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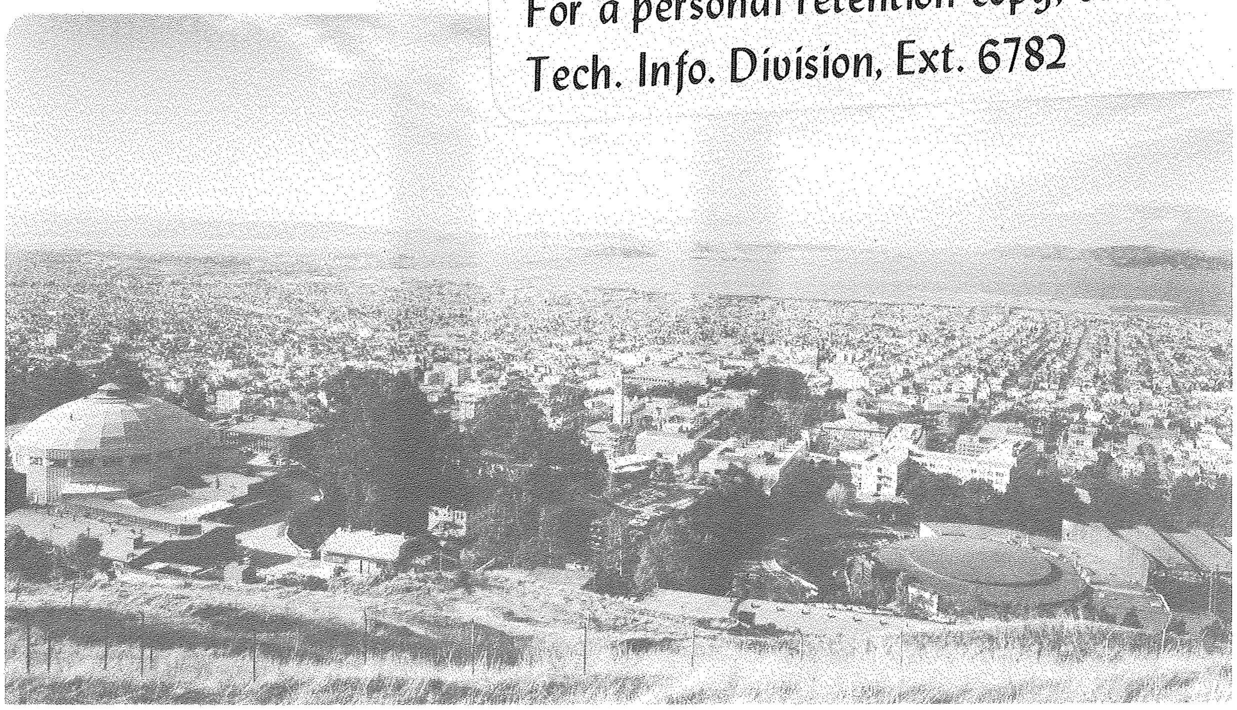

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INTERPRETATION OF A HYDRAULIC FRACTURING EXPERIMENT, MONTICELLO, SOUTH CAROLINA

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Abstract. Pressure transient data from a hydraulic fracturing experiment have been analyzed using a numerical model. Several system parameters and their sensitivities were evaluated, assuming a vertical, penny-shaped fracture geometry. Although the best-fit parameters may not constitute a unique set, they do appear credible from what current field experience would indiate. It was found that the injection pressure transient is sensitive to initial fracture aperture, fracture stiffness, minimum horizontal stress, rock toughness, and host-rock permeability.

Introduction

The measurement of in-situ tectonic stresses through hydraulic fracturing is an established field technique. However, data on variable injection rates and wellhead injection pressures collected during these tests are usually inter preted in a very simplistic fashion. The hydraulic fracturing process is characterized by geometric and material properties that vary with time. The resulting non-linear differential equations necessary to describe the process are difficult to solve analytically. With a view to extracting more information from the experimental data, we have applied a numerical model to carry out the pressure-transient analysis of a hydraulic fracturing experiment conducted at Monticello, South Carolina by the U.S. Geological Survey (Zoback, personal communication, 1979)

In order to account for the many variable coefficients we have used a parametric approach. This paper summarizes the essential features of the numerical technique, as well as the importance of different system parameters in controlling the pressure/time response during the hydraulic fracturing experiment. More detailed discussion of these aspects can be found in the doctoral dissertation of Palen (1980).

Theory

The hydraulic fracturing experiment essentially consists of injecting a fluid of known viscosity and density into a packed-off interval of a bore hole at a known rate and observing the fluid pressure build-up and decline in the well as the fracture initiates and propagates. It is usual to vary the flow rate with time, as well as to shut in and bleed off the fluid between successive cycles of pressurization and propagation.

For purposes of simulation, the process can be briefly conceptualized as follows. Initially, before the initiation of the fracture, the fluid pressure builds up resulting in an increase of stored potential energy in the compressed fluid. Part of this energy is expended in dilating the plumbing system, compressing the packers, and dilating the borehole cavity. Eventually, as the pressure and the potential energy in the fluid occupying the fracture exceed the least principal stress and rock toughness, a fracture will be initiated and begin to propagate in a plane normal to the least principal stress. Depending on the rate of fluid invasion into the fracture being formed, the observed pressure in the well will rapidly drop (break down pressure) soon after fracture initiation. The actual correlation between the recorded injection rates and fluid pressure transients will depend on the geometry and the volume of the fracture, the aperture and stiffness of the fracture, the least principal stress, rock toughness, permeability of the unfractured rock, and fluid viscosity.

For any volume element in the system, we may write the equation of conservation of mass as follows:

$$G + \int_{\Gamma} \frac{k\rho g}{\mu} \nabla(z+\psi).\vec{n}d\Gamma = V_s\gamma_w(e\beta_w + a_v)\frac{\partial\psi}{\partial t} \quad [1]$$

The volume element could be made up of the fracture, the rock matrix, the borehole cavity, or the tube conveying the injected fluid. For a fracture element, the absolute permeability is treated as a function of the aperture according to the relation, $k = (2b)^2/12$, and the fracture compressibility coefficient, a_v, is defined to be equal to the rate of change of aperture with change in effective stress. For the bore-hole cavity or for the injection pipes, a_v is related to their compliance. While (1) has been numerically programmed to handle fixed geometries (Narasimhan et al, 1978), the model had to be extended to handle time-dependent changes in the geometry of a hydraulic fracture. This was achieved by Palen (1980) who modified the model to include the growth of a penny-shaped fracture in discrete jumps, in addition to handling the leakage of fluid from the growing fracture into the unfractured rock.

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The discrete extension of the propagating fracture and the creation of a new fracture element during the computational procedure deserves mention. In our model, we require two criteria to be satisfied before creating new fracture surface. The first is that the fluid pressure in the vicinity of the fracture tip must be equal to or in excess of the least principal stress, $\sigma_{H,min}$. The second is that the excess potential energy in the fluid (defined as the total energy supplied by the injection pump less that expended in dilating the plumbing, used in keeping the fracture open by working against the least principal stress, and lost into the host rock with the leaking fluid) is larger than the product of rock toughness and the area of the new fracture surface created. Within the computational model, no assumption is made in regard to the pattern of pressure profile within the fracture.

Non-linear parameters, such as k, and other time-dependent quantities, such as injection rate, are handled within the model in a quasi-linear fashion. The implicit set of equations were solved by a direct solution technique. Details of the algorithms can be found in Narasimhan et al (1978) and Palen (1980).

Application to the Monticello Experiment

As part of their earthquake research program, the U.S. Geological Survey has made in-situ tectonic stress measurements at Monticello, South Carolina using the hydraulic fracturing technique. The data collected from one particular borehole (Monticello No. 2) was provided to us by Mark Zoback of the USGS for purposes of numerical analysis. The details of the experiment are summarized in Table 1.

TABLE 1.

Details of the Hydraulic Fracturing Experiment, Monticello, South Carolina

Host Rock	Granite
Tectonic Set-up	Compressional
Depth to Fracturing	~ 310 m.
Packed-off Interval	~ 3 m.
Pattern of Injection	Consecutive injection cycles separated by shut-in and bleed-off periods. Total duration ~ 1500 secs.
Rate of Injection	Variable; of the order of $1.6 \times 10^{-3} m^3/sec$, maximum
Nature of Fluid	Oil-water mixture $\rho = 930\ kg/m^3$ $\mu = 2.35 \times 10^{-3} kg/m.sec$

The variation of flow rate as well as the well-head pressure changes during the first of the three cycles is given in Figure 1. The pressure history observed over all the three cycles is shown as a solid line in Figure 3. The corresponding flow rates, however, have not been presented.

The various system parameters that had to be varied in order to match the pressure history are shown in Table 2. The results of the parametric studies are discussed below.

TABLE 2

Monticello Hydraulic Fracturing Experiment: Parameters Considered in Simulation

1. Geometry
   Penny-shaped, vertical, propagating fracture.
2. Compliance of well-bore cavity and plumbing
3. Fracture initiation pressure
4. Initial fracture aperture, e_o
5. Fracture Compressibility (stiffness), a_v
6. Least horizontal principal stress, $\sigma_{H,min}$
7. Rock toughness, γ
8. Permeability of host rock, k

In this hydraulic fracturing experiment, the bulk of the fluid storing potential energy resides in the wellbore-plumbing system and the system acts as an energy "capacitor". The first step in the study was therefore to evaluate the characteristics of this capacitor, in particular, the compliance of the system. Towards this end, the first injection cycle was simulated and the results are shown in Figure 2 along with the system parameters used. The well-bore compliance estimated from this simulation was used as a constant quantity in subsequent simulations.

The next step was to simulate the entire history of the experiment, including the shut-in and bleed-off periods. The best-fitting parameters resulting from this effort and the corresponding history-match are shown in Figure 3. Note that match is reasonably good during the first two cycles but is poor for the third cycle, the computed pressures being higher than the observed pressures. It is not quite clear whether this poor fit is due to the fracture intercepting a natural fracture system, due to the fracture changing in aspect (vertical to horizontal), or due to leakage around the packers. Comparison of Figure 2 and 3 show that some of the parameters had to be changed significantly in the longer simulation for best match. For example, the initial fracture aperture (e_o) and rock toughness were decreased by 78 percent and 60 percent respectively. This change does not appear to be entirely computational. In addition, a small amount of leakage into the host rock had also to be considered in the longer simulations by assigning $k = 10^{-17} m^2$ [20 microdarcies (μd)] to the intact rock. Finally, in all the simulations we used the best-fitting estimate, $\sigma_{H,min} = 0.78\sigma_v$, where σ_v is the lithostatic stress at the depth of the fracture. Later it was learned from Zoback (personal communication) that he had independently arrived at an at an estimate of $0.8\sigma_v$ for the least principal stress.

Although one cannot claim that the best-fitting parameters represent a unique set for the observed experiment, judgment and experience attest to their physical realism. Indeed, our sensitivity analysis presented below reinforce our confidence in the credibility of the best-fitting estimates to characterize the field system.

The purpose of the sensitivity analysis was to gain an insight into the relative influence of the various parameters on the system behavior. We performed sensitivity analysis by varying one parameter at a time while keeping the rest fixed. The following parameters were varied: e_o, initial fracture aperture (Figure 4); a_v, fracture stiffness (Figure 5); $\sigma_{H,min}$, least principal stress (Figure 6); γ, rock toughness (Figure 7) ; and k, host rock permeability (Figure 8). It is obvious from a study of Figures 4 through 8 that the pressure transient response of the system is quite sensitive to e_o, a_v, $\sigma_{H,min}$, γ, and k.

As a result, it is possible to estimate a set of these parameters within a narrow range of values, if some prior knowledge in available about the approximate magnitude of these parameters. It may be that the range within which these parameters are estimated by the numerical simulation is well within the statistical range of these parameters as measured in the laboratory.

Concluding Remarks

Pressure responses associated with hydraulic fracturing experiments occur rapidly over a period of seconds. To gather early time data and to minimize extraneous effects, it may be advisable to make pressure measurements within the wellbore cavity using automatic pressure transducers. Since the well-bore itself acts as a capacitor, it may be possible to control fracture propagation by not only controlling the volume of the wellbore annulus where fluid is stored, but also carefully controlling the rate of fluid injection.

Notation

a_v	Coefficient of compressibility; rate of change of void ratio with stress	LT^2/M
b	One-half of fracture aperture	L
e, e_o	Void ratio and reference void ratio	
g	Acceleration due to gravity	L/T^2
G	Rate of fluid generation from a volume element	L^3/T
k	Intrinsic permeability	L^2
z	Elevation above datum	L
β_w	Compressibility of water	LT^2/M
γ	Toughness of rock	LT^2/M
γ_w	Unit weight of water	M/L^2T^2
Γ	Surface bounding volume element	L^2
μ	Fluid viscosity	M/LT
ρ	Fluid density	M/L^2
$\sigma_{H,min}$, σv	Least principal stress and lithostatic stress	M/LT^2
ψ	Pressure head	L

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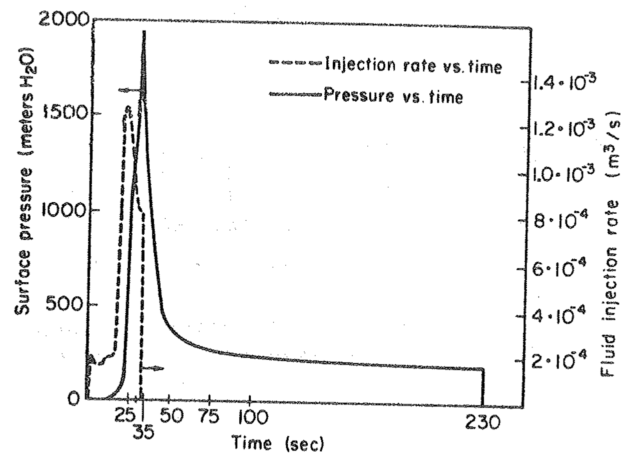

Figure 1. Monticello hydraulic fracture experiment. Flow rate and pressure head changes during first cycle of fracturing. XBL 807-3481

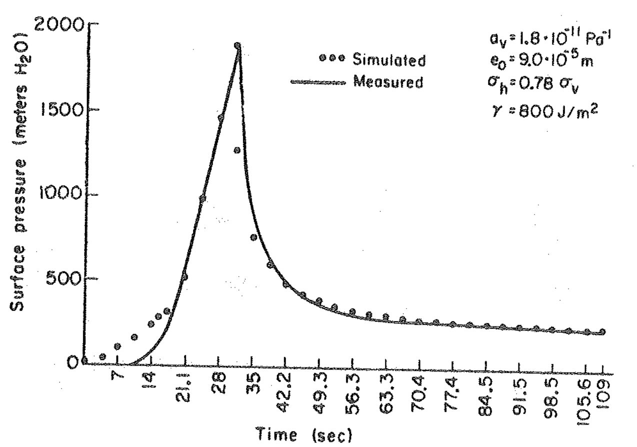

Figure 2. Calibration of well-bore compliance and simulation of the first injection cycle. XBL 807-3479

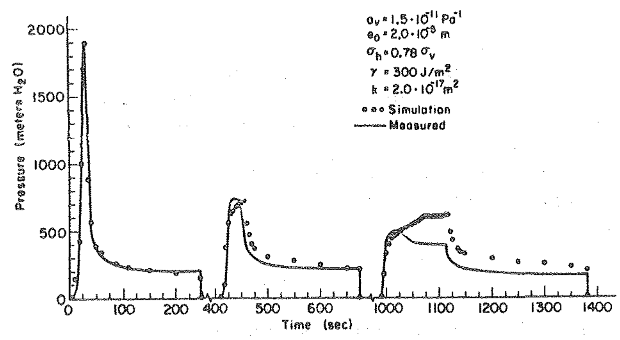

Figure 3. Best-fitting parameters over all the three cycles.

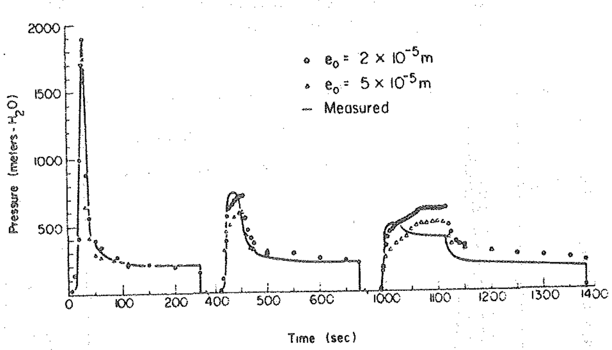

Figure 4. Influence of initial void ratio on pressure transient response. XBL 806-9933

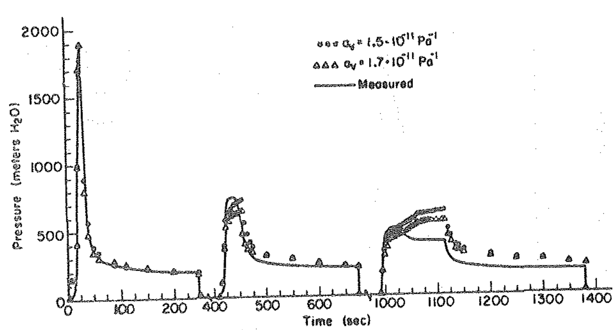

Figure 5. Influence of fracture stiffness on pressure transient response. XBL 807-3487

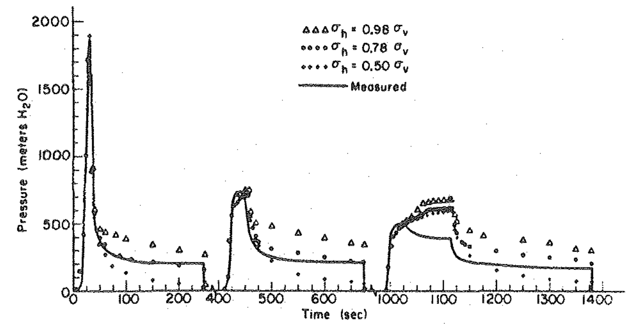

Figure 6. Influence of least prinicipal stress on pressure transient response. XBL 807-3486

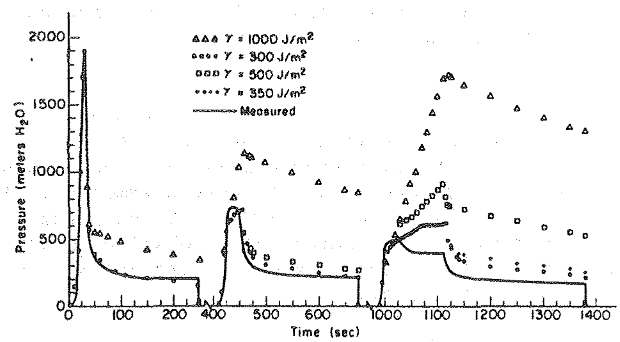

Figure 7. Influence of rock toughness on pressure transient response. XBL 807-3484

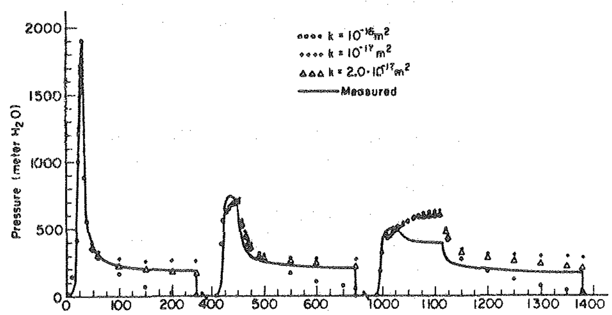

Figure 8. Influence of intact rock permeability on pressure transient response. XBL 807-3485