ABSTRACT

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Title: Shear Response of Rock Discontinuities: Through the Lens of Geophysics
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Failure along rock discontinuities can result in economic losses as well as loss of life. It is essential to develop methods that monitor the response of these discontinuities subjected to shear loading to enable the prediction of failure. Laboratory experiments are performed to investigate geophysical techniques to monitor shear failure of a pre-existing discontinuity to detect signatures of impending failure. Previous studies have detected precursors to shear failure in the form of maxima of transmitted waves across a discontinuity under shear. However, those experiments focused on well-matched discontinuities. In nature, rock discontinuities are not always perfectly matched because the asperities may be weathered by chemical, physical or mechanical processes. Further, the specific shear mechanism of mismatched discontinuities is still poorly understood. In this thesis, the ability to detect seismic precursors to shear failure for various discontinuity conditions—well-matched (rough and saw-tooth), mismatched (rough), and nonplanar (discontinuity profile with a half-cycle sine wave (HCS))—was assessed. The investigation was carried out through a coupled geophysical and mechanical experimental program that integrated detailed laboratory observations at the micro- and meso-scales. Shear experiments on gypsum discontinuities were conducted to observe changes in compressional (P) and shear (S) waves transmitted across the discontinuity. Digital Image Correlation (DIC) was used to quantify the vertical and horizontal displacements along the discontinuity during shearing to relate the location and magnitude of slip with the measured wave amplitudes.

Results from the experiments conducted on planar, well-matched rough discontinuities (grit 36 sandpaper roughness) showed that seismic precursors to failure took the form of peaks in the normalized transmitted amplitude prior to the peak shear stress. Seismic wave transmission detected non-uniform dilation and closure of the discontinuity at a normal stress of 1 MPa. The results showed that large-scale roughness (presence of a HCS) could mask the generation of

precursors, as it can cause non-uniform closure/dilation along the fracture plane at low normal stress.

The experiments on idealized saw-toothed gypsum discontinuities showed that seismic precursors to failure appeared as maxima in the transmitted wave amplitude and conversely as minima in the reflected amplitudes. Converted waves (S to P & P to S) were also detected, and their amplitudes reached a maximum prior to shear failure. DIC results showed that slip occurred first at the top of the specimen, where the load was applied, and then progressed along the joint as the shear stress increased. This process was consistent with the order of emergence of precursors, i.e., precursors were first recorded near the top and later at the center and finally at the bottom of the specimen.

Direct shear experiments conducted on specimens with a mismatched discontinuity did not show any precursors (in the transmitted amplitude) to failure at low normal stresses (2 MPa), while those precursors appeared at higher normal stresses (5 MPa). The interplay between wave transmission, the degree of mismatch, and the discontinuity's micro-physical, -chemical and -mechanical properties was assessed through: (1) 3D CT in-situ Xray scans to quantify the degree of mismatch at various normal stresses; (2) micro-indentation testing, to measure the micro-strength of the asperities; and (3) Scanning Electron Microscopy (SEM) and Electron Xray Diffraction (EDX), to study the micro-structure and chemical composition of the discontinuity. The X-ray results showed that contact between asperities increased with normal stress, even when the discontinuity was mismatched. The results indicated that: (1) at 2 MPa, the void aperture was large, so significant shear displacement was needed to interlock and damage the asperities; and (2) the micro-hardness of the asperities of the mismatched discontinuity was larger than that of the well-matched discontinuity, which points to inducing less damage for the same shear displacement. Both mechanisms contribute to the need of larger shear displacements for the mismatched discontinuity asperities to cause damage, which is consistent with the inability to detect seismic precursors to failure. The experimental results suggest that monitoring changes in transmitted wave amplitude across a discontinuity is a promising method for predicting impending failure for well-matched rock discontinuities. Precursor monitoring for mismatched rock discontinuities seems only possible when there is sufficient contact between the two rock surfaces, which occurs at large normal stresses.