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FINITE ELEMENT MODELING OF LARGE DEFORMATION FAULTING CONTACT PROBLEMS WITH VARIABLE FRICTION

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ABSTRACT

Geologic faults evolve from shearing across a series of echelon joints forming pockets of highly damaged rock. Deformation is typically concentrated within a cataclasite core, or fault zone, through frictional slip. The coefficient of friction within a fault zone is known to vary with slip, speed, and a state variable reflecting the maturity of the contact interface. In recent works [1,2] we used a classical Coulomb friction law (i.e., constant friction) to study similar geologic phenomena subject to discontinuous displacement fields. Herein we formulate the problem of high speed frictional faulting within the framework of nonlinear finite element contact mechanics with variable friction. Novel features of the formulation include the implementation of a variable friction model in the finite deformation regime, and an extrapolation of a well-known phenomenological slowness law for the coefficient of friction to the regime of high-speed shearing. This rate and state dependent frictional law was derived from experiments confined to nonzero slip rates. Therefore, it does not capture a stick condition or static frictional responses. The original friction law predicts an infinite (negative) coefficient for static friction [3] while a more recent regularized version [4,5] overcomes this singularity but predicts that the coefficient of friction is zero when there is no sliding. Our constitutive law which is implemented in a Coulomb friction framework captures (i) the fundamental distinction between static friction and a lower kinetic friction thru a linear slip weakening model and (ii) a rate and state dependent frictional response during sliding as proposed by Rice and Ben-Zion [4,5].

Our finite element implementation considers a penalty scheme to impose the constraints along the fault. The geometric discretization of the fault is carried out with node-to-segment contact elements. We model the mechanical response of the rock layers during the faulting process with a non-associative three-invariant Matsuoka-Nakai plasticity model [6,7]. Its numerical integration is done implicitly by a return mapping algorithm along the directions of the principal elastic stretches according to Borja et al. [7]. The frictional model for the fault and the inelastic constitutive model for the rock strata are implemented in an implicit Fortran finite element code based on a fully Lagrangian description. Iterations for nonlinearities induced by finite deformation effects, plasticity,

and large deformation contact mechanics are carried out by a full Newton–Raphson scheme under quasi-static loading conditions. The mechanical model is demonstrated by a series of plane strain numerical problems involving variable friction. These numerical simulations include high-speed sliding that cause significant drop in the value of the coefficient of friction. The constitutive description that we propose was motivated from experimental studies developed for slow rate frictional sliding. It is hoped that the algorithm advocated in this work can be used along with more realistic frictional constitutive laws, as they eventually develop, that are valid not only for slow rate sliding but also for seismic-rate faulting.

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