Seismic monitoring of shear stress on fractures/faults

Aoife Toomey and Seiji Nakagawa, Lawrence Berkeley National Laboratory*

Summary

Laboratory experiments have shown that the static shear stress acting on a fracture displays a distinctive seismic signature. For plane P waves normally incident on a fracture, the application of a static shear stress results in converted, plane S waves. For incident S waves converted P waves are produced. The amplitude and polarity of these converted waves are directly related to the magnitude and direction of the static shear stress acting on the fracture. We use a numerical model to investigate the relationship between converted waves, fracture geometry and in-situ shear stress. This model can capture the response of fractured rocks to both dynamic and quasi-static stresses, allowing 'time-lapse' seismic simulations to be carried out across the fracture during changing stress conditions. Our simulations show that the anomalous scattering of seismic waves from sheared fractures is reproduced in this numerical model, making it an appropriate tool for further investigation of this phenomenon. It is hoped that this research will lead to the development of a quantitative tool for evaluating subsurface shear stress.

Introduction

Fractures play an important role in many geological processes, from fluid migration in the crust to earthquake nucleation. A fracture can be defined as two rough surfaces in partial contact. Due to the presence of void spaces between the asperities of contact on their surfaces, fractures are significantly more compliant than intact rock, as a result of which they generally control the stability of the host rock. Fractures also have a significant influence on the hydrological properties of rocks, acting either as pathways or barriers to fluid flow, depending on the nature and degree of infill between the fracture surfaces. The application of a normal load to the fracture results in increased contact area between the surfaces, leading to reduced compliance (and hence increased mechanical stability) and reduced permeability. Shear stresses acting on a fracture may play an even more important role in rock mass stability, since failure of rocks generally occurs in shear mode. Shear-induced slip can produce either dilation or compaction of the rock and can have a significant impact on the hydrological properties of the rock mass.

The mechanical, hydrological and seismic properties of fractures are thus controlled by the fracture geometry, nature and degree of infilling material, and the in-situ normal and shear stresses. A method of inverting seismic data for these properties would have many applications.

Many experimental, theoretical and numerical studies have been carried out to investigate the link between amplitudes and travel times of waves scattered by the fracture and fracture properties. Field and laboratory experiments have shown that fractures have a frequency-dependent effect on the amplitudes and travel times of waves transmitted and reflected at the fracture and that a variety of interface waves can propagate along the fracture surfaces. Converted waves are produced by waves at non-normal incidence. The displacement discontinuity model (also known as linear slip model) has been successful in relating the seismic response of a fracture to its specific compliance (Pyrak-Nolte et. al., 1990; Schoenberg, 1980), which is a function of the elastic properties of the host rock, the fracture surface roughness and the area of contact between the fracture surfaces (Brown and Scholz, 1986a).

Seismic Signature of the Static Shear Stress on a Fracture

Recent experiments have shown that fractures subjected to static shear stresses exhibit anomalous scattering of seismic waves. Nakagawa (1998, 2000) carried out ultrasonic transmission tests on a fractured granite specimen (figure 1) to investigate the effect of static shear stress applied to the fracture on its seismic response. The granite specimen was subjected to both axial and lateral load, and seismic waves were transmitted perpendicular to the fracture. During the experiment the normal stress was held constant and a range of shear stresses was applied. For plane P waves normally incident on the fracture, the application of the static shear stress was found to result in the generation of converted,

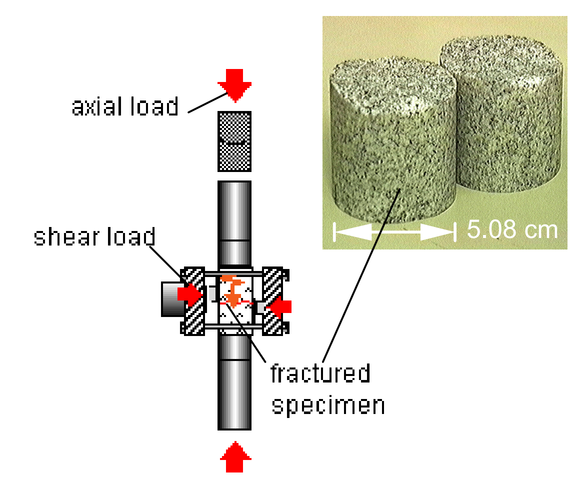

Figure 1: Experimental setup for ultrasonic transmission tests across a sheared fracture in granite.

plane S waves (figure 2). For incident S waves, converted P waves are generated. The amplitude of the converted wave increased with the magnitude of the applied static shear stress, and the particle motion of the converted waves was related to the direction of shear.

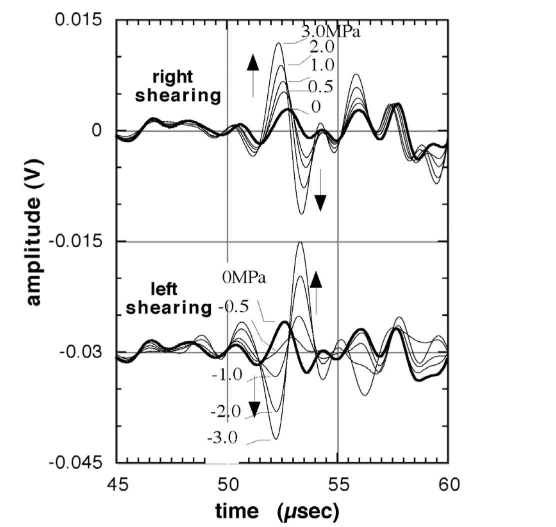

Figure 2: Changes in converted S waves for different applied static shear stresses.

The mechanism behind this shear-induced conversion can be understood by considering the distribution of compliance along the fracture surface before and after shearing. A fracture surface consists of irregularities at many scales, from below grain scale to scales comparable with the fracture dimension itself. Brown et. al. (1986b) showed that the spectral components of two surface profiles across the fracture are more correlated at longer wavelengths than at shorter wavelengths, especially for mated fractures. The compliance of a fracture decreases as the two surfaces are pushed together mainly due to increase in contact between irregularities with relatively short spatial wavelength. During shearing, the local compliance of the fracture due to contacting asperities becomes either stiffened or relaxed, depending on the relative approaching motion of the fracture surfaces. On the approaching sides of the fracture slopes the local compliance of the fracture increases due to increasing contact area between opposite sides of the fracture. This behavior is governed by the long spatial wavelength component of the fracture surface profiles that are more or less correlated across the fracture. If the applied shear stress is large, the compliance of the relaxed contacts approaches infinity, while the compliance of the approaching contacts approaches zero and the fracture effectively behaves as an array of inclined open flat microcracks.

The link between converted waves and static shear stress on a fracture raises the possibility of using converted waves as a tool for monitoring subsurface shear stress. Possible applications of such a tool include monitoring subsurface stress changes in oil and gas reservoirs, evaluating the stability of CO_2-injected reservoir rock, and monitoring the stress build-up along seismically active faults, among others. A quantitative relationship between fracture structure, in-situ shear and normal stresses, seismic frequency and amplitude of mode-converted waves must be established in order to develop such a tool. We are using a particle-based numerical model to investigate the relationships between these parameters.

Particle-Based Numerical Modeling

The Discrete Particle Scheme (DPS) is similar to the discrete element method and can be used to simulate both quasi-static and dynamic deformation of heterogeneous, fractured materials. The accuracy of the model for wave propagation and rock deformation problems has been confirmed in previous work (Toomey & Bean, 2000; Toomey, 2001). The geological medium is represented by a 2D lattice of frictionless particles arranged in a hexagonal geometry. Particles interact at their contacts in accordance with Hooke's law:

$$F_{(i,j)} = K_{(i,j)} \left(r_{(i,j)} - r_{0(i,j)} \right)$$

where $F_{(i,j)}$ is the force between particles i and j, $K_{(i,j)}$ is the bond stiffness, $r_{(i,j)}$ is the distance between the particles and $r_{0(i,j)}$ is the particle equilibrium spacing. Hooke's law describes a linearly elastic medium. The particle size and bond stiffness determine the elastic properties of the model. Depending on the scale chosen by the user, particles can represent atoms, grains of sand, blocks of crustal rock etc.

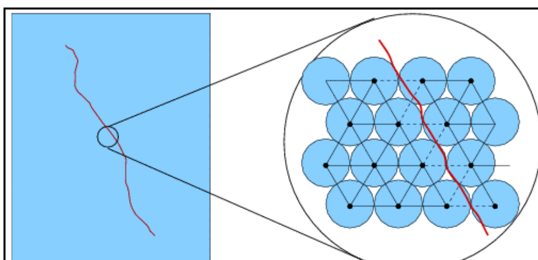

Figure 3: In particle-based schemes the geological medium is represented by a lattice of interacting particles.

Fractures can be modeled as discontinuities with greater compliance than the surrounding rock. They exhibit nonlinear deformation when stress is applied, due to the increasing contact area between the fracture surfaces, which causes the fracture to stiffen. This behavior is captured in the DPS using Hertzian contact laws (Johnson,

1985) between particles on opposing sides of the fracture. The interaction of these particles is described by the following equations:

$$F_{(i,j)} = 0. \qquad r_{(i,j)} \geq r_{0(i,j)}$$

$$F_{(i,j)} = K_{(i,j)}\,(r_{(i,j)} - r_{0(i,j)}) \qquad r_{(i,j)} < r_{0(i,j)}$$

where the bond stiffness is now a function of the contact area, a, between the particles, i.e. a function of stress:

$$K_{(i,j)} = \frac{\pi G}{(1-\nu)\,[2\ln(2\,r_{0(i,j)}/a)-1]}$$

ν and G are Poisson's ratio and the shear modulus, respectively.

Because rock discontinuities are explicitly modeled in particle-based schemes, it is easy to incorporate realistic fracture structure and geometries. An advantage is the ability of this scheme to capture fracture closure, dilation or shear with changes in the stress field. Waves can then be propagated through the model to create 'time-lapse' images of the fault or fracture.

Numerical Experiments

We investigated the seismic response of a rough fracture as a function of applied static shear stress using a model containing an idealized rough fracture (sinusoidal geometry, perfectly mated surfaces, figure 4). The model properties are listed in table 1. Low, medium and high shear stresses were applied along the top boundary of the model, which was fixed in the vertical direction. The lower boundary was also fixed, so that these experiments do not correspond exactly to simple shear. After the model reached its new equilibrium state, a plane P wave was input along the top of the model. We used a source frequency of 2.5 kHz, which gives a ratio of compressional wavelength to fracture height of about 5:1.

P wave velocity:	4.8 km/s
S wave velocity:	2.771 km/s
shear modulus:	19.96 GPa
Poisson's ratio:	.25
density:	2600 kg/m^3
source frequency:	2.5 kHz
particle diameter:	.05 m
time step:	9μsec

Table 1: Simulation parameters used in the numerical experiments.

Figure 5 shows snapshots of the horizontal component of velocity after 320 time steps, for increasing static shear stress magnitudes. A P wave at normal incidence on a rough, unsheared fracture generates a reflected and transmitted P wave, and some scattered energy. The horizontal component of displacement for this case shows some boundary reflections and scattered energy (figure 5a). By contrast, figures 5 (b), (c) and (d) show that when a shear stress is applied to the fracture, converted S waves are generated. The amplitude of the mode-converted waves is seen to increase as the shear stress is increased from 1 MPa to 10 MPa. When the direction of shear is reversed, the particle motion of the converted S waves flips (figure 5d).

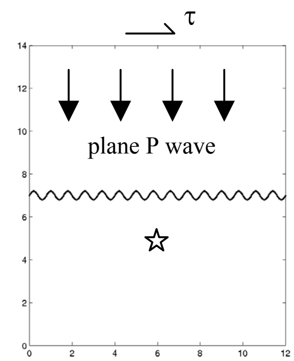

Figure 4: The numerical model used to investigate seismic response of a rough fracture as a function of applied static shear stress.

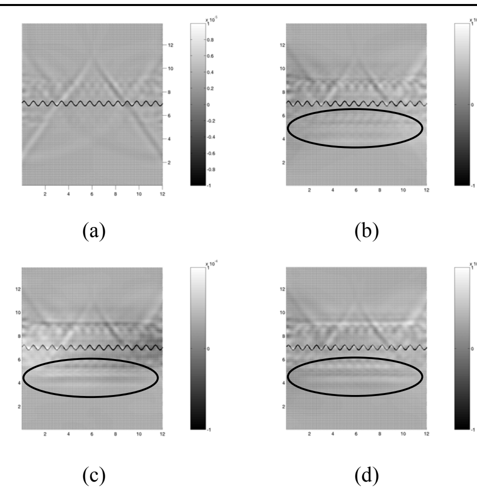

Figure 5: Snapshots of the horizontal component of displacement at time step 320, for (a) no applied shear stress, (b) 1 MPa dextral shear stress, (c) 10 MPa dextral shear stress, (d) 10 MPa sinistral shear stress. Mode-converted waves are circled.

Figure 6 shows seismograms of the horizontal component of displacement sampled at the location marked by a star in figure 4. The amplitude of the converted waves clearly increases with static shear stress and the particle motion changes its phase by 180 degrees when the direction of shear is reversed. These results compare well with those observed in laboratory experiments (figure 2).

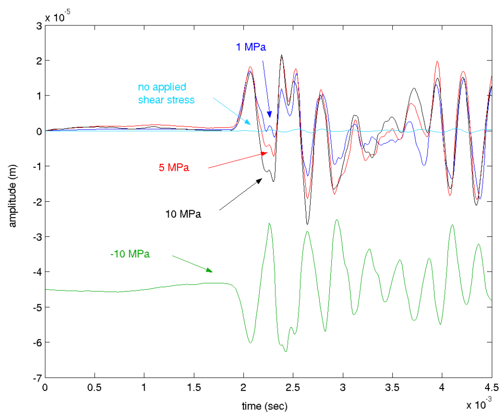

Figure 6: Converted S waves produced in the numerical model, for different applied shear stresses.

Conclusions

Using a particle-based numerical model we have reproduced results of laboratory experiments in which mode-converted waves were produced by waves normally-incident on a sheared fracture. These mode-converted waves contain information about the magnitude and direction of shear stress acting on the fracture. The amplitude and particle motion of the converted waves provide a direct link to the in-situ shear stress on the fracture.

Our numerical results were obtained using an idealized rough fracture with perfectly mated fracture surfaces. In future work we will extend this study to more realistic fracture geometries. Meaurements of fracture surface roughness have shown that fractures exhibit the properties of self-affine fractals (e.g. Schmittbuhl et. al., 1995). Correlations between the long spatial wavelength components of roughness on the fracture surfaces are expected to control the generation of mode-converted waves by sheared fractures. The DPS allows us to easily study shear-induced wave conversion as a function of fracture surface topography. We aim to establish a quantitative relationship between fracture structure, in-situ shear and normal stresses, seismic frequency and amplitude of mode-converted waves.

Possible applications of a seismic tool for monitoring shear stress include ensuring the stability of boreholes and fractured reservoirs during fluid production and injection, optimisation of fracture directions during geothermal reservoir development, and monitoring of local stress increase near an active fault as a precursor to an earthquake.

References

Brown, S. R. and Scholz, C. H., 1986a, Closure of rock joints: Journal of Geophysical Research, **91**, no. B5, 4939-4948.

Brown, S. R., Kranz, R. L. and Bonner, B. P., 1986b, Correlation between the surfaces of natural rock joints, Geophysical Research Letters, **13**, 1430-1433.

Johnson, K. L., 1985, Contact Mechanics: Cambridge University Press.

Nakagawa, S., 1998, Acoustic Resonance Characteristics of Rock and Concrete Containing Fractures: Ph.D. thesis, University of California at Berkeley.

Nakagawa, S., Nihei, K. T. and Myer, L. R., 2000, Shear induced conversion of seismic waves across single fractures: Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., **37**(1-2), 203-218.

Pyrak-Nolte, L. J., Myer, L. R. and Cook, N. G. W., 1990, Transmission of seismic waves across single natural fractures: Journal of Geophysical Research, **95**, no. B6, 8617-8638.

Schmittbuhl, J., Schmitt, F. and Scholz, C., 1995, Scaling invariance of crack surfaces: Journal of Geophysical Research, **100**, no. B4, 5953-5973.

Schoenberg, M., 1980, Elastic wave behavior across linear slip interfaces: Journal of the Acoustical Society of America, **68**, 1516-1521.

Toomey, A. and Bean, C. J., 2000, Numerical simulation of seismic waves using a discrete particle scheme: Geophysical Journal International, 141, 595-604.

Toomey, A., 2001, Particle-based numerical modeling of seismic wave propagation in fractured rock: Ph.D. thesis, University College Dublin, Irelamd.

Acknowledgements

This work has been supported by the Director, Office of Science, Office of Basic Energy Sciences, Division of Chemical Sciences, Geosciences, and Biosciences of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098