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January 1990

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.
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Seismic Characterization of Fracture Properties

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This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Engineering and Geosciences Division, and by the Director, Office of Civilian Radioactive Waste Management, Office of Facilities Siting and Development, Siting and Facilities Technology Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.
ABSTRACT

Laboratory measurements of the mechanical stiffness, hydraulic conductivity and seismic properties of three natural fractures were made as a function of applied normal stress. Seismic measurements were made under both dry and saturated conditions. Results showed that an empirical and theoretical correlation exists between seismic properties of a fracture, its hydraulic conductivity and mechanical stiffness, both the hydraulic and seismic properties could be ranked according to the mechanical stiffness of the fractures. By treating a fracture as a displacement discontinuity, quantitative relationships are developed between the mechanical stiffness of a single fracture and the seismic impedance of the intact rock, and the group time delay and amplitudes of the reflected and transmitted waves. For saturated conditions, additional relationships are developed between the group time delay and amplitudes of shear waves and the specific viscosity of a fracture. Good agreement was observed between theoretical predictions and laboratory seismic measurements. Finally, theory and experimental results are presented to show the applicability of the displacement discontinuity theory to wave propagation in rock containing multiple parallel fractures.

INTRODUCTION

A critical component of site characterization and performance assessment involves the demonstration that any fluid flow which might reach the accessible environment is within acceptable limits. Various methods of analyzing flow in fractured rocks have been proposed, but choice of an appropriate method and its application to a specific site probably requires some knowledge of the spacing and length (or density) of fractures, their orientation and their hydraulic conductivity. Some of this information will undoubtedly come from geologic mapping on surface and in excavations, as well as from boreholes, cores and laboratory tests. However, it will be necessary to detect and characterize fractures in the rock mass between these direct observations. The remote detection and characterization of fractures by geophysical methods is, therefore, of considerable interest in connection with geologic repositories.

The purpose of this paper is to show that there is a relationship, both empirical and theoretical, between the measured seismic response, the mechanical stiffness (also referred to as specific stiffness) of fractures and their hydraulic conductivity. Laboratory measurements of the mechanical stiffness, hydraulic conductivity and seismic properties of natural fractures are summarized. A theoretical model for the amplitude and group time delay for compressional and shear waves transmitted across a single fracture is presented. Predictions based on this model are compared with laboratory measurements. Finally, the results for a single fracture are extended to multiple parallel fractures.

EXPERIMENTAL PROCEDURES

Mechanical, hydrologic and seismic tests were performed on three samples (referred to as E30, E32 and E35) of quartz monzonite measuring 52 mm in diameter by 77 mm in height. Each sample contained a single natural fracture orthogonal to the long axis of the core. Apparatus for the experiments is illustrated schematically in Figure 1. Fracture displacement (or closure) measurements were made using Linear Variable Differential Transformers (LVDT's) such that deformations within the fracture were isolated from deformation of the intact rock. Measurements were made at axial stresses up to 85 MPa.

The quadrant flow technique was used to measure the hydraulic conductivities of each of the fractures. In this technique the fracture was assembled and its intersection with the circumference of the specimen was sealed along two diametrically opposed quadrants. Fluid flow then occurred between inlet and outlet ports attached to the two remaining quadrants. A pressure difference of 0.4 MPa was applied and flow measurements were made as the axial stress was increased in steps to a maximum of effective stress of 85 MPa.
Seismic measurements were performed on the specimens using the pulse transmission method. The specimens were uniaxially compressed between transducers containing compressional (P-) and shear (S-) wave piezoelectric elements having a resonant frequency of about 1 MHz. Waveforms were collected for eight axial stress levels from 1.4 MPa to 85 MPa under dry and saturated conditions. Reference signals were obtained under the same conditions for three intact specimens cut from the same core in close proximity to the fractured specimens.

RESULTS OF MECHANICAL, HYDROLOGIC AND SEISMIC MEASUREMENTS

Results of the displacement measurements on the three fractured specimens are shown in Figure 2. Frac-
by smooth parallel plates. At high stresses it is seen that flow approaches a constant value (for E30 and E32) while the fractures continued to close. The changes in flow rate with fracture closure (increasing stress) are also related to the changes in void geometry in the fracture. It has been shown\textsuperscript{6,7} that flow through a fracture is dominated by the restrictions which exist along the connected pathways. The geometry of these flow paths is related to the spatial correlation of the apertures of the void spaces and adjacent areas of contact.\textsuperscript{8,9} At high stresses the results from E30 and E32 imply that the principal impediment to fluid flow must be comprised of tubes or orifices with equidi­mensional cross-sections that do not diminish significantly with increasing stress.

Because of the dependence of both fluid flow and mechanical displacement (closure) on void geometry in a fracture, it seems reasonable to expect a correlation between the stiffness of a fracture and its hydraulic conductivity. A rank correlation was observed in that E32 with the highest specific stiffness had the lowest hydraulic conductivity while E35, with the lowest stiffness, had the highest hydraulic conductivity.

Typical results of the seismic measurements are presented in Figure 4, which shows amplitude spectra of P-wave pulses for intact and fractured specimens at selected stress levels under dry conditions. The spectra were calculated by performing a Fast Fournier Transform on signals which had been tapered to isolate the initial pulse from subsequent reflections.

As seen in Figure 4 increasing stress resulted in increasing spectral amplitudes for both fractured and intact specimens. However, there are important differences between the spectra for the intact and fractured specimens which reflect the effect of the fractures on the transmitted wave. At low stresses, the spectral amplitudes for the fractured specimens were smaller and peaked at a lower frequency than those for the intact specimens at the same stress level. In addition, as stress...
increased, the difference between the spectra of the intact and fractured specimens diminished; at 85 MPa for specimens E30 and E32, spectra for the fractured specimens were almost identical to those for the intact specimens.

The differences between results for the fractured and intact specimens are due to the specific stiffness of the fractures. If the specific stiffness of a fracture is very high, which can be the case under high normal stress, the fracture deforms very little in response to the dynamic stress of a propagating wave and therefore the wave is barely affected by the presence of the fracture. Thus, as was seen for specimens E30 and E32, the spectra for intact and fractured specimens were similar at high stress levels. At low stress levels, the specific stiffness of a fracture is lower resulting in appreciable deformation in response to the dynamic stresses. The consequence of this deformation is the reduction in amplitude and shift in frequency seen for the fractured specimens at low stress levels. A theory which quantitatively relates the specific stiffness of a fracture to the amplitude and group time delay of a propagating plane wave is outlined in the next section.

Just as the mechanical displacement measurements show the difference in specific stiffness of the three fractures, so do the seismic measurements. As a result of the high specific stiffness of fracture E32, the fractured specimen transmitted energy almost as well as the intact specimen at a stress of 20 MPa. In comparison, a stress of 85 MPa was required on fracture E30 before the specific stiffness was increased sufficiently to erase the effect of the fracture on the transmitted wave. The least stiff fracture E35 still affected the transmitted wave even at 85 MPa.

Comparison of the seismic and fluid flow results on these three specimens shows there is also a rank correlation between the hydraulic conductivity of fractures and their affect on seismic wave propagation; that is, the fracture which caused the greatest apparent attenuation of the transmitted seismic wave also had the highest hydraulic conductivity while the fracture with the lowest conductivity affected the transmitted wave least. Apparently the reason for this correlation is that the apparent attenuation of the transmitted wave is related to the specific stiffness of the fracture and both specific stiffness and hydraulic conductivity are dependent upon the geometry of the fracture voids.

The laboratory seismic measurements also revealed a correlation between the amplitude of the wave transmitted across a fracture and its saturation. The results indicated that amplitudes of the transmitted P-wave will, in general, be higher under saturated conditions than under dry conditions. The reason is again related to the specific stiffness of the fracture under saturated and dry conditions. As a P-wave propagates across a saturated fracture the dynamic load will be distributed between the water in the voids and the solid asperities of contact. Thus, compared to dry conditions, the deformation of the fracture would be less, leading to a higher specific stiffness and less apparent attenuation of the P-wave. The degree to which a saturated fracture will be stiffened depends on the area and aperture of the voids. These experiments have addressed only the two extreme conditions, completely dry and completely saturated. Under partially saturated conditions it is expected that, in addition to fracture stiffness, loss mechanisms, such as pumping, would affect the amplitude of the transmitted wave.

Finally, the laboratory measurements revealed that, for all three fractures, at low to intermediate stress, more S-wave energy was transmitted under saturated than dry conditions. Because of the negligible shear stiffness of water these results can not be explained by changes in the specific stiffness of the fracture. We hypothesize, as will be explained in more detail below, that the increase in shear wave transmission is caused by viscous coupling between the two fracture surfaces.

SUMMARY OF SEISMIC THEORY

The fracture displacement experimentally measured on the three fractures represented, on average, the deformation which occurred in the specimen in excess of that which occurred in the intact rock. Since it was localized in the plane of the fracture, it can be shown that the fracture displacement constitutes a discontinuity in the displacement field produced in the specimen by the applied stresses.

To analytically predict the seismic response of a single fracture under dry conditions it is modelled mathematically as a displacement discontinuity, the magnitude of which is inversely proportional to the specific stiffnesses of the fracture. The general solution of the wave equation for arbitrary angles of incidence and materials of different seismic impedance above and below the fracture has been given by others.\(^\text{10,11}\)

For seismic waves normal to a fracture in an elastic isotropic medium, the magnitudes of the reflection coefficient (R(\(\omega\))) and transmission coefficient (T(\(\omega\))) are given by:

\[
|R(\omega)| = \left[\frac{\omega^2}{4(\kappa/z)^2 + \omega^2}\right]^{1/2} ; |T(\omega)| = \left[\frac{4(\kappa/z)^2}{4(\kappa/z)^2 + \omega^2}\right]^{1/2} \tag{1}
\]

where

\[
\omega = \text{circular frequency}
\]
\[
z = \rho_c \text{ for P-waves or } \rho_s \text{ for shear waves}
\]
\[
c_p = \sqrt{\lambda + 2\mu/\rho}
\]
\[
c_s = \sqrt{\mu/\rho}
\]
\[
\lambda = \text{Lame's constant}
\]
\( \mu = \) shear modulus  
\( \rho = \) density  
\( \kappa = \) specific normal stiffness for P-waves or specific shear stiffness for S-waves

The magnitude of both the reflection and transmission coefficients are functions of the frequency of the incident wave as well as the ratio of the specific stiffness of the fracture to the seismic impedance of the adjacent rock. For an infinite value of specific stiffness, \(|T| \to 1\), so energy is transmitted as if no fractures were present. For a zero value of specific stiffness, \(|R| \to 1\), so, in this limit, the fracture acts as a free surface.

From the phase of \( T(\omega) \) a group time delay, \( t_{gT} \), can be found, which, for the same conditions as in Eq. (1), is given by:

\[ t_{gT} = \frac{2(\kappa / z)}{4(\kappa / z)^2 + \omega^2}, \]  

where subscript \( T \) refers to transmission. Thus, the theory predicts that a single fracture will slow a wave propagating across it, and the amount it is slowed will depend upon the frequency of the wave and the ratio of its specific stiffness to seismic impedance.

To model shear wave propagation across a saturated fracture, the effect of apparent viscous coupling is accounted for by introducing a velocity discontinuity in addition to a displacement discontinuity. Resulting values of \(|R(\omega)|\) and \(|T(\omega)|\) for normal incidence are:

\[ |R(\omega)| = \left[ \frac{\omega^2}{4(\kappa / z)^2 + (\omega / z)^2 (2\eta / z)^2} \right]^{1/2}, \]  

\[ |T(\omega)| = \left[ \frac{4(\kappa / z)^2 + (\omega / z)^2 (2\eta / z)^2}{4(\kappa / z)^2 + (\omega / z)^2 (2\eta / z)^2} \right]^{1/2}, \]  

where \( \eta = \) specific viscosity, i.e., the viscosity of the fluid in the fracture divided by the separation between the fracture surfaces. The corresponding group time delay is given by:

\[ t_{gT} = \frac{8\gamma^3 - 4\xi \omega^2 (2\xi + 1)}{(4\gamma^2 + \xi \omega^2 (2\xi + 1))^2 + (2\omega \eta)^2}, \]  

where \( \gamma = \kappa / z \) and \( \xi = \eta / z \).

The effect of adding viscosity to a fracture with finite stiffness is to reduce the energy transmitted at low frequencies and increase the energy transmitted at high frequencies. In the absence of stiffness, Eq. (4) shows that the group time delay for shear waves is zero at all frequencies.

An example of a quantitative comparison between theory and experimental results is shown in Figure 5a,b. To obtain the predicted spectra, the experimentally observed spectra for the companion intact rock specimen were multiplied by theoretical values of \(|T(\omega)|\) given by Eq. (1) for P-waves under dry conditions, and Eq. (2) for S-wave under saturated conditions. Values of specific stiffness and specific viscosity were determined by trial and error to give the "best fit." Good agreement is obtained between observed and predicted results. In Figure 5a the predicted curves based on values of \( \kappa \), alone, simulate both the increasing spectral amplitudes as the specific stiffness of the fracture increases with stress and...
the shift toward higher frequencies of the maximum spectral amplitudes. For the S-wave under saturated conditions (Fig. 5b) there was little shift in the frequency of the maximum spectral amplitudes as stress was increased due to the effect of viscous coupling.

EXTENSION TO MULTIPLE FRACTURES

The model for a single fracture has been extended to calculate the anisotropy in group velocities and amplitudes of seismic waves transmitted at oblique angles across multiple parallel fractures. It is assumed that multiple reflections do not contaminate the first arriving pulse and that the specific stiffness of one fracture, and hence its affect on wave propagation, is not a function of the proximity of other fractures.

The validity of the latter assumption was evaluated from measurements in which the spacing between two idealized fractures was varied. The idealized fractures were created by compressing rows of thin, parallel strips (1.0 mm wide by 0.03 mm thick) of lead between steel surfaces as shown in the insert of Figure 6. The effect of the idealized fractures on the amplitude of the transmitted P-wave (wavelength of about 23 mm) can be seen from a comparison of the amplitude spectrum of the transmitted wave with that from a solid steel specimen with a welded joint. The tests were conducted with a strip spacing (2R) of 3.0 mm. The configuration of the idealized fractures permitted direct calculation of their specific stiffness. Using Eq. (1), the spectrum from the welded joint tests, and the calculated specific stiffness, the predicted spectrum was generated assuming no interaction between fractures. As can be seen there was essentially no affect of interaction until the spacing between the fractures (2.36 mm) was on the order of the spacing between the strips. At this close spacing the deformations of the voids and asperities in one fracture were affected by the presence of voids and asperities in the other fracture.

These experiments show that as long as fractures are not so close as to interact mechanically under an imposed stress, then, to a first order, they can be treated independently in calculating their effect on the propagating wave. Under these circumstances, the magnitude of the transmission coefficient for a wave propagating across a set of parallel fractures is $|T|^N$, where $|T|$ is the value for a single fracture and N is the number of fractures.

The total group time delay under these conditions is given by the sum of the individual group time delays over the length of the travel path. The total group travel time is composed of the travel time through the intact rock between fractures plus the group time delay. For seismic waves normally incident upon a set of plane parallel fractures the effective group velocity, $V_{eff}$, is given by:

$$V_{eff} = \frac{V[1+(\omega(2Kiz))^2]}{1+(\omega(2Kiz))^2+(NVZ/2LK)}$$

where V is the intact rock group velocity and L/N is fracture spacing. These relationships, in addition to those for transmitted wave amplitudes, provide a means for using amplitude and velocity data to estimate mechanical stiffness of fractures occurring in the field.

CONCLUSIONS

Laboratory measurements of mechanical stiffness, hydraulic conductivity, and seismic amplitudes carried out on the same three natural fractures have demonstrated that a correlation exists between each of these physical properties. Fundamentally all three responses, mechanical, hydrologic and seismic, could be explained based on the spatial distribution of voids and asperities in the fractures and the changes in this distribution due to an applied stress. It was observed that the properties of all three fractures could be ranked according to their mechanical stiffness. Thus the stiffest fracture exhibited the smallest hydraulic conductivity and resulted in the least reduction of seismic amplitudes. The least stiff fracture exhibited the greatest hydraulic conductivity and greatest reduction in seismic amplitudes. The fracture of intermediate stiffness was also intermediate in hydraulic conductivity and seismic response.

By treating a fracture as a displacement discontinuity, quantitative relationships have been developed
between the group time delay and amplitudes of the reflected and transmitted waves, the mechanical stiffness of single fractures and the seismic impedance of the intact rock. For saturated conditions additional relationships have been developed between the group time delay and amplitudes of the reflected and transmitted waves, the mechanical stiffness of single fractures and the seismic impedance of the intact rock. The displacement discontinuity theory has been extended to predict an effective group velocity and amplitudes of waves propagating through multiple parallel fractures.

Based on laboratory results, the displacement discontinuity theory appears to predict the effects of fractures on the transmission of seismic waves well. The frequency-dependence of the group time delay and of the coefficients of reflection and transmission should enable the specific stiffness and specific viscosity of single fractures and multiple parallel fractures to be determined. It may be further possible to identify hydraulically conductive features and those which may be saturated.

ACKNOWLEDGMENTS

This work was supported by the DOE Assistant Secretary for Energy Research, Office of Basic Energy Sciences and by the Director, Office of Civilian Radioactive Waste Management, Office of Facilities Siting and Development, Siting and Facilities Technology Division of the U.S. Department of Energy Contract No. DE-AC03-76SF00098.

REFERENCES


