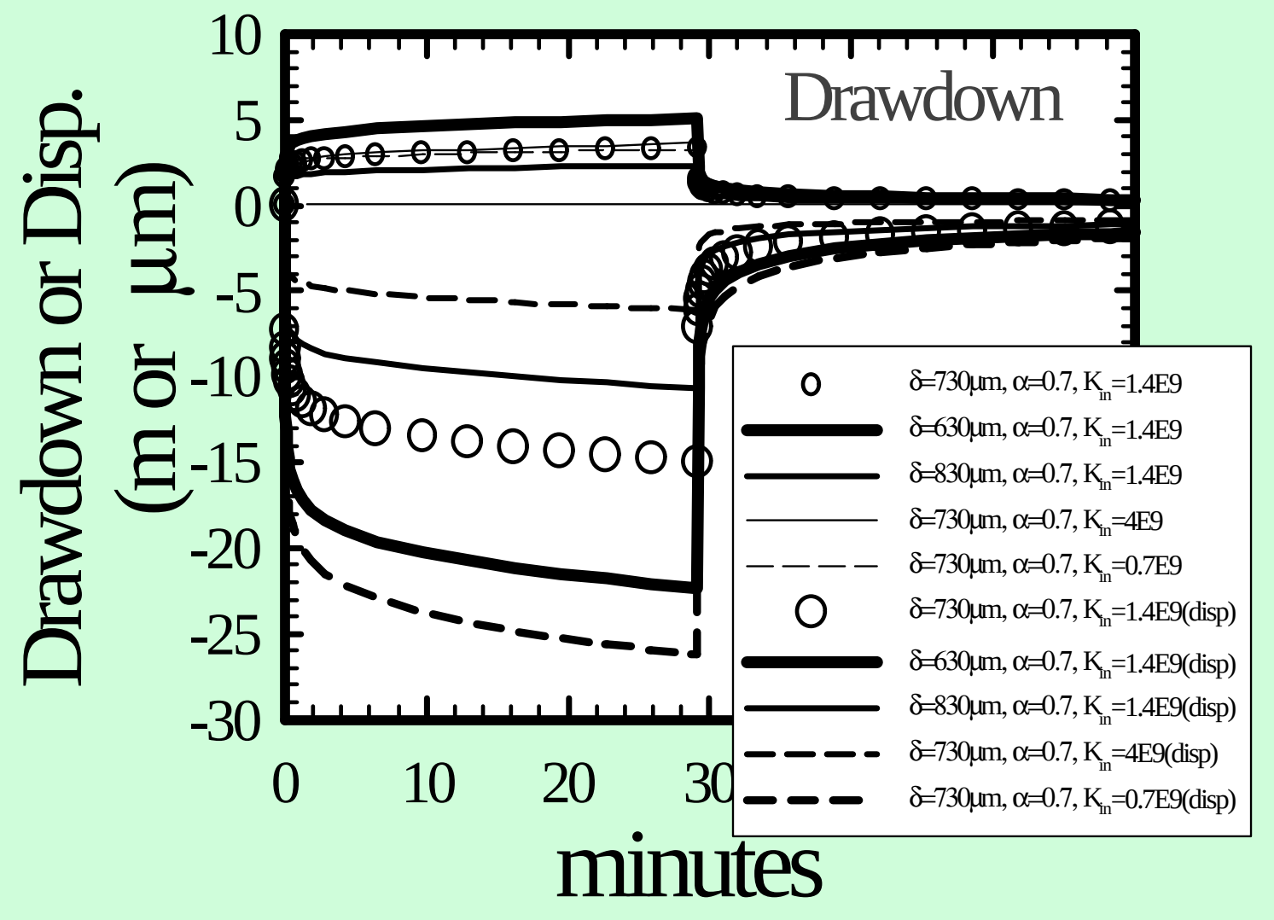
Sensitivity analysis of slug test (above). Type curve highly sensitive to aperture, but also sensitive to stiffness and relative area of asperities (Biot alpha)

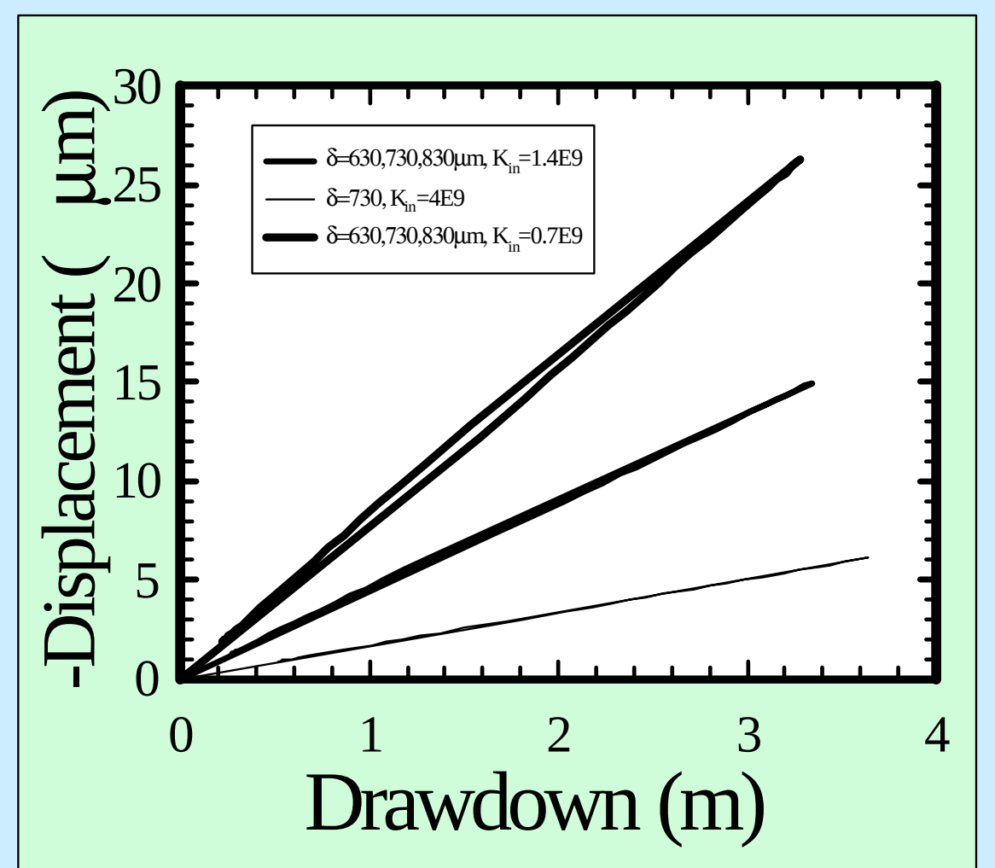
Profiles of pressure and displacement in fracture during slug test. (below) 790 µm



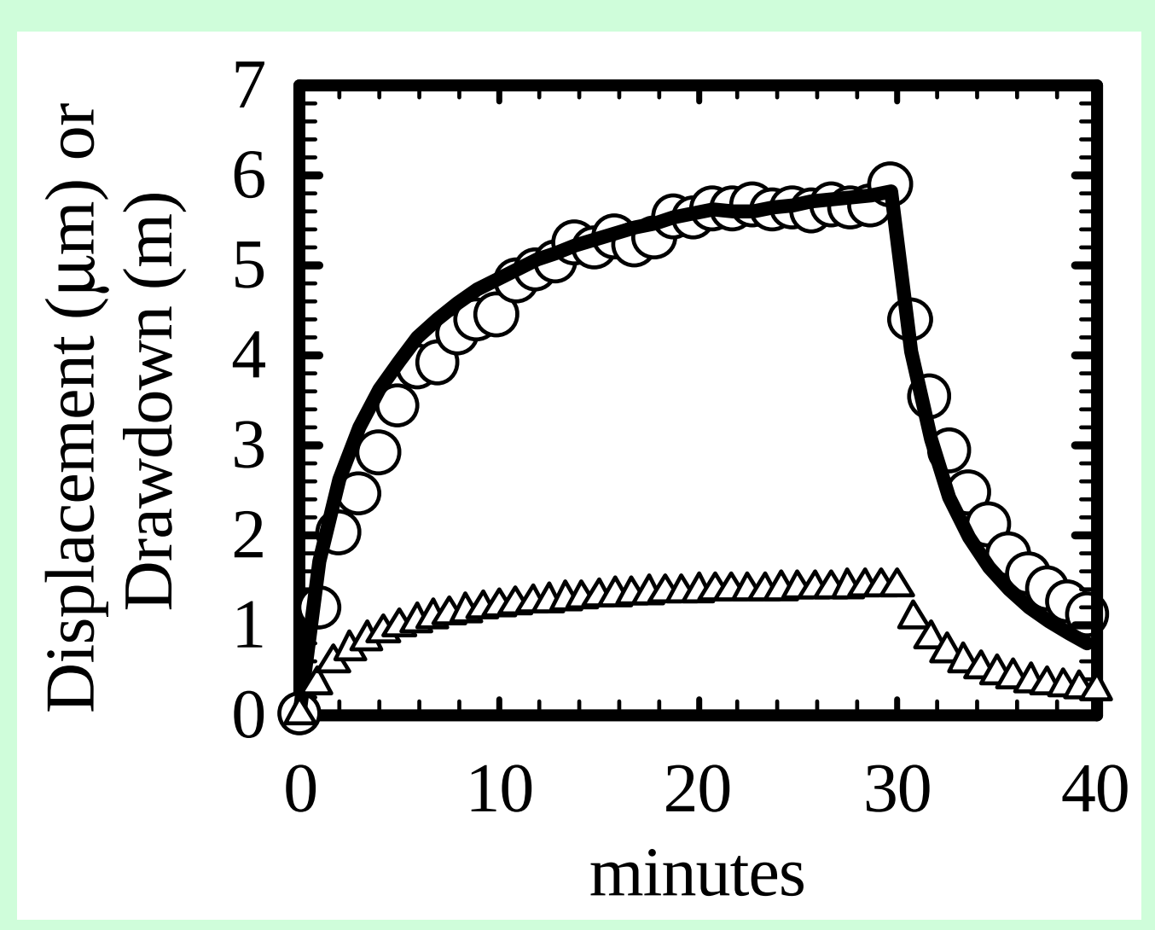


Parameter estimation. Theoretical analysis used with implicit filtering algorithm (IFFCO) to estimate aperture and stiffness from slug test data.

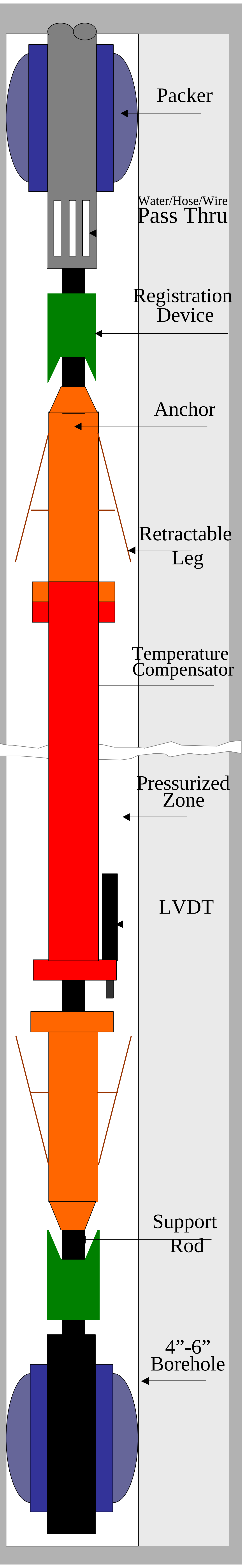




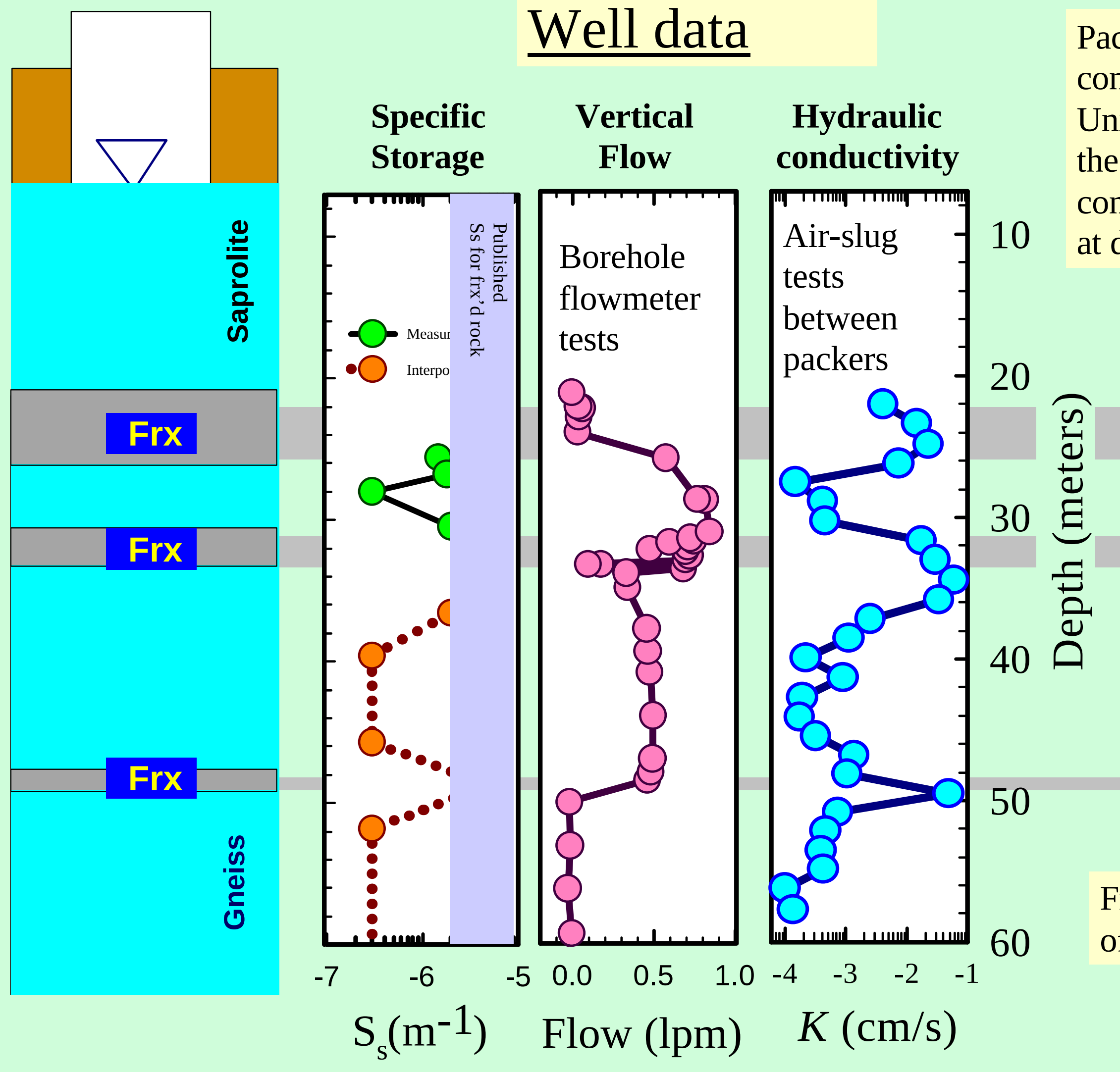
Sensitivity analysis of constant rate test. Drawdown sensitive to aperture, but not to stiffness. Displacement sensitive to both aperture (because of pressure effect) and stiffness (above). Slope of displacement vs. drawdown independent of aperture, sensitive to fracture stiffness (above right). Note mild hysteresis similar to field observations.



Parameter estimation using IFFCO to estimate fracture parameters from open well constant rate test. Symbols are displacement data, line is predicated. Drawdown used as b.c. because of open well.

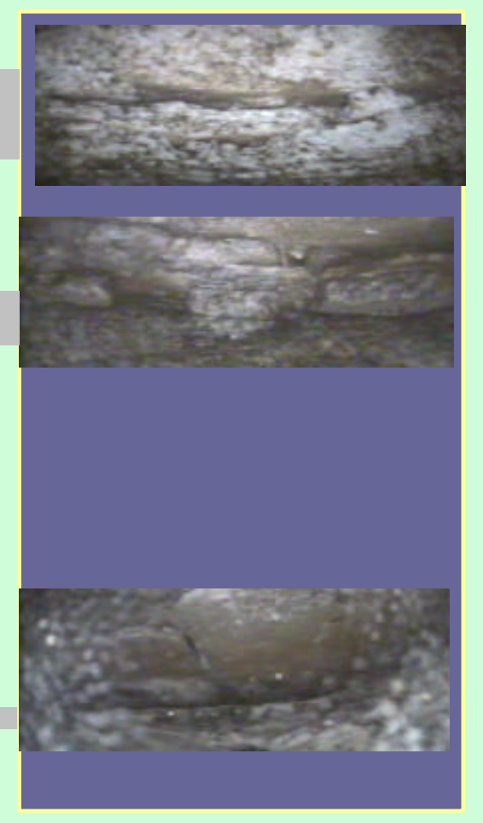


Well data



Packer tests and borehole flow tests were conducted in a borehole at the Clemson University Well Field. The results from the hydraulic tests indicate three conductive intervals a few meters thick at depths of 25 m, 34 m, and 49 m.

Borehole video



Fractures were identified on the walls of the borehole using a video camera.

Specific Storage

Specific storage estimated using displacements

The specific storage (Ss) was calculated using the displacement measurements to determine local aquifer compressibility. Those measurements were integrated over the length of the borehole to give an estimate of storativity. This approach gives $S = 1.2 \times 10^{-4}$. Storativity estimated using Jacob Straight-Line Method ranges from $S = 1 \times 10^{-4}$ to 6×10^{-4}. The higher S values result from tests using the entire well, and probably reflect contributions to storativity from the overlying saprolite, which is not included in the displacement measurements.

$$S = \int_0^b (C_r + nC_w)dz \approx 1.2x10^{-04}$$

6. Conclusions

- **A theoretical analysis** of a deformable fracture has been developed to simulate the well tests and predict aperture changes. The analysis considers both local and global displacements on a single fracture coupled to pressure changes accompanying flow in the fracture. A new semi-analytical solution to elastic displacements allows the solution to execute relatively quickly.
- **A field technique** has been developed to measure the axial displacements of a borehole to infer changes in aperture of flat-lying fractures during hydraulic well tests. Basic data from the tests can be used to determine compliance or stiffness. Larger values of compliance occur where flat-lying fractures cut the well and smaller values are in relatively unfractured intervals.
- **Inverse methods** can be used to estimate fracture parameters from pressure and displacement data. We are optimistic that additional details about the distribution of fracture properties and interactions between a fractures and matrix can be determined by inverting field data.
- **Normal compliance** values that vary from 0.5 microns/(m of drawdown) to 9 microns/m in biotite gneiss.
- **Specific storage** can be estimated from compliance values, and specific storages obtained using this approach are consistent with published values for fractured rock.
- **Pressure dependent transmissivity.** It appears that the aperture of all fractures will change with pore pressure during a well test. This will be particularly significant where initial apertures are small or where drawdowns are large. Measuring displacements during well tests can be used to evaluate the effects of pressure dependent transmissivity.