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Connecting linear and nonlinear ultrasonic responses of stressed fractured rock to fracture and bulk characteristics derived from in-situ synchrotron X-ray imaging

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The linear and nonlinear elastodynamic responses of fractured rock depend on bulk rock's properties (e.g., porosity size and distribution) and fracture morphology (e.g., aperture, contact area, contact size distribution), which in turn controls the hydromechanical properties of the fractured rock. We conduct a series of coupled in-situ synchrotron X-ray imaging and through-transmission ultrasonic testing on intact and saw-cut Westerly granite and Berea sandstone samples to quantify the influence of bulk/fracture characteristics on the elastodynamic properties of fractured rock undergoing quasi-static and dynamic stresses. A subset of Westerly granite samples is thermally damaged by exposure to high temperatures (450oF, 850oF) without and with saw-cut fractures to simulate fractured rock with varying degrees of distributed bulk damage. The time-lapse ultrasonic data collected during quasi-static loading/unloading of the samples are analyzed to obtain the evolution of wave speed, amplitude and center frequency with increasing/decreasing stress. Three-dimensional X-ray computed tomography (CT) scans captured during quasi-static loading/unloading are analyzed to estimate the 'true'fracture contact area, contact size and aperture distribution as well as changes in bulk porosity. The ultrasonic data recorded continuously during dynamic stress oscillations are used to estimate the in-situ acoustic nonlinearity parameter β from the stress-dependency of wave speed and amplitude. A series of time-lapse 2D radiographic images captured during dynamic stress oscillations are analyzed to estimate the strain distribution in the bulk and opening/closing of the fracture. The stress-dependency of the ultrasonic attributes (wave speed, amplitude, frequency and β) is then evaluated in relation to the information gleaned from high resolution in-situ synchrotron X-ray imaging during quasi-static loading/unloading and dynamic oscillations. Our findings reveal a reciprocal relationship between the fracture aperture and the center frequency of the recorded ultrasonic response, which cannot be explained by the widely adopted displacement discontinuity model. We also find a strong correlation between transmitted wave amplitude and true contact area (and not the embracing area), which appears independent of the contact area distribution, in contrary to the existing literature based on very simplified experiments. The presence of a fracture influences the wave amplitude much more than the wave. Finally, both true contact area and contact size distribution appear to influence the acoustic nonlinearity parameter β; fractured rocks with smaller and more distributed contacts exhibit higher acoustic nonlinearities. These findings provide new insights into the interpretaion of ultrasonic attributes in relation to fracture properties with potential implications in inferring fractures'characteristics from their seismic signatures.

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