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Investigating the impact of preexisting weaknesses on macroscopic geomechanical response using discrete element method simulations

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Natural rocks contain mechanical weaknesses that span several orders of magnitude in scale, from grain contacts to plate boundary faults. Bedding-parallel fractures between strata, and bedding-perpendicular fractures that terminate at layer contacts demonstrate that interfaces between sedimentary strata can act as mechanical weaknesses that concentrate stresses, localize strain and impact macroscopic failure. However, many numerical models of crack growth and fault development assume homogeneous and isotropic host rock properties due in part to the scarcity of field and laboratory data that quantitatively constrain how these weak interfaces impact the macroscopic geomechanical behavior of the host rock.

To constrain the influence of preexisting mechanical weaknesses, such as sedimentary layers, crustal faults, or metamorphic foliation, on macroscopic geomechanical response, we conduct a series of numerical triaxial compression tests on simulated layered sedimentary rock. Using the 3D discrete element method simulation package ESyS-Particle, we build bonded particle assemblages comprised of layers where the bonds between adjacent layers (i.e., the layer interfaces) are weaker than bonds within the layers themselves. We also develop a novel particle packing technique that builds layer interfaces of varying roughnesses. We perform triaxial compression tests for a range of confining pressures to determine how the internal friction, μ_0, and uniaxial compressive strength, S_0, change as we systematically vary: 1) layer orientation (with respect to maximum compression direction), 2) layer interface roughness and 3) total layer interface area. The failure of the simulated sedimentary rocks share characteristics observed from laboratory experiments, including steepening failure envelopes at lower confining stresses, σ_2, broadening loading curves near peak stresses at higher σ_2, and decreasing elastic modulus at higher σ_2. Consistent with laboratory experiments, S_0 and $\mu_0$are minimized at 30°, and maximized at 0° and 90° from σ_1 in models with the smoothest layer contacts and highest layer contact area. In these models, a 30° rotation in layer orientation (or σ_1) produces a 66% and 20% difference in S_0 and μ_0, respectively. At steeper layer dips, the magnitude and rate of strain localization along layer interfaces relative to within layers systematically increase as the rock approaches failure. At shallower layer dips, this magnitude increases, plateaus and in some cases decreases. The spatial distribution of particle velocities reveal insights consistent with these strain localization evolutions. With shallower layer dips, particle movement (indicating bond breakage) is concentrated along layer interfaces early in the experiment but disperses to within layers later in the experiment. With steeper layer dips, the distribution of particle velocities indicates that slip occurs between layers throughout the experiment, suggesting that deformation continues to localize along the layer interfaces. Estimates of the Coulomb shear stress required for failure of intact rock within the upper seismogenic zone (7 km) using the upper and lower limits of μ_0 and S_0 determined from the models indicates that a rotation of 30° of σ_1 relative to planes of weakness may reduce the shear stress required for failure by 100 MPa.