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Finite element modeling of fault related folds using large deformation contact mechanics

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Thrust faults are geologic structures that can experience considerable slip along a surface of discontinuity. The ductility of the overlying rock layers dictates whether the fault propagates to the Earth's surface or produces a fold. Movements experienced by folded strata are typically very large and may include considerable rigid body rotation and translation, significant stretching, and relative slip along bedding planes. In this work we present a mechanical model to study thrust fault related folds using finite element modeling and non-linear contact mechanics. We simulate the rigid body translation and finite rotation with nonlinear kinematics; the response of the rock layers with an elastoplastic constitutive law; and the rupturing and evolution of preexisting faults as well as relative slip on bedding planes with finite deformation frictional contact mechanics. Our approach uses a node-to-segment (2D) and node-to-surface (3D) contact element, where arbitrary sliding of a node over the entire interface area is allowed. The actual sequence of deformation and the associated mechanical responses are responsible for activating old faults as well as for generating new ones. For a preexisting fault we utilize the contact model to capture the activation and development of slip. Additionally, we quantify the perturbations in the stress field induced by slip on the discontinuities, and show that these perturbations are enough to generate new discontinuities in the form of deformation bands.

Our fully implicit finite element implementation considers a penalty scheme to impose the constraints and a regularized friction law to represent the mechanical response of the layer interfaces. The elastoplastic model for rock layers considers a three-invariant criterion to define plastic loading and a non-associated flow rule to control inelastic dilatancy. The finite deformation formulation is implemented using multiplicative plasticity theory. We employ a return mapping algorithm formulated in principal stress axes to integrate the stresses over discrete loading increments.

We observed that the following variables exhibit direct and significant effects on deformation and fault movement: fault dip, fault depth, fault length, and coefficient of friction. The first three variables are structural features, whereas the fourth one is a material parameter. The ductility and stiffness of the rock above the fault is another material property that controls the deformation pattern. We show that slip on a thrust fault generates an asymmetric anticline and that the degree of asymmetry is a function of the fault dip and fault depth. We also capture the onset of localized deformations at the tip of the fault and on the forelimb of the fold. This work enables us to follow the evolution of the stress state and the discontinuities throughout the deformation process, to predict the occurrence of deformation bands, and to investigate the relationship between fold shape and fault configuration. It is also useful to integrate mechanical and geological principles in order to formulate models constrained by available geological data. From several simulated fault patterns we infer how one may form an anticline similar to that observed at Sheep Mountain, Wyoming.

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