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Fluid-induced failure and sliding of a gouge-filled fault zone: Hysteresis, creep, delay and shear-strengthening.

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Many previous studies have explored the role of granular media in controlling friction of faults. A gap exists though in understanding the failure process and sliding of a fluid-saturated fault gouge. Here we use a coupled 2D DEM-fluid code to simulate fault-gouge as a layer of grains, sheared by a constant stress boundary. We explore and compare two scenarios: 1) a dry granular layer, in which shear stress on the top wall is incrementally increased, or 2) a fluid-saturated granular layer, into which fluid is injected, so that fluid pressure is incrementally increased. Once the applied stress/pressure is high enough, the layer fails and starts accelerating, until it reaches a steady-state sliding rate (determined by the layers' velocity-strengthening friction). We next incrementally step-down the shear stress or fluid pressure. Consequently, the slip-rate is observed to slow down linearly with decreasing stress/pore-pressure, until the layer finally stops, at a stress/pressure lower than that required to initiate the failure. Both the dry and fluid-saturated granular systems exhibit two main behaviors: 1) velocity-strengthening friction, following the mu(I) rheology, 2) a hysteresis effect between friction and velocity, porosity and grain coordination numbers. The hysteresis and strain-rate dependence agree with previous experimental, numerical and theoretical results in dry granular media, yet our work suggests these behaviors extend to fluid-filled granular media. We theoretically predict the transient and steady-state observations for dry and fluid-saturated layers, using the mu(I) friction rheology with an added component of hysteresis. Importantly, we show that fluid-filled faults exhibit a process which is absent in dry systems: fluid-injected layers may exhibit failure delay, with some time passing between pressure rise and failure. We link this delay to pre-failure creeping dilative strain, interspersed by small dilative slip events. Our numerical and analytical results may explain: (i) field measurements of fault creep triggered by fluid pressure rise (e.g. via injection), (ii) fault motion which is triggered by fluid-injection but continues even after fluid pressure returns to its pre-injection level. (iii) observed delay prior to failure in fluid-injection experiments.