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Towards a unified framework for modeling fault zone evolution: From particles comminution to secondary faults branching

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ABSTRACT

The brittle portion of the crust contains structural features such as faults, jogs, joints, bends, and cataclastic zones that span a wide range of length scales. These features may have a profound effect on earthquake nucleation, propagation, and arrest. Incorporating these existing features in modeling and the ability to spontaneously generate new one in response to earthquake loading is crucial for predicting seismicity patterns, distribution of aftershocks and nucleation sites, earthquakes arrest mechanisms, and topological changes in the seismogenic zone structure. Here, we report on our efforts in modeling two important mechanisms contributing to the evolution of fault zone topology: (i) Grain comminution at the submeter scale, and (ii) Secondary faults generation at the scale of few to hundreds of meters. We model grain comminution within the framework of Shear Transformation Zone theory, a nonequilibrium statistical thermodynamic framework for modeling plastic deformation in amorphous materials. We postulate, based on energy balance, an equation for the grain size reduction as a function of the applied work rate and pressure. We show that grain breakage is a potential weakening mechanism at high strain rate. It promotes strain localization and may explain the long-term persistence of shear bands in natural faults. To model secondary faults generation we developed a nested fault scheme using the finite element software PyLith. As the dynamic rupture propagates on the main fault the stress state changes and eventually the off-fault shear stress is high enough to overcome the pressure-dependent rock strength defined by the Mohr–Coulomb failure envelope. If the Mohr–Coulomb failure criterion is satisfied, a new secondary fault is generated. The angle of the secondary fault with respect to the main fault is taken to be equal to the angle of the critical shear plane. This procedure is repeated until there is no need to add new faults (i.e., stresses everywhere are below the failure threshold). The secondary faults relax the medium contributing to slip and energy partitioning. They also lead to wave diffraction, slip heterogeneity, and slowing down of the rupture on the main fault. They provide potential nucleation site for future ruptures promoting complexity in earthquake cycle simulation. Under repeated earthquake ruptures, regions in the vicinity of primary slip surfaces become heavily fragmented. These regions are modeled using STZ theory. Incorporating the microscale granular model within the macroscopic finite element simulation provide a physics-based multiscale description for damage accumulation. The model provides insight into the dynamic evolution of fault zone topology coupled within the different phases of the seismic cycle. This is crucial for better evaluation of seismic hazard and risk.