ABSTRACT

Author: Han, Kyungsoo
Institution: Purdue University
Title: Monitoring of Saturated Rock Discontinuities under Elevated Temperatures and Water Pressures
Major Professors: Antonio Bobet and Laura J. Pyrak-Nolte

A key challenge in the assessment of the stability of fractures in rock is the identification of precursory geophysical signatures of shear failure. Accurate estimation and prediction of shear failure along rock discontinuities is crucial to prevent failure of geotechnical structures and potential natural hazards, such as landslides and earthquakes. Active seismic monitoring, such as compressional (P) and shear (S) waves, has been used to monitor the evolution of contact area and contact stress along rock discontinuities. Past laboratory experiments determined that changes in the amplitude of the transmitted, reflected, and converted P- and S-waves can be used to assess local changes in contact area and fracture specific stiffness, and to identify precursory events to shear failure of rock fractures. Those studies have identified the peaks (maxima or minima) in wave amplitudes as the seismic precursors to shear failure. Past studies were performed on dry artificial rock discontinuities with homogeneous and well-matched contact surfaces. However, in nature, rock discontinuities are not always homogeneous and well-matched, and are often found below the water table. In addition, at large depths, e.g. in enhanced geothermal systems (EGS), fractures are subjected to high temperatures.

The objectives of this research are to: (1) characterize the geophysical response of rock fractures during shear for dry and saturated conditions at room temperature, and saturated conditions at elevated temperatures; and (2) detect and identify seismic signatures of shear failure/slip for each of the three conditions. To achieve the goal of the research, a novel shear test apparatus was designed and built to test saturated jointed rock specimens under normal and shear loading, with a back pressure and at elevated temperatures, while also being capable of housing seismic transducers to monitor simultaneously the mechanical and geophysical response of the rock joints during shear. The system

consisted of a sealed and heated pressure chamber and a biaxial compression frame. The pressure chamber was also used to perform B-value tests on cylindrical rock specimens to determine the minimum magnitude of back pressure required for fluid saturation.

Laboratory direct shear tests were performed on tension-induced fractures in Indiana limestone and Sierra White granite specimens with non-homogeneous rough contact surfaces. The contact surfaces were created by axial splitting of prismatic rock blocks. Shear tests were conducted on the rock fractures at a constant displacement rate in the pressure chamber, which enabled control of effective normal stress, pore water pressure, and temperature. During the tests, transmitted and converted P- and S-waves propagated across rock fractures and their changes in wave amplitude were monitored to assess the evolution of local contact areas during shear and detect precursory changes in wave amplitudes prior to shear failure.

Seismic precursors were observed in the wave amplitude data from all tests conducted under the three conditions. Precursors were most identifiable in the transmitted S-wave data. For all three conditions, the transmitted S-wave showed the same form of a seismic precursor; a peak (maximum) in wave amplitude was observed prior to the peak shear strength, as local contact surfaces interlocked and failed before macroscopic shear failure. However, the transmitted P-wave and converted waves (P-to-S and S-to-P) exhibited different behavior compared to the transmitted S-wave and depended on the test conditions. While, for dry conditions, the transmitted P-wave and converted waves still exhibited seismic precursors as peaks in their wave amplitudes, they did not display an observable peak for saturated fractures at room temperature, but rather either a very slight increase or a continuous reduction in amplitude. Instead of observable peaks, an abrupt change in the rate of reduction in the transmitted P-wave and converted amplitudes was observed that either coincided or occurred close to the peak in the transmitted S-wave amplitude. Thus, an onset of dramatic change in the reduction rate can be also taken as a seismic precursor to shear failure. This phenomenon can be explained by the large stiffness of the highly incompressible fluid, water, which leads to a decrease in P-wave sensitivity to changes in the normal fracture stiffness that arise from rock asperities under saturated conditions.

Even though the seismic wave amplitude generally contains a seismic precursor to shear failure, some exceptions exist: the wave amplitudes also depend on the local characteristics of the frictional area. No peak or seismic precursor in wave amplitude is observed prior to failure when the contact area between the fractures surfaces decreases because of dilation/opening. In addition, a delay peak in amplitude after shear failure may be observed when the fracture surfaces contain an initial large void or aperture in the region probed by the sensor. These exceptions may occur at a relatively low effective normal stress (2 MPa) and may disappear when a better contact has been established between the fracture surfaces by increasing the effective stress. Direct shear tests under an effective stress of 6 MPa, but at 50ºC, showed that both the transmitted P-waves and converted waves exhibited peaks in their amplitudes prior to the failure. However, these exceptions still require further exploration for the systematic identification and detection of seismic precursors.

The research shows that seismic monitoring is an effective tool to monitor the shear behavior of discontinuities, to provide an assessment of the local behavior of the frictional surface under the transducer, and to predict failure of the discontinuity. It can be used for dry, saturated discontinuities and for a wide range of pore pressures and temperatures. Other potential applications include fault monitoring, and even possibly earthquake prediction with additional research.