DEVELOPMENT OF SCOOP-SHAPED LISTRIC FAULTS DURING GRAVITY-DRIVEN EXTENSION. A COMMON MECHANICAL PROCESS?

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Abstract
Gravity-driven deformation in a variety of geologic settings typically leads to “Scoop-shaped” failures, suggesting a common mechanical process may operate. This paper proposes a study of the development of failure surfaces associated with landslides and listric normal faults. Although there has been extensive research on both of these phenomena, few studies have investigated the mechanics behind the development of their scoop-shaped geometry or integrated studies of a variety of phenomena to try to reach a general understanding of why scoop-shaped failures form. The proposed project will integrate structural mapping, deformation mapping of active structures, and numerical modeling to better understand the process of gravity-driven failure.

Previous Work
A large volume of literature exists on both landslide deformation and listric normal faulting. The majority of work on listric faulting has been observational or based on physical modeling while landslide research has included more extensive numerical modeling (see Weirjmaris, 1993; Duncan, 1996 for reviews of modeling salt tectonics and landslides respectively).

Landslides
It has long been observed that landslides typically form a simple, scoop-shape in the case of rotational slides in homogeneous media, or a scoop-shaped head, translational body, and compressional toe in the case of translational slides (eg. Varnes, 1958). It has also been observed that much of the deformation associated with landslide movement occurs along discrete “slip surfaces”. Palmer and Rice (1973) cited observed strain localization to support the application of concepts from fracture mechanics in developing propagation conditions for failure surfaces in consolidated clays. Fleming and Johnson (1989) also noted that the geometry and kinematic evolution of slip surfaces is similar to that observed for faults and predicted by fracture mechanics. They proposed a conceptual model (Figure 2) for the development of a slide-bounding slip surface from an initial slope-parallel failure near the base of an incipient landslide.

Mathematical modeling of landslides has concentrated on refining models of pre-failure stress fields and deformation in established slides, but little work has tackled the problem of how failure surfaces initiate and grow. Modeling of pre-slide stress fields has grown increasingly sophisticated (see Duncan, 1996 for summary), progressing from simple one-dimensional models used for failure analysis, to two-dimensional dry-
Figure 1. a) Landslide, La Conchita, California, - spring 1995. Photograph by R.L. Schuster, U.S. Geological Survey. Sketch of idealized landslide. Drawing by Janet Appleby, Richard Kilbourne, and Thomas Spittler; modified from Varnes (1978) b) Map and seismic section of listric normal faults, Gulf of Mexico (From Diegel et al., 1995). Note prevalence of arcuate traces and segments in map pattern. Seismic profile of listric normal faults, Pleistocene Gulf of Mexico, top-uninterpreted, bottom interpreted section. c) Map and Sketch cross-section of Etna volcano showing arcuate pattern of failure in map view, and interpreted listric nature in cross-section (From Rust and Neri, 1996).
earth models, to fully-decoupled poroelastic modeling (Iverson and Reid, 1992). Models of fully developed slides have generally used plastic rheologies. These models appear to accurately capture large scale deformation of the slide mass itself, but do not successfully model deformation associated with slip surfaces. Figure 3 compares inclinometer data from a landslide with results from a plastic landslide model. The measured data shows deformation concentrated over a relatively narrow zone (basal slip plane) with little deformation in the body of the slide itself while the plastic model predicts an elliptical distribution of deformation.

The problem of slip surface development has received much less attention from landslide modelers. Recently Muller and Martel (in press) used fracture mechanics to model the stress field around a propagating, slope parallel failure. They found stress concentrations at the tips of a propagating rupture (Figure 4), but did not consider that the stress concentrations were large enough to propagate to the surface without exploiting pre-existing weaknesses. Strain localization modeling techniques (eg. Reueiro and Borja, 1999) may provide a means for modeling development of failure surfaces over time using realistic failure criteria.

A new type of data that has the potential to improve our understanding of landslide failure is geophysical observation of active deformation. Geophysical methods such as satellite interferometry (INSAR) and Global Positioning systems (GPS), commonly used for studying crustal deformation, have recently been applied to landslide research and may provide a new opportunity to better constrain 3-dimensional deformation and the geometry and nature of underlying failure surfaces. Fruneau et al. (1996) showed that SAR interferometry could be applied to a 1-km$^2$ landslide to outline the deformation with better than 10m spatial resolution and 1 cm displacement resolution. Recent work by the USGS on the Slumgullion slide (Coe, et al., 2000) has shown that GPS can also be applied to quantifying landslide deformation with high precision. These new geophysical tools provide additional data for constraining the development of landslide slip surfaces.
Listric Normal Faulting

Listric normal faulting, associated with gravity spreading of large deltas, shares much of the basic geometry of landslides. Fault systems typically include scoop-shaped faults at the head that are arcuate in map pattern and concave in cross-section (Figure 1), regions of translation over low-angle detachments, and compressional toes with well-developed thrusts (see Morely and Guerin, 1996 for a review of salt and shale tectonics). Research into the mechanics of listric faulting and deltaic spreading has principally focused on analog modeling. Nettleton and Elkins (1947) first introduced the concept of modeling a brittle overburden above a ductile substratum by introducing granular materials that faulted during model deformation. This method evolved into sandbox modeling that has been the main means of physically modeling deltaic spreading in the late 1980’s and the 1990’s. Weijermars et al. (1993) provides a thorough discussion of the scaling approach used in these models. They argue that models using sand as an overburden and polymers as viscous substrates can be dynamically scaled and yield quantitative model results. These models yield geometrically similar results to observed structures, however they do not clearly explain the mechanism behind listric faulting. Vendeville and Cobold (1988) showed that listric faults can develop simply through syn-deformational sedimentation. This model, however, requires footwall rotation, which is not always present, confirming the need for a more general explanation.

Mathematical models have also been used to explain listric faulting, although they have not been as widely applied or as sophisticated as landslide models. It has long been observed that there is a close association between listric faults and overpressured shales (Bradshaw and Zoback, 1988). Most proposed models have focused on the weakening effect of overpressure and the development of slope parallel slip surfaces (e.g. Price, 1977 and Crans, et al., 1980). The model of Crans et al. is based on plasticity theory and therefore predicts failure in the direction of maximum shear (45° to the principal stress planes). Slope parallel maximum shears can develop near free faces of slopes similar to landslides, but may be more difficult to explain in deep-seated listric faulting where sub-horizontal detachments are located kilometers below the sediment/water interface. Bradshaw and Zoback, (1988) noted that, similar to landsliding, deformation associated with listric faults is concentrated along discrete fault surfaces and is therefore principally a frictional process. Based on a Coulomb failure model and realistic values for the coefficient of internal friction ($\mu_i=0.6-1.0$) they found that sliding could only occur on surfaces oriented at angles less than ~20°.

Figure 3. a) Inclinometer displacement data from a landslide in Japan (from Landslides in Japan, Japan Landslide Society webpage). Curves from left to right show series of borehole surveys over a seven week period. Note localization of strain along discrete slip surface with little internal deformation of slide mass. b) Velocity profiles with depth generated from plastic Landslide model (Savage et al., 1986). Note elliptical shape with deformation distributed across depth of slide. Curves generated for various physical parameter values (f - angle of internal friction, q - angle of slope, and p - dimensionless pore pressure.)
to the maximum compressive stress. To generate nearly horizontal detachments, either the principal compressive stress must be oriented at a relatively low angle, or the fault must be unusually weak. Bradshaw and Zoback (1988) proposed a model where stress orientations changed with depth due to changes in rock viscosity. This model assumes that the underlying process is essentially ductile so that rock viscosities, which are poorly known, could affect a change in the stress orientation. Better knowledge of both the pre-failure stress field and the process of fault development is required to fully understand the mechanics behind listric faulting.

**Proposed Research**

In order to gain a better understanding of the mechanics behind gravity failure and the development of scoop-shaped faults I am proposing a linked investigation of landslide deformation and listric faulting in spreading deltas. The proposed study will integrate structural mapping, mapping of active deformation, and numerical modeling to attempt to develop a general mechanical model of gravity failure.

**Landslides**

I plan to map a series of landslides from the earliest stages of failure to the full development of bounding failure surfaces to capture the geometry and evolution of slip surfaces. The approach will be similar to that taken by Fleming and Johnson (1989), mapping structures and displacements in detail using GPS surveying techniques. The objective of this work will be to capture “snapshots” of the early stages of landslide development to better understand the development of failure surfaces. The structural mapping will be linked with mapping of active deformation using SAR interferometry and/or a GPS grid to better constrain movement of material and subsurface slip. The structural and deformation data will be instrumental in providing constraints for development of a time-stepped finite element model, including both fluid effects and strain localization, to try to quantify the mechanics behind gravity failure.

**Listric Faulting**

The second major aspect of this research will involve an investigation of submarine normal faulting. Similar to the approach used for landslides, I propose to map structures associated with a series of listric growth faults to track the development of structures from the earliest stages of failure to fully-developed, fault-
bounded systems. This structural mapping could potentially be completed from a single 3D survey stretching from the continental slope up onto the shelf or from a set of surveys covering structures at a variety of stages of development. If possible, deformation associated with active structures will be mapped from high-resolution bathymetric data (e.g. SEABEAM sonar data). This is a new approach to active deformation studies and its success will depend on the resolution that can be attained from the sonar data. Borehole stress data will also be critical in constraining the pre-failure stress field. The goal of the structural, deformation, and stress observations will be both to illustrate the structural development of listric fault systems and to provide constraints for numerical modeling. Ultimately the comparison between the results from landslide and listric fault studies should lead to a more general understanding of the mechanical processes associated with gravity failure.

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References


