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Analysis of the hydromechanical behavior of a flat-lying fracture during a slug test

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Summary Slug tests dilate and contract fractures in aquifers. We developed a coupled hydromechanical analysis of an idealized fracture to evaluate effects of these deformations in fractured crystalline rock aquifers. The analysis shows the abrupt increase in pressure at the beginning of a slug test causes a slight opening of a fracture, but the fracture continues to open as the pressure falls in the wellbore. This happens because the pressure increases over an ever-widening area even though it decreases in the wellbore. Eventually decreasing pressure in the vicinity of the wellbore offsets the spreading pressure and the fracture starts to close, ultimately returning to its initial aperture when the pressure equilibrates. The displacement in the wellbore when the pressure head is rising is always smaller than when the head is falling, and this produces a loop-like, hysteresis when displacement is plotted as a function of pressure. A sensitivity analysis shows the displacement at the wellbore is sensitive to the magnitude and distribution of aquifer properties, suggesting that the displacement signal could be combined with pressure measurements to improve the interpretation of slug tests during aquifer characterization.

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Slug tests are without question the most widely used method for characterizing aquifers because they are relatively easy to perform, avoid removing potentially contaminated water, and require modest field equipment (Butler, 1998). The basic procedure involves suddenly changing the total

hydraulic head in the wellbore and measuring the falling or rising head as a function of time until an equilibrium state is reached in the aquifer. Interpretation of field data typically involves matching the transient head data to type curves in order to obtain average values of transmissivity and storativity. Analyses of slug tests have received considerable attention, with early papers by Hvorslev (1951), Cooper et al. (1967), Bouwer and Rice (1976), providing a foundation for basic aquifer cases, and more recent papers providing important refinements (e.g. Barker and Black,

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1983; Black, 1985; Moench and Hsieh, 1985; Sageev, 1986; Grader and Ramey, 1988; Karasaki et al., 1988; Novakowski, 1989; Widdowson et al., 1990; Zlotnik, 1994; Hyder et al., 1994). A thorough review of analyses and field applications of slug tests is given by Butler (1998).

Conventional slug tests are not without shortcomings. The transient pressure signal from slug tests is weakly sensitive to storativity (Butler, 1998, pp. 59–64), 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 the inversion (McKenna and Poeter, 1995). Pressure signals from many piezometers, and switching around the location of the well is used in hydraulic tomography to increase the resolution of aquifer properties (Zhu and Yeh, 2005; Brauchler et al., 2003; Bohling et al., 2002; Butler et al., 1999; Paillet, 1995). Data from geophysical methods, such as ground penetrating radar, electrical resistivity tomography, or cross-hole seismic techniques have been combined with hydraulic or tracer tests to improve the interpretation of aquifer parameters (Day-Lewis et al., 2006; Moysey et al., 2006; Kowalsky et al., 2005; Hyndman and Gorelick, 1996; Hubbard and Rubin, 2000; Tsofilas et al., 2001). The underlying theme of those methods is the fusion of several streams of data to sharpen aquifer characterization. We suggest that displacement measurements can also be used to improve aquifer characterization.

Changes in fluid pressure during a well test will cause displacements in both porous sediments and fractured rock aquifers (Rutqvist, 1995; Wang, 2000; Rutqvist and Stephansson, 2003). The magnitude and distribution of displacements will depend on the distribution of aquifer parameters, suggesting that displacement measurements could be fused with pressure signals, or perhaps other data, to improve the resolution of aquifer characterization. Gale (1975) is to our knowledge the first investigator to simultaneously measure displacements and fluid pressures during a well test. Gale's work was followed by several other field demonstrations 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; Cappa, 2005; Cappa et al., 2005). In general, however, the application of this technique has been rather rare, probably because the field applications have required specialized equipment, and 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., 2006).

We have developed field and theoretical tools for measuring and interpreting small displacements during slug tests in fractured rock. The motivation has been to evaluate the use of displacement signals as a means to improve the information about aquifer properties and heterogeneities available from slug tests. The field equipment consists of removeable borehole extensometers, which are described

in detail by Schweisinger et al. (2007) and Murdoch et al. (2005). The interpretations are based on an analysis of pressures and displacements in an idealized, deformable fracture presented by Murdoch and Germanovich (2006).

The purpose of the following paper is to present the important details of the hydromechanical response of an idealized fracture to a slug test, according to the theoretical model. This information will be used to interpret field observations, which will be described in a companion paper (Svenson et al., in press).

Conceptual model

Sub-horizontal fractures can be particularly important in rock aquifers because they provide a permeable framework that extends the influence of a well in all directions. Accordingly, we will idealize a fractured rock aquifer by considering only a single, flat-lying fracture embedded in a matrix of low permeability crystalline rock. The spacing between opposing fracture walls varies from as much as a few millimeters down to negligible values. Fluid can be transmitted through interconnected void spaces in the fracture plane, and these voids are arranged around regions where the transmissivity is essentially zero because the fracture is closed by contact with asperities on the opposing surfaces, or bridges of intact material spanning fracture segments (Neuzil and Tracy, 1981; Cook et al., 1990; Renshaw, 1995; NRC, 1996; Zimmerman and Main, 2004). Patches of mineral precipitates may also reduce the local transmissivity of the fracture.

The aperture is defined as the displacement of two points that were neighbors before the fracture formed, but now lie on opposite walls of the fracture. This defines the aperture in terms of mechanical displacements relative to the intact rock. A positive fracture aperture can occur at depth in rock because the displacement is maintained by fluid pressure in voids and stresses on contacting asperities (Pyrak-Nolte and Morris, 2000; Mourzenko et al., 1997). The aperture will change in response to changes in the fluid pressure; decreasing fluid pressure will increase the compressive stress on asperities and reduce the aperture, whereas increasing fluid pressure increases the aperture (Fig. 1; Neuzil and Tracy, 1981; Mourzenko et al., 1997).

The change in aperture that occurs due to a change in fluid pressure at a point along a fracture will depend on local effects, such as the fraction of the fracture area in contact and the stiffness of asperities, and global effects, such as deformation of the rock containing the fracture (Noorishad and Doe, 1982; Rutqvist, 1995; Rutqvist et al., 1998). The aperture change occurring where asperities are formed from relatively stiff quartz or feldspar, for example, is expected to be less than where asperities are formed from relatively compliant clay minerals. Aperture dilation due to a pressure increase near the center of a fracture is expected to be greater than when the same pressure change occurs near the fracture tip.

Those effects are important because changes in fracture aperture will fundamentally affect the hydrologic response to pressure variations during a well test. Aperture change due to pressure is closely related to storativity. Transmissivity is related to the aperture cubed, so slight changes in aperture will produce much larger changes in transmissivity.

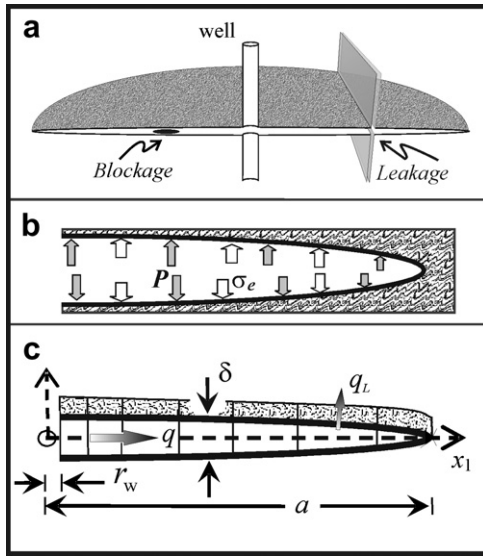


Figure 1 (a) Idealized flat-lying fracture used in the analysis; (b) fracture represented as a hole loaded by fluid pressure and effective stress; (c) Fracture divided into segments with finite difference grid, coordinate axes, and dimensions used in the analysis.

This inevitably causes the transmissivity to change during a well test, although the change may be too small to notice in many tests.

Processes that occur during and after the creation of a fracture can affect how readily it transmits fluid. For example, a fracture that forms by the coalescence of en-echelon segments may be spanned by unbroken bridges of matrix material (Pollard et al., 1982). The bridges would create a high resistance to flow but a negligible resistance to normal displacement (Germanovich and Astakhov, 2004a,b). As a result, the transmissivity of the fracture could be strongly reduced by the bridges, while the macroscopic aperture remains similar to neighboring regions. Mineral precipitates in some fractures fill regions that were once open, and dissolution may etch away the walls of other fractures. These processes that block a fracture could significantly reduce transmissivity, but they probably would have little effect on aperture defined by mechanical displacement. A region of low transmissivity in a fracture will be termed a *blockage*.

Most fractures of hydrologic interest intersect other fractures to form a percolating network (NRC, 1996). A flat-lying fracture, such as the one considered here, could be intersected by a steeply dipping fracture or fault to form such a network. Presumably the steeply dipping fracture would cause water to leak out of the flat-lying fracture and this would affect the response during a well test (Doe, 1999). The effects of cross-cutting fractures or other localized permeable zones will be termed *leakage*.

Theoretical analysis

Processes inferred to occur during a slug test in fractured rock will be represented by considering fluid flow and normal deformation within an axisymmetric fracture of radius, a , and aperture, δ . Fluid flow and normal deformation are coupled during the solution.

Fluid flow

Continuity of mass on the fracture in cylindrical coordinates gives (Nilson and Griffiths, 1986)

$$0 = \frac{\partial \rho q \delta}{\partial r} + \frac{\rho q \delta}{r} + \frac{\partial \rho \delta}{\partial t} + \rho q_L \quad (1)$$

where r is the radial distance from the center of the well-bore, t is time, ρ is fluid density, q is volumetric flux or average velocity, and q_L is the flux leaking out through the wall of the fracture. Hydraulic head in the fracture, h , affects ρ , q , δ , and q_L in (1), and expressions characterizing these relations are used to relate (1) to hydraulic head (details of how this is done are given by Murdoch and Germanovich, 2006). The aquifer is assumed to be at equilibrium at the start of the test, so the initial condition is $h(r, t = 0) = h_0$.

The hydraulic head increases rapidly early in a slug test, so the boundary condition where the fracture intersects the borehole is

$$h_w(r_w, t) = h_0 + m_s t, \quad t < t_p \quad (2)$$

where m_s is the rate of change of head at the start of the test, and t_p is the time required to pressurize the wellbore. The boundary condition changes to

$$q(r_w, t) = -\frac{r_c^2}{2\delta_w r_w} \frac{\partial h_w}{\partial t}, \quad t \geq t_p \quad (3)$$

where the w subscript indicates the wellbore, such that q_w is the flux into the fracture at the wellbore, h_w is the hydraulic head in the wellbore, δ_w is the aperture at the wellbore, r_w is the radius of the wellbore, and r_c is the radius of the well casing. The boundary condition at the tip of the fracture ensures no flow

$$\frac{\partial h}{\partial t}(a, t) = 0, \quad r = a \quad (4)$$

Assuming laminar conditions throughout the fracture gives (Witherspoon and Wang, 1980)

$$q = -\frac{\delta^2 \gamma}{12\mu} C_f \frac{dh}{dr} \quad (5)$$

where γ is the unit weight of water, μ is the dynamic viscosity of water, and C_f is a friction coefficient that accounts for roughness of the fracture walls and the tortuosity of flow paths through a partially open crack (Renshaw, 1995; Zimmerman and Main, 2004; Cook et al., 1990; Walsh, 1981). Effects of blockage that locally reduces the transmissivity of the fracture will be included by adjusting C_f .

The leakage flux out of the fracture is represented using

$$q_L(r) = 2C_w(h - h_0) \quad (6)$$

where, C_w is the conductance of the fracture wall and h_0 is assumed to be constant. Leakage can be represented more comprehensively by discretizing the matrix and requiring continuity is satisfied there. The code used for this analysis allows the matrix to be represented in two dimensions, so it is possible to include more general flow behavior in the matrix (Murdoch and Germanovich, 2006). However, we found that (6) provides a reasonable approximation to more complicated cases, but it executes considerably faster than when flow through the matrix is considered in detail.

Matrix deformation

The rough opposing surfaces of real fractures will be idealized by assuming the fracture is a flattened hole in an elastic material (Fig. 1a), and the wall of the hole is loaded by a radially distributed fluid pressure, P , and effective stress, σ_e (Fig. 1b). Explicit consideration of the details of the deformation of asperities will be ignored and replaced by a relation between effective stress and aperture. Therefore, asperity stress represented in Fig. 1a is averaged per unit area of the fracture and represented as effective stress σ_e (Fig. 1b).

A uniform far-field compressive stress, σ_c , is assumed to oppose fluid pressure and effective stress in the fracture. The driving pressure is the difference between the sum of the weighted fluid pressure and effective stress that open the fracture and the confining stress that closes it.

$$P_d(r) = \alpha P + \sigma_e - \sigma_c \quad (7)$$

where α is the ratio of the area of open space to total fracture surface. A positive driving pressure will cause a fracture to dilate and result in positive aperture. Likewise, a fracture with some mechanical aperture must be supported by a positive driving pressure.

Contact aperture, δ_0 , is the aperture when asperities first lose contact when a fracture is opening, or make contact when it is closing (Murdoch and Germanovich, 2006). Contact aperture varies over a fracture face depending on the details of slight shear displacements, amplitude of asperities or roughness, or other factors that cause local contacts between opposing fracture walls.

The fracture is assumed to deform both globally and locally, and this is one important difference between the analysis used here and those assuming an aquifer consists of equivalent porous media, where deformation is only local. Global deformation of the fracture is the displacement that occurs in one location in response to a change in the driving pressure at another location on the fracture face. In contrast, local deformation occurs only in response to changes in local fluid pressure or effective stress.

All deformation is assumed to be linear elastic. The local relationship between effective stress and fracture aperture can be non-linear because the area of contact between asperities increases with normal compressive stress in accordance with the results of laboratory experiments (Bandis and Lumsden, 1983) and theoretical analyses (Mourzenko et al., 1997; Pyrak-Nolte and Morris, 2000; Unger and Mase, 1993). Local apertures will be described using

$$\delta_L(r) = \delta_0 - \frac{(\delta_0 - \delta_{\min})\sigma_e}{K_{ni}(\delta_0 - \delta_{\min}) + \sigma_e} \quad (8)$$

which is similar to the relation proposed by Bandis and Lumsden (1983, Eq. 11), based on lab experiments. The stiffness of the fracture at zero effective stress is K_{ni} and the effective normal stiffness under load, K_{ns} , are related using

$$K_{ns} = \frac{1}{d\delta_L/d\sigma_e} = \frac{(\sigma_e + K_{ni}(\delta_0 - \delta_{\min}))^2}{K_{ni}(\delta_0 - \delta_{\min})^2} \quad (9)$$

Applying (8 or 9) requires describing how the contact aperture, δ_0 , and the irreducible aperture, $\delta_{\min}$, are distributed

over the fracture. The analyses presented here assumes contact aperture is distributed as

$$\delta_0(r) = \delta_{ow} \left(1 - \left(\frac{r}{a} \right)^2 \right)^{1/2} \quad (10)$$

where δ_{ow} is the contact aperture at the well. Eq. (10) was used because it gives a fairly uniform initial distribution of σ_e , (Murdoch and Germanovich, 2006), although additional work is required to evaluate how this term is actually distributed over real fractures. $\delta_{\min}$ was assumed to be $0.1\delta_0$. Assuming the driving pressure in (7) is distributed over a circular crack in an infinite medium allows the aperture to be determined by (Sneddon, 1995, p. 489)

$$\delta_g(r) = \frac{8a(1 - \nu^2)P_d}{\pi E} \int_{r/a}^1 \frac{\mu}{(\mu^2 - r/a)} d\mu \int_0^1 \frac{\tau P_d(\tau \mu a)}{\sqrt{1 - \tau^2}} d\tau \quad (11)$$

Eq. (11) can be solved exactly for the case where the driving pressure is uniformly distributed over a narrow radial ring. Then the aperture resulting from an arbitrary distribution of driving pressure in radial coordinates can be determined by superposition (Murdoch and Germanovich, 2006).

Solution

A slug test in a fractured aquifer involves coupling between the fluid pressure and the fracture aperture. Increasing the fluid pressure changes the aperture, but changing the aperture affects the transmissivity and storage, which affect the pressure distribution during fluid flow Eqs. (1–6). In addition, the changes in aperture must satisfy the relations between both the local and global aperture changes. The local effect assumes aperture changes as the same function of effective stress observed in laboratory tests (Eq. 8). The global effect is characterized by elastic deformation as in Eq. (11). Coupling requires $\delta_L(r) = \delta_g(r)$.

The coupled problem is solved by recognizing h and σ_e as vectors of unknowns. The continuity Eq. (1) is written in finite difference form and the fracture is discretized into m blocks (Fig. 1c). Eqs. (8) and (11) are solved at each grid block and the results are equated. This produces $2m$ equations and unknowns, and this system is solved using Hybri1 in MINPACK. It is important to recognize that the problem is defined in the unloaded state, so the first analysis consists of determining δ and σ_e using the applied loads of σ_c and the initial fluid pressure. Then the fluid boundary conditions are applied and the solution is marched through time. The analysis is implemented in a code called DFrx and details of the code are described by Murdoch and Germanovich (2006).

Results

A baseline analysis was developed using dimensions and parameters that approximate conditions at our field site in fractured biotite gneiss underlying western South Carolina (Table 1). The baseline grid consists of 100 blocks along the fracture. Six evenly spaced blocks were adjacent to the wellbore, and the grid spacing increased thereafter as a geometric progression using a 1.15 multiplier. The baseline case used 40 time steps, with $\Delta t = 0.2$ s during the first 6 steps. The wellbore was assumed to pressurize in 1 sec-

Table 1 Input parameters for baseline analysis

Parameter	Value	Unit
Young's modulus, E	4.0×10^{10}	Pa
Poisson's Ratio, ν	0.3	
Initial Normal Stiffness, K_{ni}	10^9	Pa/m
Base Contact Aperture, δ_{ow}	0.0005	m
Area ratio, α	1.0	
Well Casing Radius, r_c	0.0381	m
Wellbore Radius, r_w	0.0762	m
Initial head, h_0	25.0	m
Confining stress, σ_c	5.88×10^5	Pa
Fracture radius, a	500	m
Matrix Conductance, C_w	10^{-30}	1/s

ond, so there were 5 time steps during pressurization ($t < t_p$). $\Delta t = 1.0$ s for time steps 6 through 10, and a multiplier of 1.2 was used to progressively increase each subsequent time step while $\Delta t \leq 400$ s.

The grid and time stepping schemes were adjusted to minimize the mass balance error while retaining a reasonable execution time. Mass balance errors for the specifications outlined above were less than 0.035, and the execution times were 2 min on a 2.8 GHz computer with 1Gb RAM.

Head and displacement response

The general behavior during the baseline case was that the hydraulic heads increase rapidly to a peak and then decrease during most of the test. The aperture behaved similarly, but the maximum displacement lagged behind the peak head (Fig. 2). In this example, the hydraulic head reached a maximum, $h_{\max} = m_s t_p$, of 1 m in 1 s and the aperture opened by $0.55 \mu\text{m}$ during this time. The aperture continued to increase and reached a maximum displacement of $0.9 \mu\text{m}$ after 40 s. The hydraulic head fell to 0.8 m when the aperture was greatest at $t = 40$ s. The heads decreased and the aperture closed when $t > 40$ s (Fig. 2).

There are four stages in all the records of displacement and head. Stage I is the brief period at the start of the

test characterized by increasing pressure and displacement. Stage II begins at the peak hydraulic head, $t = t_{h\max}$, and ends when the fracture gap opens to its maximum extent, $t = t_{d\max}$. Both pressure and displacement decrease during Stage III. A final stage, Stage IV, marks the late-time behavior and occurs when $h/h_{\max} < 0.1$, $t > t_{h0.1}$ (Fig. 2).

Displacement was a hysteretic function of hydraulic head during the baseline slug test; displacement was smaller while head was rising in the well than it was while head was falling. This produced a loop-like shape in the plot of displacement as a function of head (Fig. 3).

Transmissivity and storativity

Transmissivity of the fracture is not an explicit parameter in the theoretical analysis, so it was assumed to be given by (Witherspoon and Wang, 1980)

$$T = \frac{\delta_w^3 \gamma n}{12\mu} \quad (12)$$

The aperture of the fracture changes with distance from the well, and this change is ignored by assuming (12).

Storativity of fractured crystalline rock can be dominated by the deformability of the fractures. A simple approach is to assume that $d\delta/dh$ is the normal fracture compliance. We follow Doe et al. (1982), Rutqvist (1995), and Rutqvist et al. (1998) and assume storativity of a single fracture can be approximated as the sum of fracture compliance at the borehole and the product of fracture aperture and water compressibility. It is apparent from Fig. 3 that $(d\delta/dh = dv/dh)$ varies with time, and Fig. 4 shows that fracture compliance increases by an order of magnitude during Stage III and approaches $1/K_{ns}$ during Stage IV of a slug test. This behavior implies that the effective storativity in this fracture increases with time. This result is contrary to the typical assumption in ground water hydrology that S is constant (indeed, $d\delta/dh$ is actually negative during Stage II). Accordingly, we assume storativity is determined by using the compliance during Stage IV because this approaches a single value, which is also equal to the inverse of the lab-derived normal fracture stiffness.

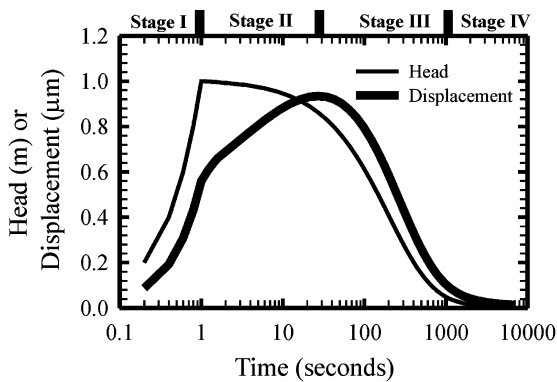


Figure 2 Hydraulic head, h , and displacement, v , at the wellbore as functions of time during slug test with baseline parameters.

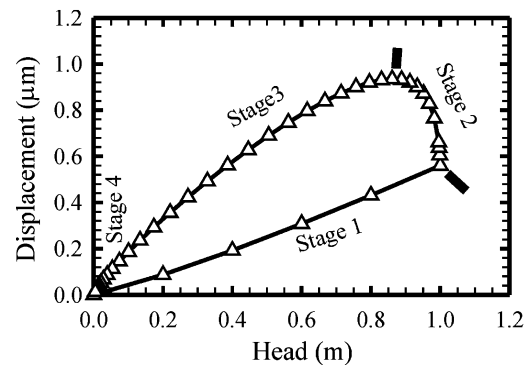


Figure 3 v - h curve showing displacement, v , as a function of head, h , during a slug test.

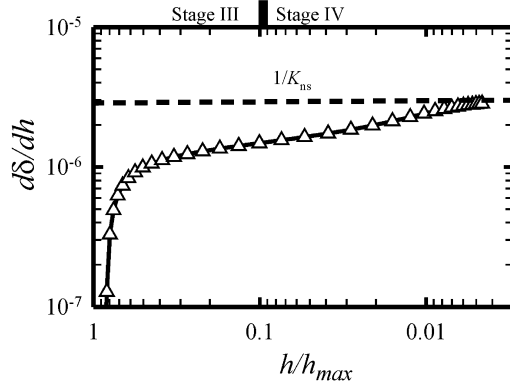


Figure 4 Compliance as a function of normalized head during baseline slug test.

This suggests an approach for estimating storativity as

$$S = \alpha \frac{d\delta}{dh_{IV}} + \delta \alpha \gamma \beta \quad (13)$$

where we assume $\alpha\delta$ = the “void aperture” in Rutqvist et al. (1998). This makes (13) equivalent to Rutqvist et al. (1998, Eq. (3)).

Results from the theoretical analysis and methods for determining T and S were verified by comparing hydraulic heads predicted by DFrX to results from the analytical solution described by Cooper et al. (1967), which accounts for an instantaneous charge of water to a well that fully penetrates a homogeneous, isotropic, confined aquifer of infinite lateral extent. Data from the Cooper et al. analysis were obtained from a software package called WinAQUIFER32 using values of

$$\alpha_c = S \frac{r_w^2}{r_c^2} = 10^{-6}, 10^{-5}, \text{ and } 10^{-4} \quad (14)$$

The numerical model was run and α_c was calculated as 1.2×10^{-5} using S defined in (13). The hydraulic heads were scaled to the maximum head, and the time was scaled according to

$$t_d = \frac{Tt}{r_c^2} \quad (15)$$

where T was determined using (12). Results from the first 1 s of the simulated test, during Stage I while heads were increasing, were discarded and the remaining data were compared to the analytical results.

The relative error between the numerical and analytical solutions ((numerical-analytical)/analytical) is less than 0.01 at early times, and it increases to 0.035 at the end of

the simulation. In general, this error is small enough to verify the numerical procedure, and it provides preliminary confirmation of the methods for calculating T and S . The far-field boundary condition in the numerical procedure prevents water from leaving the crack when C_w is essentially zero everywhere. This requires that the hydraulic head decays to an equilibrium value large enough to increase storage in the fracture by the amount of the slug volume. This causes the relative mass balance error to increase with time. This error is inevitable, although it can be kept small when the slug volume is small compared to the fracture volume and compliance, as in the baseline case.

Hydraulic heads predicted by DFrX resemble results from the Cooper et al. (1967) analytical solution (e.g. Murdoch and Germanovich, 2006; Fig. 4), so we evaluated the possibility of developing a simple approach for estimating T . We ran analyses for a variety of different parameters and plotted them after scaling using Eq. (12)–(15). At the same time, we also compared the results to other slug test solutions. We found that the numerical results differed considerably from the semi-log form of the Hvorslev analysis, in the same way the Cooper et al. analysis predicts a long tail to the heads that is absent in the Hvorslev analysis. However, we noticed that T can be approximated using

$$T \approx 1.2 \frac{d_c^2}{t_{0.37}} \quad (16)$$

where d_c is the diameter of the casing, and $t_{0.37}$ is the time when the head has decreased to 0.37 of its initial value, the same time used in the Hvorslev analysis. The $\approx$ symbol is used in (15) because results varied slightly with the different parameters used in the analyses, which is similar to the finding that α_c causes slight variations in the head predicted by the Cooper et al. (1967) analysis. The error from using (16) is approximately ± 0.3 . This result is similar to the approach for using the Cooper analysis outlined by Butler (1998, p. 58). Both methods appear to yield relative er-

Table 3 Parameters used to evaluate sensitivity to contact aperture

δ_0 (μm)	δ_{0w} (μm)	K_{ns} (Pa/m) $\times 10^9$
200	82	8.5
400	222	3.9
500	302	3.2
600	385	2.7
800	560	2.2
1000	740	1.9

Table 2 Range of parameters used in sensitivity analysis

E (Pa)	δ_0 (μm)	K_{ni} (Pa/m)	c_I (m)	c_{II} (m)
2×10^{10}	200	5.00×10^8	1	1
3×10^{10}	400	7.50×10^8	3	3
4×10^{10}	500	1.0×10^9	—	—
6×10^{10}	600	2.50×10^9	14	14
8×10^{10}	800	5.00×10^9	38	38
1×10^{11}	1000	—	76	76

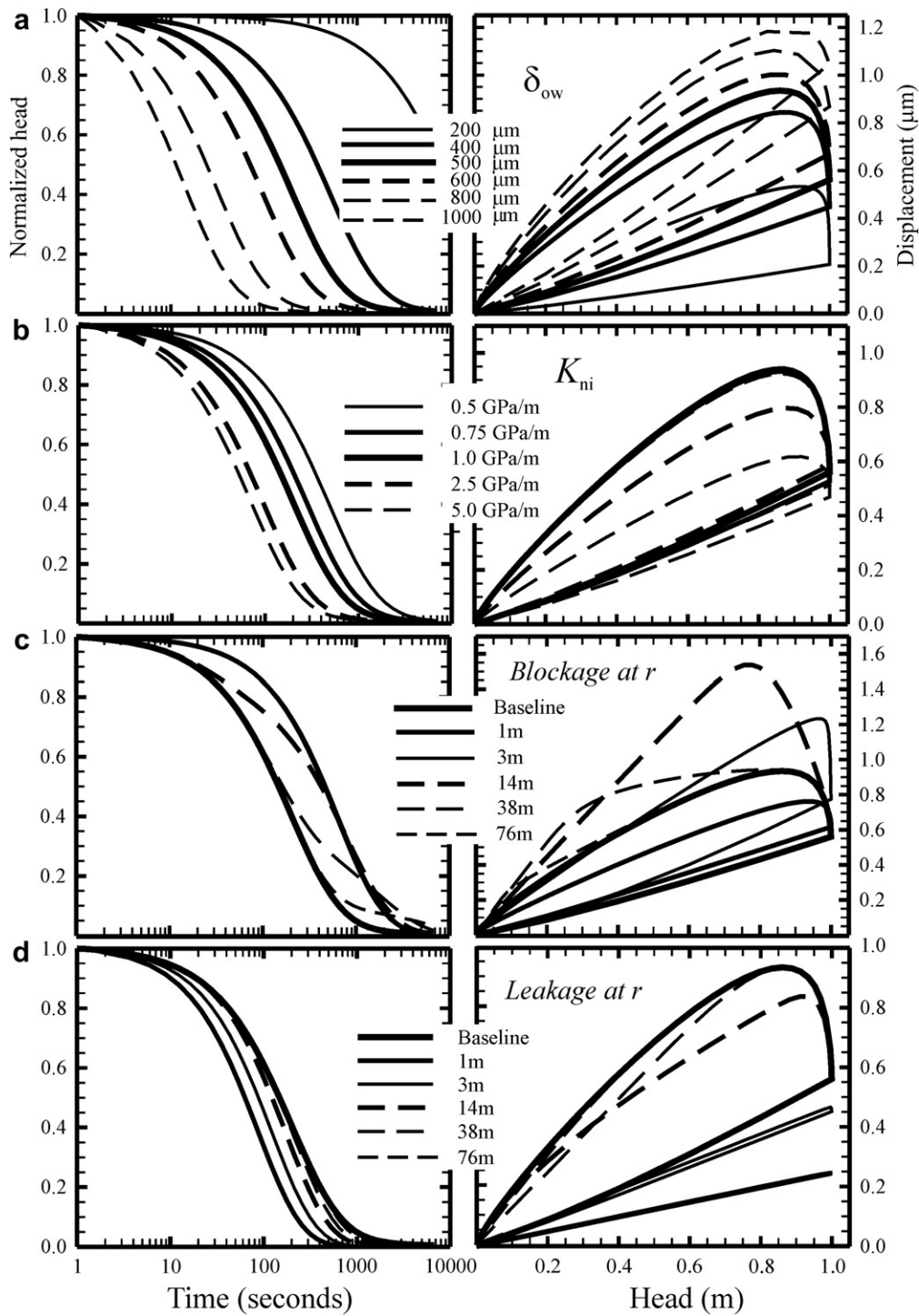


Figure 5 Hydromechanical responses during slug tests in formations with (a) different contact apertures; (b) different initial normal stiffnesses; (c) blockage at different locations; (d) leakage at different locations. $h-t$ curves on left side, $v-h$ curves on right side.

rors of ± 0.3 due to uncertainties in storativity, which is suitable for some applications.

Sensitivity

Preliminary interpretation of field data can be accomplished using the methods outlined above, but more detailed inter-

pretation will require inverse methods. Sensitivity analyses were conducted to support the application of inverse methods by systematically changing key input parameters in the theoretical analyses while leaving the remaining parameters unchanged (Table 2). In particular, δ_{ow} , K_{ni} , E , and the radial location of heterogeneities (i.e. leakage and blockage) were evaluated.

The predicted heads were normalized to their maximum value, graphed as a function of time on semi-log axes and compiled into a family of curves with the baseline response for comparison. Plots of head vs time will be termed $h-t$ plots. Displacements are shown as functions of head, and results are also presented with the baseline case. Plots of displacement, v , as a function of head will be termed $v-h$ plots.

Contact aperture

The contact aperture at the wellbore, δ_{ow} , was varied from 200 μm to 1000 μm , and this created fractures with initial apertures spanning from 82 μm to 740 μm . It also caused the effective stiffness, K_{ns} , to decrease from 8.5×10^9 to 1.9×10^9 Pa/m (Table 3).

The results show (Fig. 5) that changing δ_o shifts $h-t$ curves along the time axis with only minor changes in shape. Indeed, the transient head records will collapse to nearly a single curve when the time is scaled according to (15). Increasing δ_{ow} also affects displacement, causing the $v-h$ curve to rotate upward as the maximum displacement increases by roughly a factor of 2. The average slope of the $v-h$ curve increases, but the overall shape of the curve appears to be insensitive to δ_{ow} (Fig. 5a).

Initial normal stiffness

Simulations were conducted for four values of K_{ni} between 5×10^8 and 5×10^9 Pa/m (Table 4), bracketing the baseline of 10^9 Pa/m. Decreasing K_{ni} causes the head in the well to drop slower, whereas increasing K_{ni} hastens the head drop relative to the baseline slug test (Fig. 5b). The overall effect is to shift the head response along the time axis, similar to the effect of changing δ_{ow} . Modifying K_{ni} also alters the initial aperture, and the $h-t$ curves in Fig. 5b will collapse to nearly a single curve when the initial aperture is used in (12) to scale the abscissa. There is some variability in the $h-t$ curves that use (12) because increasing K_{ni} will decrease S . This variability is small, however, and resembles the difference between $\alpha_c = 10^{-5}$ and $\alpha_c = 10^{-6}$ (Murdoch and Germanovich, 2006, Fig. 4).

Increasing K_{ni} diminishes the displacement during a slug test, but this change occurs after the initial pressurization-the Stage I curves are similar for all 5 values of K_{ni} (Fig. 5b). Increasing K_{ni} above the baseline value causes the maximum displacement to diminish, with an increase in K_{ni} by a factor of 5 causing a reduction in displacement from 0.95 μm to 0.6 μm . This occurs by reducing the displacement during Stage II, which closes the hysteresis in the $v-h$ curve. It appears that increasing K_{ni} causes the $v-h$ curve to become more nearly linear. However, reducing K_{ni} below the baseline value has negligible effect on the $v-h$ curve (Fig. 5b). This occurs because K_{ns} changes little in response to reducing K_{ni} below the baseline (Table 4).

It is important to recognize that changing one of those input parameters will cause several aspects of the resulting model to change. For example increasing the contact aperture δ_{ow} will widen the aperture of the fracture, but it will also increase the asperity stiffness, K_{ns} (Table 3). Similarly, increasing K_{ni} (Table 4) will raise, K_{ns} , but it also increases the aperture used in the simulation (7). These effects are a result of using (8) and (9) and defining δ_{ow} and K_{ni} in an unloaded state-the actual aperture and stiffness can only be

Table 4 Parameters used to evaluate sensitivity to initial normal stiffness

K_{ni} (Pa/m)	δ_{ow} (μm)	K_{ns} (Pa/m) $\times 10^9$
5.00×10^8	225	3.3
7.50×10^8	270	3.1
1.0	302	3.2
2.50	391	4.3
5.00	438	6.7

determined by applying the initial load and analyzing the problem. Increasing contact aperture will increase σ_e , and this will elevate K_{ns} in (8) accounting for the data in Table 3. Similarly, increasing K_{ni} will open the aperture, but it also changes σ_e and the result is a decrease in K_{ns} , according to (8).

Young's modulus

Young's Modulus was varied from 20 GPa to 100 GPa, and this produced remarkably modest variations in aperture and normal stiffness-aperture was reduced by 0.7 μm , and K_{ns} increased by 0.17 GPa/m. The resulting effect on the $h-t$ curves was equally modest, but the $v-h$ curves are sensitive to the change in E (Fig. 6). The aperture increases with a reduction in E , and this causes the $v-h$ curves to steepen.

Blockage

The effects of blockage in a fracture were determined by setting $C_f = 0.01$ in one cell and varying the location of the cell across $r = 1, 3, 14, 38$, and 76 m.

Blockage causes the head to fall slower than it does during the baseline case (Fig. 5c). The effect increases and the time when it occurs diminishes as the blockage moves closer to the well. Blockage in the range of $r = 14$ m to $r = 74$ m changes the shape of the $h-t$ curve by causing it to abruptly flatten. Blockages close to the well, at 1 m and 3 m, produce $h-t$ curves resembling the baseline but translated to a later time. The $h-t$ curve produced by blockage close to the well would probably be interpreted as a uniform fracture with a transmissivity lower than the value determined from the aperture-an effect resembling the errors produced by interpreting slug tests from wells with skin (Sageev, 1986; Butler, 1998).

Blockage also affects displacements, producing a range of distinctive shapes in $v-h$ curves. Distant blockages cause the $v-h$ curve to bulge upward during Stages III and IV. A blockage at 14 m increases the maximum displacement from 0.95 mm to 1.5 mm, and extends the beginning of the effect to the middle of Stage II-the early part of Stage II still resembles the baseline. Blockage within a few meters of the well affects displacement starting with Stage I; however, the maximum displacement is diminished compared to the baseline.

Leakage out of fracture

The effect of a cross-cutting fracture or other features that could cause water leakage out of the horizontal crack was evaluated by increasing the wall conductance in one grid cell. The location of the leakage cell was varied (Table 2), so the conductance value was scaled to the area of the grid

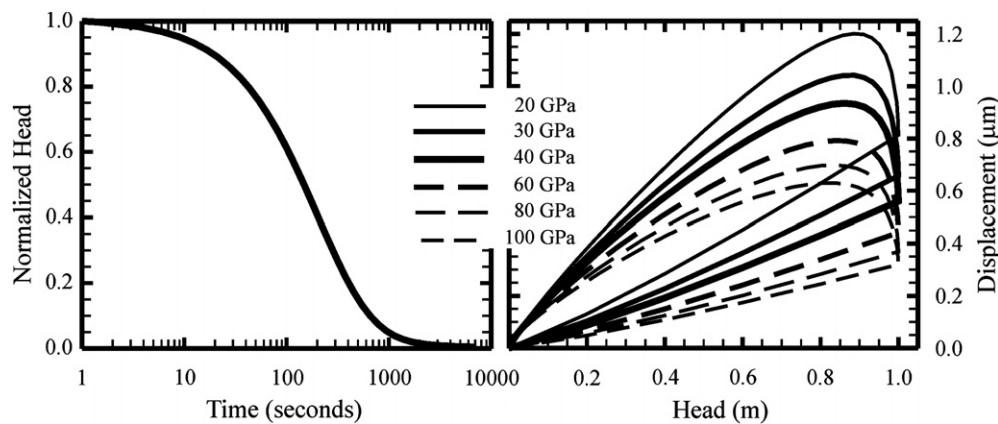


Figure 6 Hydromechanical responses during slug tests in formations with different Young's Moduli.

cell using $C_w = 10^{-2}/(2\pi\Delta r^2)$, where Δr is the width of the cell. Simulations were performed with the scaled C_w value in cells at $r = 1, 3, 14, 38$, and 76 m, the same locations that were used to evaluate blockage.

Leakage causes the head to drop more quickly than it does during the baseline test (Fig. 5d), just like blockage. The magnitude of this effect increases and the time when it occurs diminishes as the leakage cell becomes closer to the well. Responses from leakage at 76 m and 38 m are similar to the baseline at early times, but later in the test the head drops slightly as a result of leakage. Responses from 14 m and closer cause heads to fall faster than the baseline case after a few seconds (Fig. 5d).

Even though the effects of leakage can be recognized in the $h-t$ curves, the response is subtle and interpretation may be ambiguous. In contrast, leakage has a striking effect on $v-h$ curves. The effects of distant leakage are realized by a flattening of the hysteresis loop during Stages III and IV, which is consistent with a late-time response (Fig. 5). The loop continues to flatten as the displacement is reduced at progressively earlier times by moving the leakage closer to the well. The $v-h$ curve follows the baseline through Stages I and II for leakage at 14 m, but the curve departs completely from the baseline when leakage is at 3 m. It appears that a highly conductive zone close to the well will reduce both the slope and hysteresis in the $v-h$ curve.

Discussion

The basic hydromechanical response of a horizontal fracture to a slug test came as a surprise to us when preliminary results from the analysis described in this paper were first available. We expected that the displacements would track the wellbore pressure, probably because this is the response that would be predicted from a porous media model where displacement is proportional to pressure change. The analysis shows, however, that the pressure and displacement signals can be markedly different and their discrepancy holds important information about aquifer characteristics.

Displacement–pressure hysteresis

The magnitude of the displacement at the well depends on the pressure integrated over the area of the fracture (as in Eq. (11)). The relatively large pressures early in a slug test

cause a surprisingly small normal displacement because they only affect a small area of the fracture surface. The displacement can increase in the face of diminishing wellbore pressures because the pressurized area is increasing rapidly during Stage II. At some point the effect of increasing the pressurized area can no longer offset the dropping pressures, and the fracture starts to close, marking the beginning of Stage III. The loading on the fracture face is relatively localized early in the slug test, and this causes the walls of the fracture to distort much like the surface of a half-space is indented under a localized load. The modulus of the rock opposes this indenting effect, and this is why the fracture appears relatively stiff early in the test. Deformation of the fracture walls diminishes with time as the pressure head drops and becomes more uniformly distributed. Late in the test, the deformation of the fracture is controlled by compressibility of the asperities, and this is why $d\delta/dh \rightarrow 1/K_{ns}$ during Stage IV. Hydromechanical analyses by Cappa et al. (2006) show how similar effects result in pressure–displacement hysteresis during pulse tests.

Storativity

The term α_c in (14) used in the verification analysis includes S , which was determined using the fracture compliance in (13). Inasmuch as the verification analysis gave results that are within a few percent of the analytical solution, it appears that (13) is a reasonable approximation for S . Despite the encouraging verification results, the analysis approach outlined here will by no means be a simple method for characterizing S , as this term is typically used in groundwater investigations. The difficulty is because the fracture compliance ($d\delta/dh$) increased by at least a factor of 10 during most of the analyses presented here (Figs 4–6), and this implies that S increases as well. This change appears to occur because the compliance is controlled by the modulus of the fracture walls early in the slug test when the pressure is large and its distribution is of limited radial extent, whereas compliance is controlled by the asperity stiffness (embodied in K_{ns}) late in the test when the pressure is small and distributed nearly uniformly. This change in storativity with time during a slug test is absent from conventional analyses of porous media. Those analyses are already recognized to be weakly sensitive to S , and they do not consider the hydromechanical effect outlined above. As a result, we

Table 5 Parameters used to evaluate sensitivity to Young's modulus

E (Pa)	δ_{ow} (μm)	K_{ns} (Pa/m) $\times 10^9$
2×10^{10}	304	3.14
3×10^{10}	303	3.17
4×10^{10}	302	3.2
6×10^{10}	300	3.23
8×10^{10}	299	3.27
1×10^{11}	297	3.31

expect that the hydromechanical effect may make estimating S from slug tests even more difficult than is suggested by the lack of sensitivity in conventional analyses alone (Table 5).

Asperity deformation

Asperity deformation plays an important role in the transient response during a slug test, and this process was assumed to be characterized by (Eq. 7), a hyperbolic relation between aperture and effective stress suggested by Bandis and Lumsden (1983, Eq. (11)). This function influenced the sensitivity response, particularly the effects of contact aperture and initial normal stiffness. For example, increasing δ_{ow} increases the aperture but diminishes K_{ns} (Table 3). In another set of tests (Svenson, 2006), we found that K_{ns} decreased with K_{ni} at relatively large values, but K_{ns} increased with decreasing K_{ni} when the stiffness was relatively low (less than 10^9 Pa/m). These effects are consequences of the form of (7). Other functions have been proposed to characterize asperity deformation (NRC, 1996; Zimmerman and Main, 2004; Murdoch and Germanovich, 2006), and details of the response outlined in the previous pages may differ when other functions are used.

Characterizing heterogeneities

The effect of pressure distribution on displacement also explains how leakage and blockage affect slug tests. Pressure spreads outward until it reaches a leakage point, and then the rate at which the pressure spreads over the fracture surface will diminish compared to the baseline case. Leakage also hastens the pressure drop by providing a fluid sink. As a result, leakage both decreases the pressure and shrinks the area of the fracture that becomes pressurized, and both of these processes diminish the displacement (Fig. 5d). In an extreme case, a horizontal fracture may never become pressurized at all if it is cut by a highly conductive vertical fracture near the well. This would produce a pressure signal that responds to the hydraulic properties of the vertical fracture, but there would be negligible vertical displacement because the pressure never loads the horizontal fracture.

Blockage slows the radial fluid flow and causes the pressure to be relatively uniform and elevated near the well compared to the baseline case. But the pressure decreases sharply across the blockage and is less than the baseline pressure on the distal side of the block. The zone of increased pressure will dilate the fracture and increase the displacement compared to the baseline when the blockage

is relatively far from the well. However, moving the blockage closer to the well shrinks the area affected by increased pressure and diminishes this effect. A blockage close to the well will boost the pressure over a small area, while reducing it over a much larger region, and the result is that the displacement is reduced compared to the baseline (Fig. 5c).

The analyses presented here are in axi-symmetric coordinates, so the geometry of a feature creating leakage out of the fracture will be ring-like, rather than the more planar geometry envisioned for a cross-cutting fracture shown in Fig. 1. For this reason, the pressure and displacement responses described here and shown in Fig. 5 should be regarded as idealized. The shapes of pressure and displacement curves responding to planar leakage features, like fractures, or irregular blockages, like a cemented zone in a fracture, will certainly differ from those shown in Fig. 5. Nevertheless, we expect that the general behavior shown in Fig. 5 will be consistent with the effects of leakage and blockage caused by more complicated geometries.

Slug tests are typically conducted in settings with mechanical heterogeneities and boundaries, like other fractures and the ground surface. In this paper, those features have not been represented explicitly because the mechanical analysis given here assumes a single fracture embedded in a uniform elastic material of infinite extent. Nevertheless, the effects of those features can be anticipated because pre-existing fractures and the presence of the ground surface will both lessen the resistance of the wall rock to deformation. The gross effect will be for the fracture to behave as if it is embedded in material with a softer elastic modulus. However, in detail, the effects of mechanical heterogeneities are expected to be manifested in the forms of the pressure and displacement curves and a theoretical model that includes these effects will be required to evaluate how they alter the response to slug tests. It seems feasible to modify the analysis presented here to include the effects of the ground surface, but other effects will probably require using a different code. Cappa et al. (2006) conducted 3-D finite element analyses of hydromechanical pulse tests in limestone, for example, and they show that pre-existing fractures and the ground surface affect the hydromechanical response by influencing the effective stiffness.

Slug tests are commonly viewed as only sensitive to conditions in close proximity to the borehole, but results shown here suggest otherwise, particularly when displacement measurements are available. It appears that modest slug tests may be sensitive to heterogeneities 15 m or farther from the wellbore (in formations characterized by baseline parameters). These findings support the contention of Butler (1998), who suggests that slug tests may be sensitive to a broader region than typically expected.

Field application of the theoretical results described here requires that micron-scale displacements can be measured along with pressures during a slug test. We have developed an extensometer (Schweisinger and Murdoch, 2002; Schweisinger et al., 2005, 2007; Murdoch et al., 2005) that temporarily anchors to a borehole wall to measure displacements during hydraulic well tests, and it provides a straightforward method for obtaining data to support the analyses outlined in the previous pages. Field applications of this device and interpretations using the

methods outlined above are described in a companion paper (Svenson et al., in press).

Conventional analyses

The analysis of slug tests in a confined aquifer with storage (e.g. Cooper et al., 1967) gives type curves that resemble the solution for a uniform deformable fracture subjected to a slug of modest size (e.g. Fig. 2 and Murdoch and Germanovich, 2006, Fig. 4), where T is given by (12) and S is given by (13). It is expected that other solutions for slug tests in confined aquifers with storage (e.g. Dougherty and Babu, 1984; Peres et al., 1989; Hyder et al., 1994), would also resemble the results obtained here. This is encouraging because it suggests that in some cases T obtained by conventional slug test analyses in a confined aquifer can be related to the hydraulic aperture of discrete fractures in rock.

A notable exception is where slug tests use pressure head changes greater than a few meters. This may cause the aperture of the fracture to change by enough so the T determined during the slug test is significantly different than the T at ambient pressure in the aquifer.

Conclusion

Slug tests will dilate fractures in aquifers, according to results of hydromechanical analyses. The abrupt increase in pressure at the beginning of the test causes a slight displacement, but the fracture continues to open even as the wellbore pressure head drops. Continued opening occurs as the pressure disturbance propagates over an ever widening area of the fracture face. Maximum displacements of microns are expected to accompany head changes of meters, but the displacements may be larger for slug tests with greater head changes. However, eventually the wellbore pressure will drop enough to offset the effect of the spreading pressure on the fracture face, and the fracture will start to close. Ultimately the aperture returns to its initial value when the head equilibrates. This process causes hysteresis in the displacement as a function of pressure-displacement is less while the head in the wellbore is rising than it is during falling head.

The transient head response to a slug test in an idealized deformable fracture resembles the response predicted by the Cooper et al. (1967) solution for a slug test in a confined aquifer. However, a coupled mechanical and hydraulic model is required to predict the displacements. The results of the coupled model used for this work show that both the pressure and displacements are sensitive to the fracture aperture, compliance, and heterogeneities resembling blockages or cross-cutting fractures. This suggests that it may be possible to sharpen the resolution of aquifer characterization by measuring displacements and simultaneously interpreting these data along with the pressure signal during slug tests.

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