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Modeling of dilatant fractures in homogenous, cohesive material and in the presence of preexisting fractures

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The formation of open cavities as a result of (normal) faulting in brittle rocks, such as carbonates, basalts and consolidated sandstones, has profound effects on the hydraulic properties of rocks both near the surface and at depth. It is however often difficult to access the fault zone directly. Furthermore, the analogue modeling of dilatant fractures in cohesive materials is notoriously difficult since most geological analogue modeling materials lack cohesion and tensile strength. We use the truly cohesive, fine powdered Hemihydrate powder, which has a true and measurable cohesion and tensile strength and scales well with the prototypes. An extensive material characterization, including the porosity dependency of both tensile strength and cohesion, showed an increase of strength of the powder with burial in the experimental box. This material preserves detailed surface structures in great detail, allowing the study of fault scarps (in the absence of erosion), as well as cavities being formed along the fault trace and the vertical transport of material through, and subsequent filling of, the open fault zone.

The model consists of a graben structure with master faults dipping 60°, a width of 25 cm, length of 70 cm and height of 20 cm. In side view observations three structural zones are observed; pure tensile failure at the surface and pure shear failure near the bottom of the box. At mid-depths we observed a transitional zone with mixed mode failure and the formation of fault cavities. The intercalation of softer sand layers, and slightly stronger mixtures of hemihydrate and graphite powder show a marked increase of the complexity of the fault zone, but the three structural zones remain clearly visible. At the surface, cliff faces and canyons form parallel to the master faults.

In a separate series of experiments, we used a sharp blade to vertically cut the top of the hemihydrates layer and thereby generate a set of cohesionless fractures, which are at an angle to the master faults. These fractures introduce a heterogeneity in the host rock, which clearly influences the deformation. Surface expressions of the fault movement are no longer parallel to the master faults, but form zig-zag shapes at the predefined fractures in a kind of broken relay-ramp manner. The resultant cliff faces consist of sections of the pre-existing fracture faces with small sections of broken- through, intact model material at high angles.

The observed structures compare well with fault outcrops and fault related caves in carbonates, basalts and consolidated sandstone. We used time-lapsed digital photography and Particle Image Velocimetry (PIV) to observe strains at small increments and plastic deformation prior to brittle failure. The Discrete Element Method (DEM) was used to numerically model the formation of open fractures without predefined fractures in brittle lithologies in three dimensions. The results are in good agreement with the laboratory and field observations. The three-dimensional numerical models allowed for detailed studies of fault initiation and connectivity. The DEM models also allow for a relatively quick way to test the effects of different fault dips and changes in the material properties. This work has shown that a combination of novel analogue modeling materials and innovative numerical modeling methods will allow for better understanding of the complex interactions of dilatant faulting and preexisting fractures in outcrops and at depth.