Title:

Energy Partitioning of Seismic Waves in Fractured Rocks

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Report Period: 8/93 - 8/97

Grantee:

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Award Number:

DOE Contract Number: DE-F602-93 ER14391

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Objectives

The primary objectives of the proposed research are to investigate through numerical and laboratory investigations: (1) the partitioning of seismic energy between body waves, guided waves, and scattered waves produced by sources of finite size that are transmitted, reflected, and channeled along single and multiple fractures, (2) techniques for exciting these waves, (3) the effect of spatial variations in the mechanical properties along the fracture on seismic wave propagation, and (4) the effects of a finite fracture on seismic waves.

Project Description

Rock masses contain fractures and discontinuities on all length scales that affect the mechanical stability of a rock mass and the flow of fluids through a rock mass. A goal of site characterization for waste isolation or mineral exploration is to detect and characterize the hydraulic and mechanical properties of fractures using seismic techniques. Seismic data are often difficult to interpret because of wave conversions that occur at interfaces. Converted wave modes can arise when seismic waves are propagated through a fractured rock mass and these waves inhibit direct interpretation of the received signals. Because the existence of interface waves has not previously been taken into account in seismic data interpretation, it is important to understand how non-welded interfaces, such as fractures and joints, give rise to interface waves. In this research project, the partitioning of seismic wave energy into body waves and interface waves caused by fractures (non-welded contacts) is studied through laboratory experiments and theoretical analysis.

Results

The specific results for the project period include: (1) observation and measurement of the polarization dependent precursors to failure before and during induced fracturing in rock; (2) measurement of the dispersion of interface waves to determine the stiffness of a fracture; (3) determination of the effect of shear stress on interface waves, and (4) observation and measurement of a compressional-mode interface wave that propagates along a fracture and is sensitive to fracture specific stiffness fracture. Additional information on the specific results and methods can be found in Appendix A which contains publications from this work.

(1) Polarization Dependent Precursors to Failure

Seismic propagation through rock masses approaching failure is affected by the formation of micro-cracks, and appears as a modification in the modulus of the rock. However, more specific information about the approach to failure can be obtained by using the fact that the micro-cracks predominantly orient along the plane of principal stress. We showed (Figure 1) that shear waves are especially sensitive to crack formation, when the particle motion is perpendicular to the fracture

plane, because these shear waves couple into interface waves that propagate along a fracture (Pyrak-Nolte & Cook, 1987). Long before catastrophic failure, when a macroscopic fracture is formed, and long before inelastic deformation of the rock can be measured, the energy in shear wave signals shows a dramatic frequency shift. This frequency shift is a signature of the partitioning of energy out of a bulk wave and into interface waves. Because this signature is observed prior to failure, it suggests the presence of an incipient interface wave that is supported by the network of oriented but discontinuous micro-cracks. Furthermore, because the incipient interface wave is strongly sensitive to fracture properties, this provides a sensitive technique for monitoring rock failure.

Figure 1. The change in amplitude as a function of load for frequencies of 0.21 MHz and 0.54 MHz for sample BS15 is shown. The displacement as a function of load is also shown for comparison. Initially, both the low and the high frequency energy increase with increasing load. A decrease in high frequency energy begins approximately at the same load when cracks begin to grow around 14 kN, and decreases by 65% just prior to failure. However, the low frequency energy component gains strength with increasing load and increases in amplitude by 120% between the initiation of crack growth and failure. As cracks grow along the plane of failure, the stiffness of this plane decreases which leads to the inception of interface waves. The growth of cracks is also indicated by a change in group velocity (not shown) of the energy traveling at these two frequencies. As the sample deforms, the low and high frequency components of the energy are both delayed.

(2) The Dispersion of Interface Waves

It has previously been demonstrated that seismic modes can propagate along macroscopic fractures in homogeneous solid media [Pyrak-Nolte and Cook, 1987; Nagy, 1991; Pyrak-Nolte et

al., 1992]. These interface waves may be regarded as propagating eigenmodes of generated by the interaction of Rayleigh waves at the surfaces of two half-spaces, coupled by the specific stiffness of the fracture. The displacement-discontinuity boundary condition [Kendall and Tabor, 1971; Schoenberg, 1980; Kitsunezaki, 1983; Pyrak-Nolte et al., 1990a and b], that describes the coupling of the two half-spaces, introduces a characteristic frequency into the dynamic response of the fracture. Therefore, the originally non-dispersive Rayleigh modes become dispersive when they are coupled in the interface modes.

The velocity dispersion is obtained using wavelet analysis and is compared with theoretical values from the displacement-discontinuity theory for interface waves [Pyrak-Nolte and Cook, 1987]. The spectral content of the interface wave signals is not stationary, but exhibits increasing frequency content for later arrival times, representing negative velocity dispersion. The dispersion (Figure 2) increases from -11 m/sec/MHz to -116 m/sec/MHz as the stress on the fracture is increased from 3.5 kPa to 33 MPa. The negative velocity dispersion agrees with predictions from the displacement-discontinuity theory of the seismic response of fractures, and can be used to fit fracture stiffness. Elastic interface waves have the potential for use in seismic characterization in the field, and may be especially useful for determining the stability of fractured rock masses.

Figure 2. Measured and theoretical group velocity of interface waves as a function frequency for a range of stresses. As stress on the fracture increases the fracture specific stiffness increases. The open circles represent shear wave data from intact aluminum (i.e., contains no cracks or fractures). The shear-wave velocity from the intact sample exhibited no velocity dispersion.

(3) Effect of Shear Stress on Interface Waves

Shear fracture specific stiffness is difficult to measure using traditional static measurements in the field and in the laboratory. Seismic interface waves provide a remote technique for monitoring changes in shear fracture stiffness that occurs from changes in stress conditions. Interface waves and other guided modes [Nihei et al., 1994] have the potential for becoming a diagnostic tool for probing the physical characteristic of fractures in rock masses. A full understanding of the behavior and energy partitioning among body waves, interface waves, and guided modes in fracture rock is needed to reach this potential.

Two interface waves exist: a fast wave that depends only on the normal fracture stiffness, and a slow wave that depends only on the shear specific stiffness. For both waves, as the stiffness of the fracture increases, the velocity approaches that of the bulk shear mode, i.e., the fracture is essentially behaving as a welded contact. For very low fracture stiffness, the velocities of the fast and slow waves approach the Rayleigh velocity, i.e., the fracture behaves as two free surfaces. From this study, the slow interface wave was used to determine shear fracture stiffness of fractures subjected to both normal and shear loading.

Laboratory measurements of interface waves in several dolomite cores were made to determine the change in the shear stiffness of fractures subjected to both normal and shear stresses. Data were collected as a function of stress (0.03 MPa to 11.5 MPa) for the fractured and intact samples. The effect of shear stress on fracture stiffness was examined by orienting the fracture at an acute angle to the direction of loading. When an additional shear stress is applied to the fracture plane, the shear fracture specific stiffness increases at a faster rate than when only a normal stress is applied to the fracture. These values of fracture shear specific stiffness are consistent with static and dynamic measurements of fracture stiffness from other investigations using different measurement techniques [Bandis et al., 1983; Yoshioka & Scholz, 1989; Pyrak-Nolte et al. (1990a)]. Pyrak-Nolte et al. [1996] also observed (on other dolomite samples and oolitic limestone samples) that shear fracture stiffness increases at a faster rate with increasing shear stress than for increasing normal stress alone. For the data shown in Figure 3, the shear stress experienced by the fracture is approximately half of the normal stress, but the rate of increase in shear stiffness with normal stress is three times higher than when only normal stress is applied to the fracture. Shear fracture stiffness is therefore more sensitive to changes in shear stress than to normal stress, suggesting that shear stresses produce contacts along components of the fracture surface profiles that are orthogonal to the fracture plane.

Figure 3. The change in fracture specific stiffness with normal stress on the fracture plane when only normal stress is applied to the fracture plane (filled symbols) and when both normal and shear stresses are applied to the fracture plane (open symbols) is shown. The effect of shear stress on fracture stiffness was examined by orienting the fracture at an acute angle to the direction of loading. The angles of the fracture plane relative to the orientation of the normal load were 7.5° , 30° , and 52.5° for samples B, 6, and C, respectively. The greater the angle, the greater amount of shear stress is applied to the fracture. Shear stiffness increases faster with increasing shear stress than for increasing normal stress alone. For sample 6, the shear stress experienced by the fracture is approximately half of the normal stress, but the rate of increase in shear stiffness with normal stress is three times higher than when only a normal stress is applied to the fracture, indicating that shear fracture stiffness is very sensitive to changes in shear stress. If the increase in shear stiffness from normal stress is based on increasing contact area, then the more pronounced increase in shear stiffness from shear stress must be from a different mechanism. For instance, shear stress may be inducing increased contact along components of the fracture surface profiles that are orthogonal to the fracture plane. This brings up the issue of the description of contact area in terms of normal and shear contact area. From our data, it appears that increasing shear contact area has a stronger effect on shear stiffness than increasing normal contact area.

(4) Compressional-mode Interface Waves

In field data, it can be difficult to detect and interpret shear waves for determining the presence of fractures and joints in rocks, which may make it difficult to use interface waves for fracture characterization. The primary or first-arriving compressional (P) wave is often easier to measure in the field. However, the effect of fractures on compressional waves propagated parallel to a fracture has not been quantified and is not well understood.

A compressional-mode interface wave propagating along a fracture was observed in a fracture in limestone (Figure 4). This compressional-mode interface wave co-propagates with the bulk compressional wave, is localized to the region surrounding the fracture, and has particle motions

Figure 4. Comparison of compressional wave signals transmitted through an intact sample (solid curve) of limestone and transmitted along a fracture (dashed curve) in limestone. Both samples were subjected to a stress of 3.09 MPa. Compared to the wave form for the intact sample, the wave form the fractured sample is broader (indicating a lower frequency content) and also shows the interference between two waves around an arrival time of 17.5 microseconds.

Figure 5. Particle motion for the intact and fractured sample at a stress of 3.09 MPa. The particle motion from the intact sample is composed only of longitudinal displacements. The particle motion measured for the fractured sample indicated both longitudinal and transverse motion. The transverse motion observed from the data for the fractured sample is indicative of a compressional-mode interface wave.

containing both transverse and longitudinal displacements (Figure 5). As stress across the fracture increases, the wave energy shifts to higher frequencies and to earlier arrival times, and is accompanied by a decrease in the transverse displacement and an increase in the longitudinal displacement of the particle motion.

Summary

Advances in locating and characterizes fractures in oil and gas reservoirs, and at waste isolation sites from seismic surveys requires improved interpretation methods. Experimental and theoretical results from this work have lead to an understanding of diagnostic signatures of energy that is partitioned into body waves and guided modes by fractures. Compressional waves and shear waves (i.e., shear waves with particle motion perpendicular to the fracture plane) are sensitive to changes in shear stress on a pre-existing fracture and to the formation of a fracture in a previously intact specimen. Both types of waves exhibit a shift in frequency content and a change in the amplitude of the wave as a fracture is formed or a pre-existing fracture is closed. The dispersion characteristics of interface waves that propagate along a fracture enable quantification of fracture specific stiffness. A new compressional-mode interface wave was measured that has the potential for becoming a diagnostic tool for changes in stress in a fracture. The results of this research provide the basis for the development of seismic imaging techniques and analyses tools for locating and characterizing fractures on the field scale.

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Appendix A: Selected Publications

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