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Variation of Shear-Wave Amplitude during Frictional Sliding

W.-Y. CHEN†
C. W. LOVELL†
G. M. HALEY‡
L. J. PYRAK-NOLTE‡

The amplitudes of shear waves transmitted across interfaces between granite samples during forced frictional sliding show a distinct difference between stable sliding and stick-slip movement. When the sliding is stable, the shear-wave amplitude decreases gradually and continuously. During stick-slip movement along the interfaces, a rapid decrease in shear wave amplitude occurs before or at the sudden slip of the interfaces. The changes in shear-wave amplitude during sliding and stick-slip events reflect the changes in the specific stiffness of the fracture.

INTRODUCTION

The brittle fracture and the stick-slip behavior of rock have received general acceptance as likely mechanisms for shallow earthquakes [1, 2]. It is therefore critically important to detect slip and movement along joints and faults for earthquake prediction. In addition, the design, construction, and operation of structures in fractured rock masses will depend on knowledge of the location of joints and on the characterization of joint behavior and movement. A number of premonitory phenomena might be used to predict imminent failure and sliding along joints and faults. These phenomena include changes in permeability, electrical resistivity, rate of acoustic emission, and seismic velocities [3]. Most of these precursors are based on the premise that crack formation within the rock under shear stress alters the physical properties of the rock. Cracks opening in the rock matrix cause dilatancy, increasing permeability, conductivity, and the rate of acoustic emissions. Laboratory experiments with simulated mid-crustal stresses [3, 4, 5] however showed that the shear stress required to cause dilatancy in rock is ordinarily greater than the stress required to cause sliding along faults. Therefore, the precursors indirectly related to dilatancy may not be applicable [5]. If dilatancy is observed directly prior to failure, this may be related to deformation of a joint or fault rather than from the rock matrix.

PREVIOUS WORK

A large decrease in the ratio of compressional to shear wave velocities (v_P / v_S) in earthquake source regions has been reported to precede earthquakes [6, 7]. The common explanation for this phenomenon is usually related to the dilatancy of the rock and the formation of microcracks within the rock [8]. In addition to velocity anomalies before earthquakes, anomalies in the amplitude ratio (S to P waves: $|W_S / W_P|$) have also been observed in the source region before earthquakes [9]. A marked decrease in the amplitude ratio was observed before and immediately after the earthquake, with the ratio eventually returning to its original value. Feng [9] suggested that the rock in the source region before the earthquake may be plastic and thus may preferentially attenuate the shear waves. The decrease in the amplitude ratio may also arise from the expansion and formation of fractures inside the rock from the accumulation of stress. Chinese seismologists succeeded in predicting the 1975 Liaoning earthquake by observing a large decrease in the ratio of compressional to shear wave velocities in the source region. However, the same seismologists were unable to predict the 1976 Tangshan earthquake, which killed almost a million people [10]. In the cases cited above, the seismic sources were near earthquakes before and after the main shock. The question remains whether active seismic monitoring (man-made sources) would be sensitive to mechanisms that cause the velocity and amplitude anomalies.

In many laboratory studies, acoustic emissions from a fracture have been recorded during frictional sliding. These acoustic emissions are not precursors to slip, but are the results of slip along a fracture [11, 12]. Monitoring changes in stress or dilatancy along a fracture undergoing shear movement requires a technique that is sensitive to changes in the physical properties of the fracture (e.g., fracture specific stiffness) that may occur before the fracture slips. Through laboratory experiments, Wang et al. [5] studied the use of seismic wave velocities as a method for detecting stick-slip behavior along rock interfaces. In a direct shear experiment on Westerly granite, compressional and shear wave velocities were measured for waves (3 MHz) propagated normal to the fracture. No change in velocity was observed during the stick-slip process. Wang et al. [5] concluded that no dilatancy occurred along the joint or in the rock during frictional sliding. No other laboratory experiments have been performed that employ active seismic monitoring during the stick-slip process.

Recent theoretical developments for wave propagation across a fracture (with a specific stiffness of 10^{10} - 10^{13}

† Department of Civil Engineering, Purdue University, West Lafayette, IN 47907

‡ Department of Civil Engineering & Geological Sciences, University of Notre Dame, Notre Dame, IN 46556-0767

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Pa/m) have shown that, at laboratory frequencies (MHz), the amplitude of a seismic wave transmitted across a fracture will be more sensitive to changes in fracture properties than the velocities of transmitted waves [13, 14]. This theoretical result is based on modeling a fracture as a non-welded contact assuming a displacement discontinuity. Typical velocities and transmission coefficient curves based on equations from [13,14] are shown in Figure 1 as a function of fracture specific stiffness. The specific values used to calculate the curves in Figure 1 are based on laboratory measurements on the rock samples that were used to perform frictional sliding experiment. For a laboratory frequency of 1 MHz, the magnitude of the transmission coefficient increases significantly with increasing fracture specific stiffness, while very small changes occur in transmitted group velocity. Figure 1 also shows that at a frequency of 100 Hz, changes in the transmission coefficient occur in the range of specific stiffness of 10^6 - 10^9 Pa/m. In this paper, we present laboratory results from an investigation of seismic wave attenuation as an indicator of imminent slip along fractures.

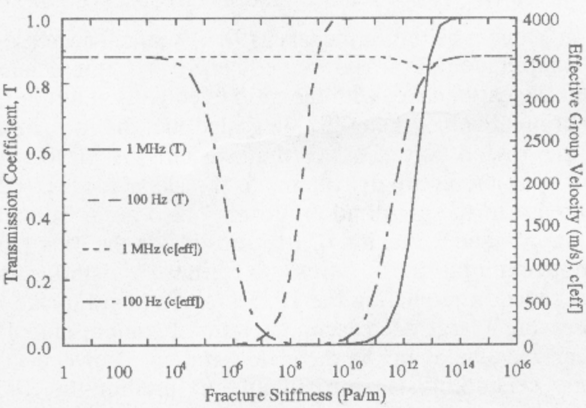

Figure 1. The magnitude of the transmission coefficient and the effective group velocity based on the measured intact phase velocity of 3533 m/s (shear-wave), and a density of 2626 kg/m^3 of laboratory samples, for frequencies of 100 Hz and 1 MHz.

EXPERIMENTAL SET-UP

Quartz monzonite (Stripa granite) samples were used to investigate the effect of frictional sliding on shear wave attenuation as the first in a series of experiments. Three cylindrical samples measuring 5.1 cm in diameter by 3.8 cm in height were coaxially aligned and placed between aluminum pistons containing piezoelectric transducers (Figure 2) in a load frame. The shear-wave velocity of the intact rock sample is 3533 m/s and the density is 2626 kg/m^3. The surface roughness profile of the interfaces that undergo sliding had a height variation of less than 300 microns, based on measurements from a laser-head profilometer. A double-shear apparatus applies a shear load to the middle block after a normal load is established. Piezoelectric transducers generate shear (S) waves that propagate along the axis of the rock stack, i.e., perpendicular to the interfaces. The natural frequency of each crystal was 1 MHz and the transmission crystal was pulsed with a 500 V spike of 0.3 μs duration at a repetition rate of 100 Hz. The shear-wave polarization was oriented parallel to the direction of shear loading.

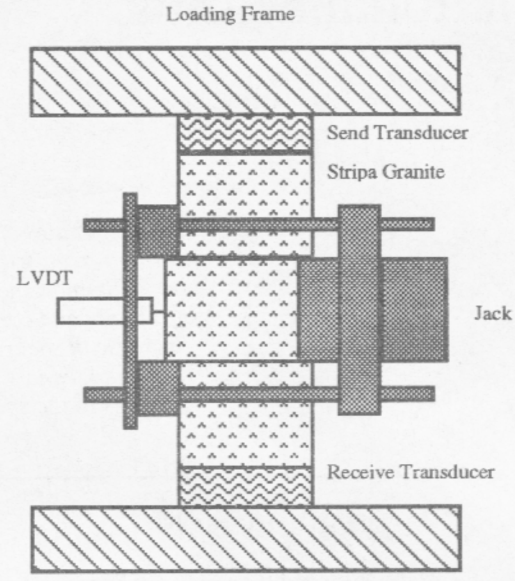

Figure 2. Sketch of the experimental set-up.

A linear variable displacement transducer (LVDT) with a resolution of 100 μm was used to measure the displacement of the middle rock. Higher resolution was not attained because of electronic noise. The normal and shear pressures on the samples were measured using electronic pressure transducers. A four-channel digital oscilloscope (LeCroy 9314) recorded the transmitted shear waveform (each waveform consists of 50 points per waveform, 0.1 μs/point), displacement, and pressures using a sample rate of 200 milliseconds, which allowed exact temporal correlation. The data were transferred to a computer that determined the peak-to-peak amplitude of the received shear waveforms. The peak-to-peak shear wave amplitude (denoted hereforth as simply the shear wave amplitude) is the difference of the magnitudes of the minimum and maximum amplitudes for the first arrival of the wave form (Figure 3). The peak-to-peak amplitude is used as a measure of the shear wave attenuation caused by sliding interfaces.

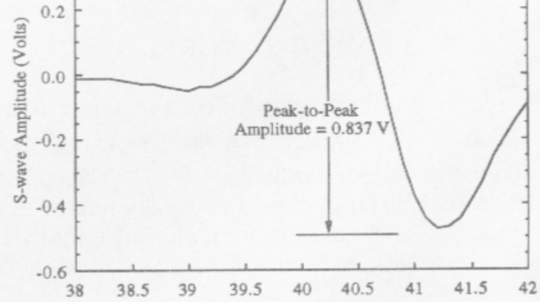

Figure 3. Example of the calculation of shear-wave peak to peak amplitude from the received waveform.

During the experiments, a constant normal load was applied to the rock column, while the center rock in the column underwent shear loading. The normal load was continuously measured during the application of the shear stress, and appeared to be constant within the electronic noise of ±11 mV (±2.13 MPa). The shear loading cycle was initiated with an increasing shear load until a slip occurs, followed by a finite amount of time during which no further load was applied. After this time, the center block was reloaded. If the middle rock slides stably (no stick-slip), the shear loading is applied continuously without interruption.

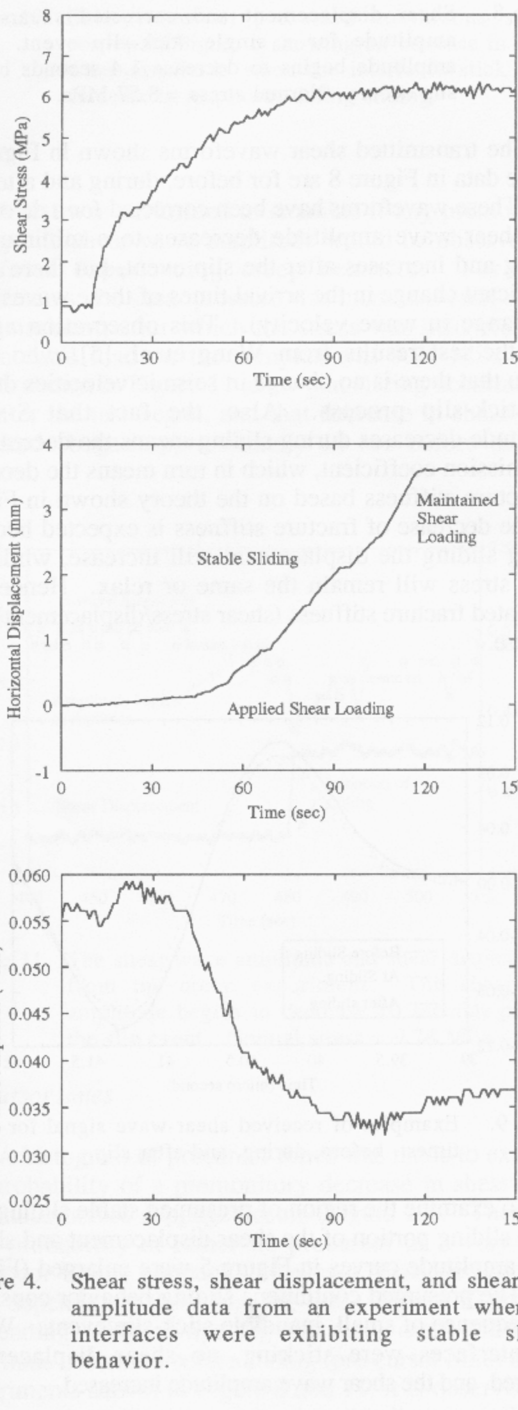

Figure 4. Shear stress, shear displacement, and shear-wave amplitude data from an experiment where the interfaces were exhibiting stable sliding behavior.

RESULTS

Three distinct movements are observed during different loading conditions: 1) stable sliding with continuous displacement; 2) stick-slip with episodic loading and displacement; and 3) creep with slow relaxation of stress.

Stable sliding & stick-slip

Stable sliding and stick-slip usually occur under low and high normal stress, respectively. From the shear-wave amplitude data, a distinct difference in shear wave attenuation was observed to occur during stable sliding as compared with stick-slip movement. Figure 4 shows the shear stress, displacement and the transmitted peak-to-peak amplitude for the condition of stable sliding for normal stress of 6.01 MPa. For stable sliding, the shear-wave amplitude decreases gradually and continuously as the middle block is displaced and as the shear stress approaches a constant value. Figure 5 shows the shear displacement and peak-to-peak shear-wave amplitude for an experiment during which stable sliding and stick-slip behaviors were observed for a normal stress of 10.22 MPa. During stick-slip (for times approximately greater than 50 seconds in Figure 5) a rapid decrease in shear wave amplitude occurs before or at the sudden slip of the middle block.

The initial conditions of the experiment shown in Figure 5 were maintained for 10 seconds to record the electronic noise of the system. The fluctuations in shear-wave amplitude are small during this 10 second period. The subsequent changes in shear-wave amplitude during the experiment are therefore caused by movement along the rock interfaces.

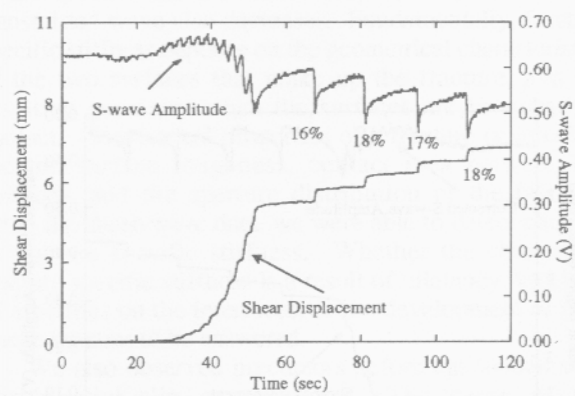

Figure 5. Shear displacement and shear-wave amplitude data from an experiment where the interfaces exhibited both continuous sliding and stick-slip behavior. The percentages represent the decrease in shear-wave amplitude prior to or during slip. Normal Stress = 10.22 MPa.

After the initial 10 seconds, shear pressure was applied manually. Between 10 seconds and 50 seconds, the shear pressure was increased and the rock appeared to be sliding; no sticking was observed visually or audibly (through acoustic emissions). During this interval, a "hump" occurred in the S-wave amplitude curve with fluctuations in the shear wave amplitude. After this period of presumed continuous sliding, stick-slip began and the shear pressure was increased. During a slip episode, the rock displaced suddenly and an audible acoustic emission occurred. This stick-slip behavior appears as a sequence of steps on the displacement curve in Figure 5. Concurrently, there is a clear indication of the stick-slip behavior in the shear-wave amplitude curve. A rapid decrease in shear-wave amplitude corresponds to every stick-slip event along the interfaces. The relative decrease in shear-wave amplitude ranges from 16% to 18%. Immediately after the slip, when no further shear load is applied, the S-wave amplitude increases. The change in system geometry, as the middle block is displaced, may reduce the amplitude for increasing displacements. In order to remove this trend, the shear-wave amplitude data in Figure 5 was normalized by the envelope shown in Figure 6. The normalized S-wave amplitude curve in Figure 7 shows that the shear-wave amplitudes after slip approach the pre-slip amplitudes.

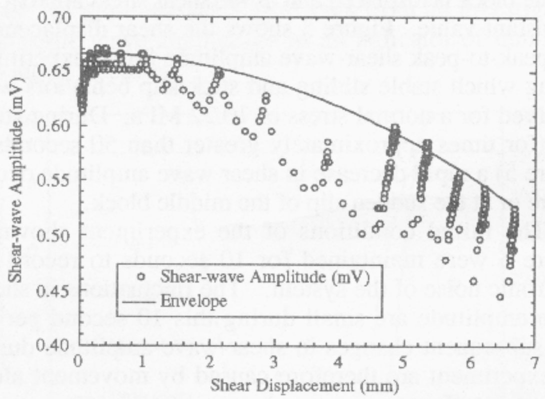

Figure 6. The envelope to the shear displacement and shear-wave amplitude curves.

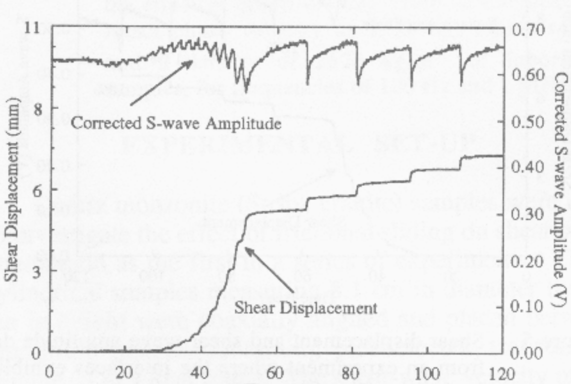

Figure 7. Shear displacement and the baseline-shifted shear-wave amplitude from the data in Figure 5.

To determine if the decrease in amplitude occurs before or after slip, shear displacements and shear-wave amplitudes were monitored at the moment of sliding (Figure 8). The precursor (the initial decrease in the shear-wave amplitude) occurs 1.4 sec before the interfaces slip. For this stick-slip event, the minimum value of shear-wave amplitude occurs during slip.

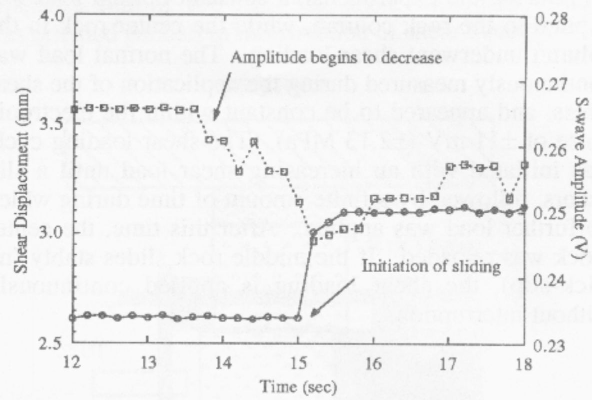

Figure 8. Shear displacement and corrected shear-wave amplitude for a single stick-slip event. The amplitude begins to decrease 1.4 seconds before slip occurs. Normal stress = 8.57 MPa.

The transmitted shear waveforms shown in Figure 9 for the data in Figure 8 are for before, during and after the slip. These waveforms have been corrected for a dc offset. The shear wave amplitude decreases to a minimum at sliding and increases after the slip event, but there is no significant change in the arrival times of these waves (i.e., no change in wave velocity). This observation agrees with the test results from Wang et al. [5], who have shown that there is no change in seismic velocities during the stick-slip process. Also, the fact that S-wave amplitude decreases during sliding means the decrease of transmission coefficient, which in turn means the decrease in fracture stiffness based on the theory shown in Figure 1. The decrease of fracture stiffness is expected because during sliding the displacement will increase, while the shear stress will remain the same or relax. Hence, the calculated fracture stiffness (shear stress/displacement) will decrease.

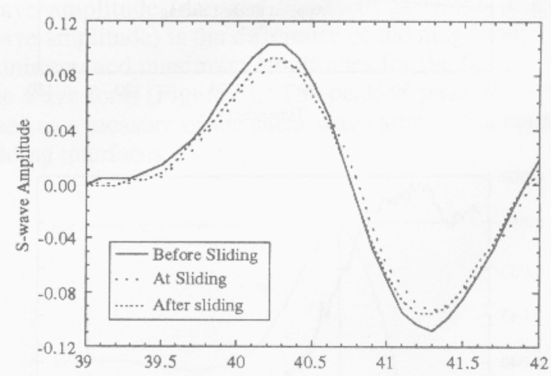

Figure 9. Examples of received shear-wave signal for three times: before, during, and after slip.

To examine the region of presumed stable sliding, the stable sliding portion of the shear displacement and shear-wave amplitude curves in Figure 5 were enlarged (Figure 10). The presumed continuous sliding behavior consisted of a sequence of small, inaudible stick-slip events. While the interfaces were sticking, no shear displacement occurred, and the shear wave amplitude increased.

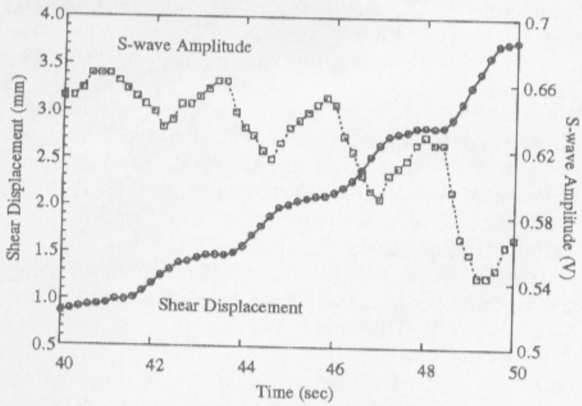

Figure 10. Enlargement of presumed continuous sliding portion of Figure 5 showing an increase in shear-wave amplitude when the interfaces stick and a decrease in amplitude during sliding.

Creep

A test was performed to examine if any premonitory changes in shear-wave amplitude would be observed for interfaces experiencing creep behavior. For these experiments, the shear pressure was increased until sliding was imminent, after which the stress was held constant. The normal load on the samples was 9.74 MPa. The results shown in Figure 11 show that sliding occurred 480 sec after the test began, and that decrease in shear-wave amplitude began approximately 10 sec before the slip occurred.

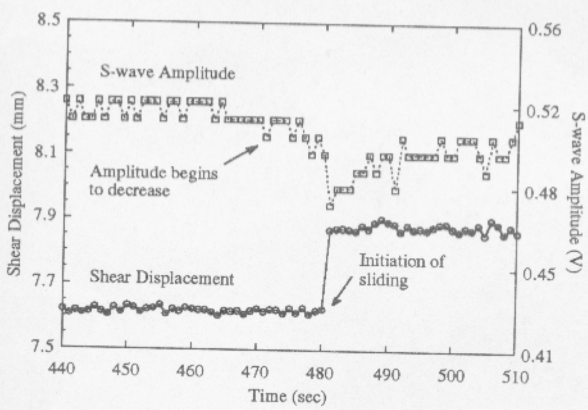

Figure 11. The shear-wave amplitude and shear displacement from the creep experiment. The shear-wave amplitude begins to decrease 10 seconds prior to the slip event. Normal stress = 9.74 MPa.

Precursor times

A histogram of precursor times was made to examine the probability of a premonitory decrease in shear-wave amplitude before slippage occurs (Figure 12). There is a high probability of either no precursor or a very short precursor before slippage. However, because precursor time depends on shear loading rate, Figure 12 may be misleading. By comparing the time over which the amplitude decreased before sliding (pre-cursor time) for the experiments shown in Figure 8 and 11, it is observed that precursor time depends on the shear loading rate. Slower loading rates produce longer precursor times. If the shear loading rate is very fast, the data acquisition rate may need to be increased from 1 point per 200 milliseconds to detect a precursor.

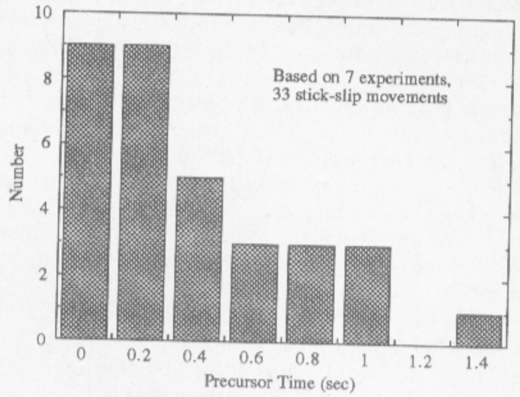

Figure 12. This histogram of pre-cursor times (length of time before slip for which the amplitude decreases) is based on 33 stick-slip events from 7 experiments.

SUMMARY

We were able to detect and differentiate between stable sliding and stick-slip behavior along interfaces in rock using active shear-wave monitoring. Continuous sliding along the interfaces is observed as a continuous decrease in the shear-wave amplitude. On the other hand, stick-slip behavior is discerned from a rapid drop in amplitude prior to or during slip, and an increase in amplitude after slip has occurred. The amplitude of a wave transmitted across a fracture depends on the specific stiffness of the fracture. If the specific stiffness decreases, the amplitude of the transmitted wave also decreases. Fundamentally, fracture specific stiffness depends on the geometrical characteristics of the two surfaces that make up the fracture, and the resulting geometry when the surfaces are brought into contact. Geometrical properties of a fracture or interface include surface roughness, contact area between the surfaces, and the aperture distribution of the fracture. From the shear-wave data, we were able to detect changes in fracture specific stiffness. Whether the changes in fracture specific stiffness is a result of dilatancy, breaking of asperities on the interfaces, or the development of fault gouge remains to be answered.

We also observed precursors before the sudden slips during stick-slip experiments. The cause of the premonitory decrease in S-wave amplitude is still not clear. Boitnott et al. report [15] that a fracture (joint) begins the first few microns of sliding at a shear stress noticeably lower than the ultimate shear strength of the joint. Therefore, this first few microns of sliding (probably at the asperity scale) may result in the change in S-wave amplitude and result in a precursor before the macroscopic sliding is observed.

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REFERENCES

1. Brace, W. F. and Byerlee, J. D., Stick-slip as a Mechanism for Earthquakes, *Science*, 153, 990-992 (1966).
2. Spetzler, H., Sobolev, G., Koltsov, A., Zang, A., and Getting, I. C., Some Properties of Unstable Slip on Rough Surfaces, *Pure & Applied Geophys.*, 137, 1/2, 95-112 (1991).
3. Byerlee, J., A Review of Rock Mechanics Studies in the United States Pertinent to Earthquake Prediction, *Pure & Applied Geophys., 116*, 586-602 (1978).
4. Hadley, K., Laboratory Investigations of Dilatancy and Motion on Fault Surface at Low Confining Pressure, Proc. Conf. on Tectonic Problems on the San Andreas Fault System, *Geol. Sciences XIII,* Standard Univ., 427-435 (1973).
5. Wang, C.-Y., Goodman, R. E., and Sundaram, P. N., Variations of V_p and V_s in Granite Premonitory to Shear Rupture and Stick-Slip Sliding: Application to Earthquake Prediction, *Geophysical Research Letters, 2,* 309-311 (1975).
6. Aggarwal, Y. P., Sykes, L. R., Armbruster, J., and Sbar, M. L., Premonitory Changes in Seismic Velocities and Prediction of Earthquakes, *Nature*, 241, 101-104 (1973).
7. Whitcomb, J. H., Garmany, J. D., Anderson, D. L., Earthquake Prediction: Variation of Seismic Velocities before the San Francisco Earthquake, Science, 180, 632-635 (1973).
8. Wang, C. Y., Earthquake Prediction and Oriented Microcracks in Rocks, *Nature*, 251, 405-406 (1974).
9. Feng, T.-Y., Anomalies of the Amplitude Ratio of S and P Waves from Nearby Earthquakes and Earthquake Prediction, *Chinese Geophysics*, 1, 1, 1-15 (1978).
10. Tazieff, H., Earthquake Prediction, P. 63 (1992).
11. Lockner, D. A. and D. E. Moore, Microcrack interaction leading to shear fracture, 33rd US Symposium on Rock Mechanics, eds. Tillerson & Wawersik, A. A. Balkema, 801 - 816, (1992).
12. Lockner, D. A., Byerlee, J, Kuksenko, V, Ponomarev, A. and A. Sidorin, A quasi-static fault growth and shear fracture energy in granite, Nature, 350, 7, 37-42 (1991).
13. Pyrak-Nolte, L. J., Cook, N. G. W., and Myer, L. R., Seismic Visibility of Fractures, *28th US Symposium on Rock Mechanics, Tucson*, 47-56 (1987a).
14. Pyrak-Nolte, L. J. and Cook, N. G. W., Elastic Interface Waves along a Fracture, *Geophysical Research Letters, 14, 11*, 1107-1110 (1987b).
15. Boitnott, G. N., Biegel, R. L., Scholz, C. H., Yoshioka, N., and Wang, W., Micromechanics of Rock Friction 2: Quantitative Modeling of Initial Friction with Contact Theory, *Journal of Geophysical Research*, 97, B6, 8965-8978 (1992).