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Effects of contact area of an interface on acoustic wave transmission characteristics

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1 INTRODUCTION

Seismic methods are being used increasingly to asssist in rock mass characterization in many geotechnical engineering applications. One reason for this increased interest is that seismic methods can indicate the presence of discontinuities such as joints, bedding planes, faults, and fractures in the rock mass. Thus it is important to understand how these features affect a seismic wave propagating through a rock mass.

Seismic refraction studies (Scott et al. 1968, Crampin et al. 1980), and crosshole seismic studies (Grujic 1974, O'Donoghue et al. 1974) have demonstrated a correlation between decreases in compressional (P) and shear (S) wave velocities and increases in fracture frequency or density. In addition to velocity decreases, increases in attenuation have been observed in response to increased fracturing in crosshole seismic studies (McKenzie et al. 1982, Wong et al. 1983, Rezowalli et al. 1984) as well as in single borehole acoustic measurements (Morris et al. 1964). Besides fracture frequency, field results have also shown that other factors, such as the in-situ stress state, presence of fluid (and its pressure), and the presence of fracture infilling materials will also affect the velocity and attenuation of seismic waves in rock masses (O'Donoghue et al. 1974, Paulsson and King 1980, Aki et al. 1982). It is interesting to note that the same effects have been observed in many different rock types using different seismic methods covering a wide range of frequencies and scales of measurement. Field evidence thus indicates that velocity and attenuation effects are due to intrinsic properties of the fractures and the material in the fractures.

It is well known that fractures will lower the overall average elastic moduli of rock. Since the velocity of elastic wave propagation is directly related to the elastic moduli by the elastodynamic equations, reduced elastic moduli form the basis in most models predicting the effect of fractures on seismic wave velocities (Kuster and Toksöz 1974, Hudson 1981, White 1983).

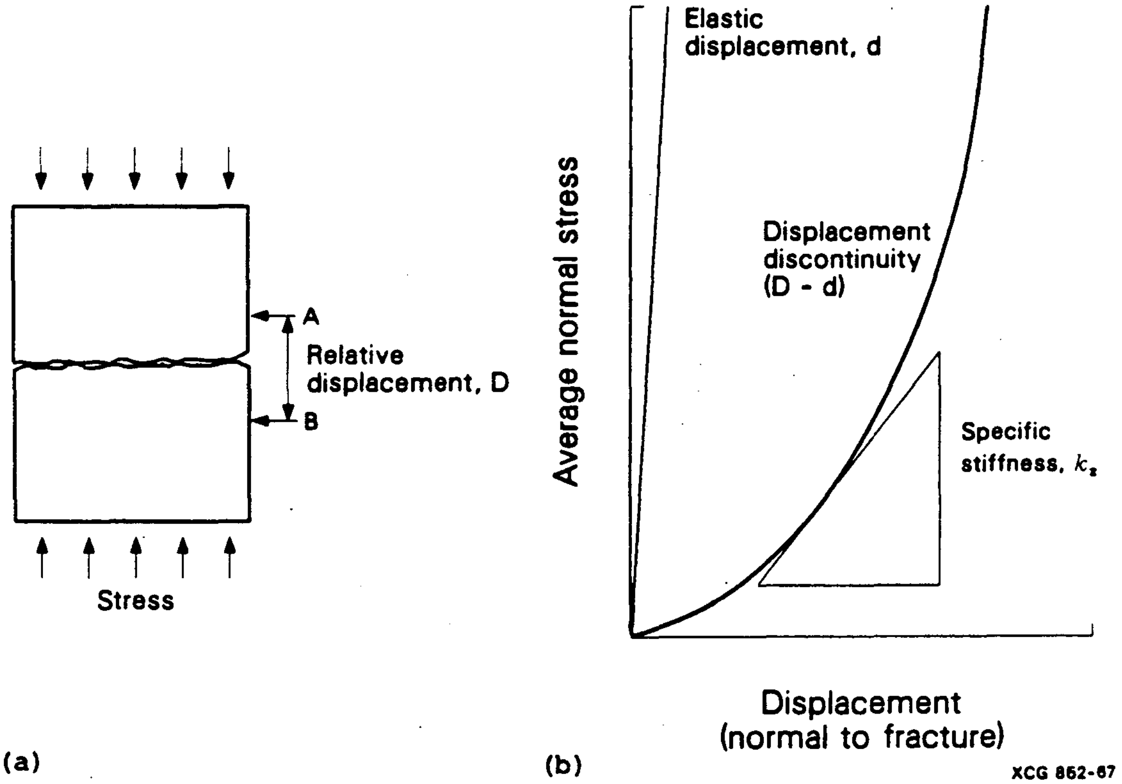
Attenuation and dispersions of waves are attributed to energy losses caused by mechanisms such as frictional sliding between areas of contact in fractures, and viscosity and flow of fluid in pores and fractures (Johnston et al. 1979, White 1983). Energy loss by these mechanisms has been accounted for in theoretical models by defining a complex material modulus (O'Connell and Budiansky 1977, Kjartansson 1979). Models predicting apparent attenuation due to scattering of seismic waves by cracks or fractures have been proposed by Yamakawa (1962) and

Hudson (1981).

This paper discusses a new model in which attenuation as well as group velocity changes are explained by a single set of assumptions. The basis of this model is that a joint or fracture represents a displacement discontinuity across which average stresses in seismic waves are continuous but displacements are not. The model is linear elastic so that all material properties are real valued. It is applicable to cases in which the fractures are large in extent but small in thickness compared to the wavelength of the seismic waves. Laboratory experiments were performed in which a single fracture was represented by an interface between two steel cylinders. Measured attenuation of compressional (P) and polarized shear (S) waves was compared with model predictions.

2 SUMMARY OF THEORY

A single fracture or joint in rock may be thought of as an interface consisting of two surfaces which are in contact over only part of their areas. An experiment could be performed in which stress is applied to a block containing a fracture as shown in Figure 1a and the displacement, D, is measured between two reference points A and B, on either side of the fracture. A portion of the displacement measured between A and B will be the elastic displacement, d, of the rock on either side of the fracture. The difference between the elastic and total displacement is the displacement discontinuity as shown by the heavy line in Figure 1b. (Though the curves in Figure 1b are hypothetical, experimental results from rock fractures (Goodman 1976) substantiate the general



(a) (b)

Figure 1. Conceptualization of experiment to determine specific stiffness of a fracture; (a) measurement of displacement across fracture, (b) specific stiffness given by slope of displacement discontinuity versus stress curve.

shape of the curve.) The tangential slope of this curve is defined as the specific normal stiffness of the interface.

The same experiment could be performed with shear stresses applied to the block, resulting in specific shear stiffnesses.

Formally, then, the specific stiffnesses, k, of a fracture are defined as:

$$\frac{1}{k_z} = \left[\frac{\partial \Delta}{\partial \sigma_z}\right]_{\sigma_z} \qquad [1]$$

$$\frac{1}{k_x} = \left[\frac{\partial \Sigma_x}{\partial \tau_x}\right]_{\tau_x} \qquad [2]$$

$$\frac{1}{k_z} = \left[\frac{\partial \Sigma_y}{\partial \tau_y}\right]_{\tau_y} \qquad [3]$$

where Δ is the average volumetric displacement discontinuity per unit area resulting from a stress normal to the plane of the interface (σ_z) and Σ_x and Σ_y are corresponding shear displacement discontinuities resulting from stresses τ_x and τ_y.

The general solution of the elastodynamic problem of plane waves obliquely incident upon an interface with prescribed stiffness has been given by Schoenberg (1980). For normally incident waves and media of the same properties on both sides of the interface, the expressions for the reflection coefficients, $R(\omega)$ and transmission coefficients, $T(\omega)$, for P-, SV-, and SH-waves are:

$$R_P(\omega) = \frac{i\omega}{i\omega + 2(k_z/Z_P)}, \quad T_P(\omega) = \frac{2(k_z/Z_P)}{2(k_z/Z_P) + i\omega} \qquad [4]$$

$$R_{SV}(\omega) = \frac{i\omega}{i\omega + 2(k_x/Z_S)}, \quad T_{SV}(\omega) = \frac{2(k_x/Z_S)}{2(k_x/Z_S) + i\omega} \qquad [5]$$

$$R_{SH}(\omega) = \frac{i\omega}{i\omega + 2(k_y/Z_S)}, \quad T_{SH}(\omega) = \frac{2(k_y/Z_S)}{2(k_y/Z_S) + i\omega} \qquad [6]$$

where:

$Z_P = \rho c_P$,

$Z_S = \rho c_S$,

$c_P = \sqrt{\lambda + 2(\mu/\rho)}$,

$c_S = \sqrt{\mu/\rho}$,

λ = Lamés constant,

μ = shear modulus, and

ρ = density.

From the phase of the transmission coefficient the group time delay, $t_g(\omega)$, is obtained as:

$$t_{gP}(\omega) = \frac{Z_P/2k_z}{1 + (\omega Z_P/2k_z)^2} \qquad [7]$$

$$t_{gSV}(\omega) = \frac{z_S/2k_x}{1 + (\omega z_S/2k_x)^2} \qquad [8]$$

$$t_{gSH}(\omega) = \frac{z_S/2k_y}{1 + (\omega z_S/2k_y)^2} \qquad [9]$$

As seen in these equations, the reflection and transmission coefficients are functions of both the frequency of the incident wave and the stiffness of the fracture. Thus, the theory predicts that the fracture will behave as a filter removing the high frequencies from the transmitted waves. If k is very large relative to z the magnitude of the transmission coefficients approach 1.0, the phase approaches 0.0 and t_g also approaches 0. For an infinite stiffness there is no discontinuity of displacements at the interface and so, if the materials on both sides of the interface are the same, energy is transmitted as if no interface were present at all. Thus, the case of infinite specific stiffness corresponds to the "welded" boundary conditions normally assumed in seismologic analysis of multilayer systems.

3 EXPERIMENTAL PROCEDURES

Experimental evidence in support of the theory was produced in a series of laboratory tests in which an interface in partial contact was created by separating two steel cylinders by thin strips of lead as shown in Figure 2. The steel cylinders measured 51 mm in diameter by 38 mm long.

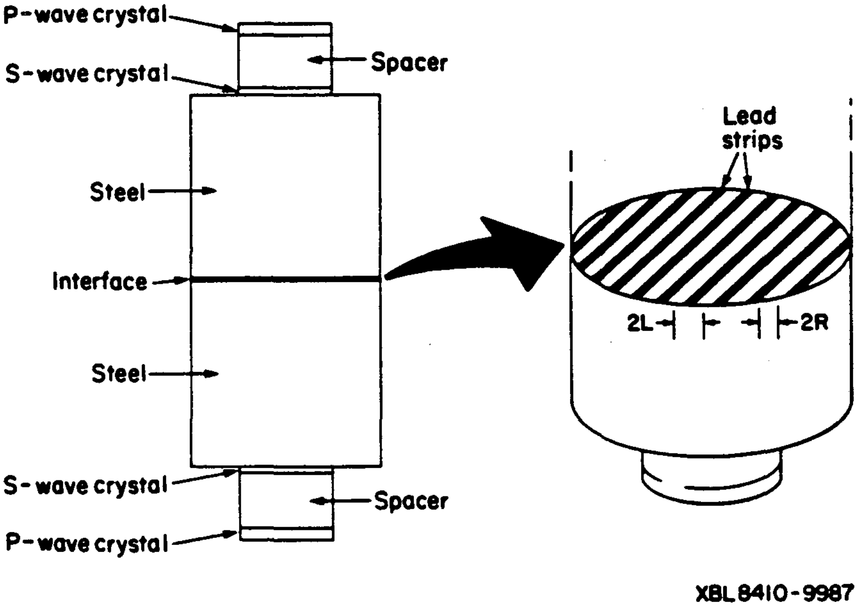


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Figure 2. Experimental sample configuration using lead strips spaced 2R apart to form interface between steel cylinders.

The lead strips were 0.03 mm thick by 1 mm wide and were placed in parallel at equal spacing on the surface of one of the cylinders. Spacing of the strips was varied according to the stiffness desired at the interface.

Elastic waves were created by 1 MHz resonant frequency P-wave and S-wave piezoelectric elements placed in a stack on one end of the sample as shwon in Figure 2. The S-wave elements were bi-polar, yielding polarized shear waves (SH waves) in the plane of the wafers. Tests were performed with the axis of polarization oriented both parallel and perpendicular to the lead strips. Identical P- and S-wave elements on the other end of the sample received the transmitted signals.

The sample-transducer stack was placed in a load frame and attached to a signal processing system for digital signal acquisition. An axial stress of approximately 15 MPa was placed on the steel cylinders and held constant during digitization of transmitted P- and S-waves.

The motivation for using lead strips in the interface was to ensure that the elastic stiffness of the interface could be calculated precisely from the geometry and elastic properties of the materials. In particular, under the applied stresses, plastic yield of the lead ensured intimate contact between the lead and the steel surfaces. Such intimate contact could not be guaranteed with hard surfaces, such as steel, for which elastic contact would produce an unknown compliance dependent upon the surface finish.

Amplitude spectra of the digitized waveforms were obtained from a Fast Fourier Transform (FFT) analysis. Before performing the FFT, a cosine taper was applied to each signal to isolate the initial pulse of P- or S-wave energy arriving at the receiving crystals.

4 RESULTS AND DISCUSSION

To provide a reference signal necessary to obtain a predicted curve, a solid lead disk with the same thickness as the lead strips was placed at the interface between the two steel cylinders. The magnitude of the transmitted wave from tests with lead strips was then predicted to be the product of the magnitude of the transmitted wave from tests with a solid lead disk and the magnitude of the transmission coefficient calculated for the interface (Myer et al. 1985).

To evaluate the theoretical expressions for the magnitude of the transmission coefficients, estimates of the specific stiffness were made for each geometric configuration of the interface. Calculated formally using equations 1-3, these estimates were based on the volumetric deformation of the lead strips and the voids between them (Myer et al. 1985).

Good agreement was found when the experimental results were compared to those predicted by the theory. Observed and predicted amplitude spectra for P-waves are shown in Figure 3. The results shown are for tests with a solid lead disk at the interface and for tests with lead strips spaced 1, 3, and 7 mm apart. The curves demonstrate the significant reduction in transmitted wave amplitude resulting from a reduction in contact area and hence, specific stiffness, of the interface. A 1 mm spacing with a stiffness of 12. x 10^7 MPa/m represented a 50% reduction in contact area at the interface compared to a solid disk and resulted in a 20% lowering of the peak Fourier amplitude of the P-wave. Reducing the stiffness to 3.2 x 10^7 MPa/m (3 mm spacing) and 1.0 x 10^7 MPa/m (7 mm spacing) resulted in peak P-wave spectral amplitudes 65% and 87% lower, respectively, than for the solid disk test. The change in shape of the curves for different strip spacings reflects a shift in the frequency

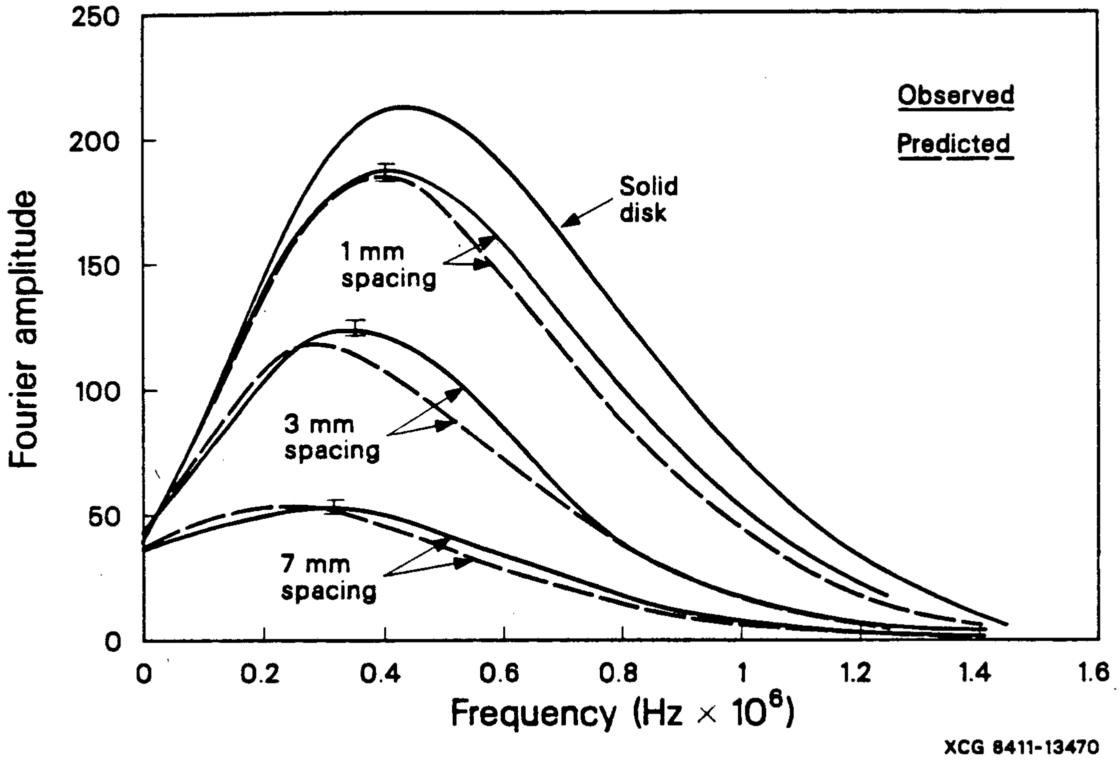

Figure 3. Observed and predicted P-wave amplitude spectra for tests with 1 mm, 3 mm, and 7 mm spacings between lead strips. Observed spectra for solid lead disk at interface shown for reference.

of the peak spectral amplitudes. The scatter in peak spectral amplitudes obtained from tests repeated with identical strip spacing is indicated by error bars on the curves.

Similar results were obtained for S-waves. For the same strip spacings, corresponding shear stiffnesses were 6.67 x 10^7 MPa/m, 2.5 x 10^7 MPa/m and 1. x 10^7 MPa/m. Peak S-wave spectral amplitudes were reduced by 12%, 42%, and 75%, respectively, as comapred to the solid disk reference signal.

The use of strips at the interface resulted in different stiffnesses in the x and y directions. Thus, theory predicted a different amplitude of the transmitted polarized shear wave depending upon whether the shear motion was parallel (SY) or perpendicular (SX) to the strips. For a 1 mm strip spacing the peak spectral amplitude for an SX-wave was predicted to be 3% greater than for an SY-wave, while for a 3 mm spacing the difference was predicted to be 9%. Figure 4 shows the experimental results for a 3 mm spacing. As can be seen in the figure the spectral amplitudes of the SY-wave were less than for the SX-wave with the difference in peak amplitudes being 11%. For a 1 mm spacing, the observed peak spectral amplitude for SY-waves was about 2.5% lower than for SX-waves.

The major discrepancy between observed and predicted results was the difference in attenuation in the high frequency portion of the spectrum as shown in Figure 3. For the majority of tests the predicted attenuation of the high frequencies was greater than observed. The most likely source of error in predictions arises from the fundamental assumption that the displacement field adjacent to the interface can be approximated by a constant (in space) average value. Complexities of deforma-

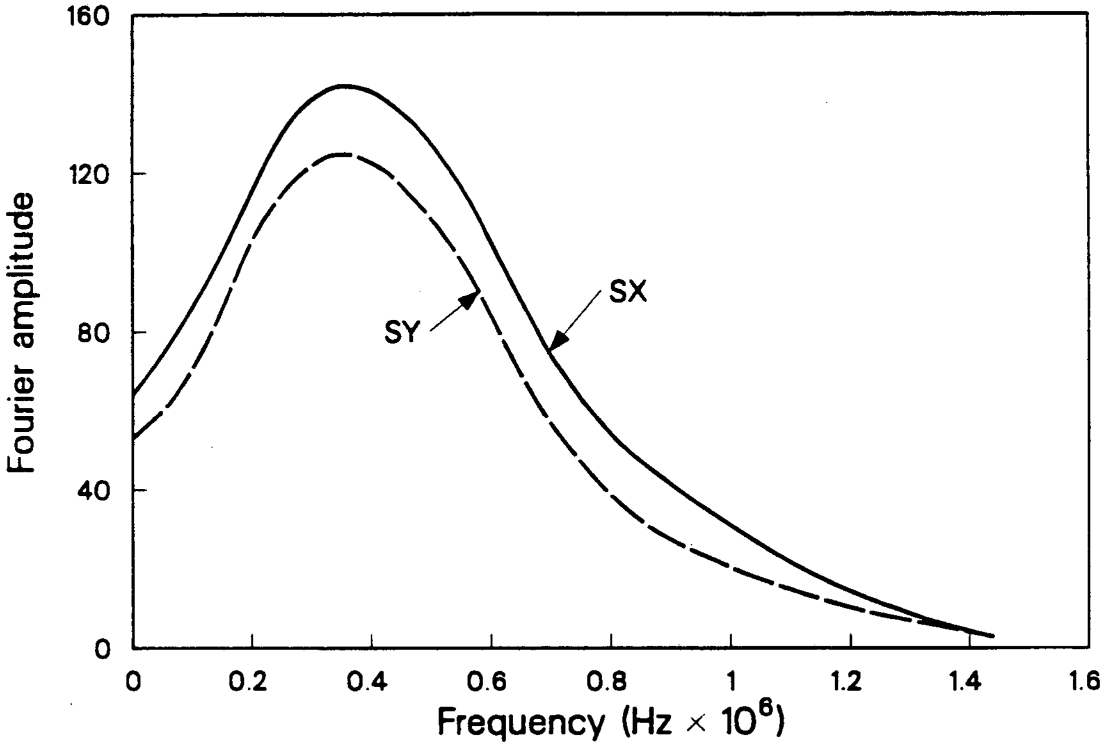

Figure 4. Comparison of observed amplitude spectra for shear waves with particle motion perpendicular (SX) and parallel (SY) to lead strips, obtained from tests with strips 3 mm apart.

tions at the interface are incorporated indirectly through the specific stiffness factor. These approximations yield predictions which correlate well with experiment in general trends, but, not surprisingly, differ in detail.

5 CONCLUSIONS

Velocity decreases and frequency dependent attenuation in field measurements have been attributed to the presence of fractures. Observation of the same type of behavior in laboratory tests indicates that an approach in which a fracture is assumed to behave as a displacement discontinuity may be fruitful in analyzing seismic measurements in fractured rock masses. Further work is, of course, required to substantiate the applicability of the approach to field situations.

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