A Quantitative Fracture Model For Initiation Of Submarine Landslides

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LONG-TERM GOALS

My long term goals are to develop, test, and clearly present new quantitative methods for evaluating stresses in the earth's crust and to through new field observations and new mechanical analyses to contribute to a better understanding of geologic fracture phenomena, especially faulting, landsliding, joint formation, and dike intrusion.

OBJECTIVES

The main scientific objectives of this project are to identify and better understand the factors controlling where submarine landslide failure surfaces nucleate, how they propagate, how deformation accumulates in the incipient stages of landsliding, and to develop methods for analyzing these phenomena. A second objective is to reconcile predictions of fracture mechanics theory with observations of secondary fractures around faults. The landslide and faulting studies are linked because they both involve shear fracture, albeit under different environmental conditions. The work also is undertaken with the objective of developing my graduate students as well-grounded research scientists.

APPROACH

This study is primarily theoretical and utilizes numerical stress analyses to understand sliding processes. Landslide failure surfaces and faults are modeled as fractures in elastic media using displacement discontinuity boundary element codes (e.g., Crouch and Starfield, 1983; Thomas, 1993). Fleming and Johnson (1989) proposed viewing landslide failure surfaces as fractures, and this concept is tested quantitatively here. The mechanical analyses for landslides have been conducted in both two- and three-dimensions and account for topography and stresses due to gravity. The stresses in a slope without a failure surface are examined to see where failure might nucleate. Stresses and displacements within a slope containing different failure surface geometries are then examined to understand how a failure surface might propagate and how the slope deforms in response. The model results are compared with observations made by other investigators to test the model predictions. For the faults, stress analyses have been conducted in three-dimensions to indicate the location, orientation, and size of secondary fractures. The mechanical analyses are then tested against my field observations of faults, collected as part of another project. Development of mechanical analysis methods is a major component of this research.

WORK COMPLETED

The displacement discontinuity boundary element method has been adapted to account for gravity and topography. The two-dimensional numerical solutions match available analytical solutions for the stresses in slopes. The analysis method has been applied in two dimensions to analyze the growth of landslide failure surfaces and the associated deformation. A three-dimensional boundary element code, POLY3D (Thomas, 1993), has been modified, tested, and shown to satisfactorily match available analytical solutions for a penny-shaped shear fracture.

Six manuscripts on the research have been completed. One was published in 1998 in the Journal of Geophysical Research (Martel and Boger). Three are in-press in a special issue of Pure and Applied Geophysics on landslides and tsunamis (Martel; Martel and Muller, Muller and Martel). The fifth manuscript is in-review for the peer-reviewed proceedings of the March 2000 National Science Foundation workshop on submarine landslides and tsunamis that was held at the University of Southern California. The sixth manuscript is in review for the Journal of Geophysical Research (Muller, Ito, and Martel).

The research results have been presented at meeting of the American Geophysical Union in 1997, 1998, and 1999. Additionally, the results have been presented by invitation at two special workshops. The first, on micromechanics, was sponsored by the U.S. Department of Energy in August, 1998. The second, on submarine landslides and tsunamis, was sponsored by the U.S. National Science Foundation in March, 2000.

Funding from ONR supported the M.S. work of two students. William Boger received his M.S. in 1997. He modified the C code POLY3D used in the three-dimensional modeling and co-authored one journal article. Jordan Muller completed his M.S. in 1999. Jordan worked with me to apply the boundary element method to the analysis of landslides. The Department of Geology and Geophysics recognized Jordan as its outstanding graduate student in 1999. He co-authored three journal manuscripts and is now enrolled in a Ph.D. program at Stanford University.

Results

(a) Modeling method development

By treating the ground surface as a long crack and casting gravitational body forces in the form of "far-field stresses" the displacement discontinuity method yield stresses beneath slopes that compare quite favorably with the exact analytical solution of Savage et al. (1985). This demonstrates that the displacement discontinuity method yields accurate results. The boundary element analysis shows that the solutions of Savage et al. (1985) represent the stresses in a laterally confined body after erosion of overburden, a point that is not obvious from an inspection of the analytical solutions. Unlike the analytical solutions, the boundary element method can easily be used to examine stresses beneath slopes of arbitrary shape and many different tectonic loads. By adjusting the boundary conditions the boundary element method also can be easily applied to analyze the stresses beneath topography that was formed by deposition rather than erosion (e.g., in a volcano).

One of the major results of the research was developing a model formulation that shows straightforwardly that the stress state in a slope depends on its geologic history, and not just on the current slope geometry and the current stress boundary conditions. For example, the stresses beneath a slope created by deposition differ significantly from those beneath a slope created by erosion.

(b) Growth of landslide failure surfaces

The boundary element analyses show that formation and location of commonly observed landslide features can be understood in the context of a fracture failure. Although the analyses assume highly idealized conditions, they support several general conclusions.

Topographic and gravitational effects impose key constraints on the near-surface stresses that drive sliding. Because the near-surface most compressive stress must be either parallel or perpendicular to the slope, the shear stress resolved along shallow slope-parallel slide surfaces must be small relative to the normal stresses. Therefore, these surfaces must be weak for slip to occur. Under such conditions, perturbations in the near-surface stress field, such as those due to notches, can have relatively large effects.

Notches in a slope promote sliding. A notch locally increases the slope-parallel shear stress, and also creates a slope geometry in which a slope-parallel slip plane can intersect the ground surface. Once a failure surface intersects the ground surface in one place, the tendency for additional sliding and further propagation of the failure surface increases sharply. Shale or clay layers within more resistant units are potential slide planes *and* can also erode preferentially to form notches, making these units particularly hazardous. Interestingly, landslides themselves leave notches in slopes and thus increase the potential for retrogressive sliding further upslope.

Stresses promoting sliding are enhanced near slope bases, so sliding is likely to initiate there and then propagate upslope. As a failure surface lengthens, deformation and stress concentrations increase within a slope. Growth of a failure surface thus is a potential mechanism for the progressive weakening of a slope over time. Episodic events such as earthquakes or influxes of large sediment loads could cause the failure surface to propagate and the slide mass to be displaced incrementally downslope. Failure surface propagation and sliding are irrecoverable; therefore, the factor of safety for the slope cannot return to its previous value. Ultimately, a single event may cause the failure surface to propagate to the ground surface, triggering large downslope displacement (i.e. slope failure).

In many of our analyses, the stress concentrations at the tips of slope-parallel slide planes are small. This suggests that a failure surface may be unable to daylight (i.e., propagate to the surface) without pre-existing weaknesses that extend to the ground or seafloor surface. However, the stress concentrations could allow short fractures to open, linking parallel slide planes and thus helping to lengthen the failure surface. These short linking fractures could form the "risers" commonly seen in a stepped failure surface. These stress concentrations also could be sufficient to open pre-existing slope-normal joints, triggering slope failure. Our results illuminate the critical role of pre-existing weaknesses evident from many landslides.

As the area of sliding increases, the depth:length ratio of a slide mass decreases, and the size of the tensile stress concentration above the upper tip of a slope-parallel slide plane tends to increase. This enhances the likelihood of new tensile fractures forming, or pre-existing slope-normal fractures opening, near the head of a landslide; both processes help a failure surface propagate to the ground surface. Our model also shows that landslide head scarps are likely to initially be very steep or overhanging, in keeping with common observations.

Our results consistently indicate that slope-parallel sliding at depth causes downslope extension in the upslope half of a slide mass and shortening in the downslope half. This result accounts for general field observations of deformation in landslide masses. In addition, slope-normal displacements in at least some cases can be used to locate slide plane tips in the subsurface, before the failure surface daylights. We also show that ground surface displacement profiles that could easily be interpreted as reflecting a curved slip surface can result from sliding along a plane. Ground surface deformation thus should be analyzed carefully to draw conclusions about sliding at depth.

The three-dimensional analyses predict that if sliding at depth spreads along a slope-parallel surface (e.g., bedding) while maintaining an elliptical perimeter that diagnostic features should develop at the surface. A series of fractures should open above the perimeter of the region of subsurface sliding; these fractures would define the head of a slide. The fractures should form in an arcuate band at the top of the slide and should be oriented as to form an echelon pattern. Normal faulting is predicted in the downslope of the head scarp fractures. Although both features are widely observed on many landslides, to my knowledge this is the first time a mechanical model has been developed to account for them.

Our model ties features commonly observed in slides to a mechanical process. The results demonstrate the utility of investigating sliding and associated ground surface or seafloor deformation in the context of fracture phenomena.

(c) Three-dimensional analyses of fracturing around faults
Field observations of secondary fractures along individual exhumed faults in crystalline rock indicate that secondary fractures typically are concentrated at the perimeter of a fault. The abundance and spacing of the fractures vary around the fault perimeter. They are smallest and most closely spaced near the tops and bottoms of strike-slip faults and largest near the ends. The location and size of the secondary fractures are consistent with the results from POLY3D elastic modeling. The modeling results also indicate that the three-dimensional shape of a secondary fracture is likely to be defined by one or two semicircles and to scale with the size of the fault. The secondary fractures locally link faults together. The size, distribution, and inferred shape of the fractures suggest strike-slip faults will tend to link end-to-end rather than top-to-bottom. The main zones of linkage are more likely to be perpendicular to the slip direction along the fault rather than parallel to the slip direction. The zones form prominent fluid flow channels, indicating that key fluid flow channels along faults will tend to be perpendicular to the slip direction. The observed orientation of secondary fractures along natural faults and the inferred shape of those fractures, differs from those observed along synthetic faults that have been studied in the laboratory. The difference probably means that the shear stress drop is much smaller (relative to the shear stresses far from the fault) for natural faults than for the synthetic faults. If the stress drop on landslides is also small, then the orientation of fractures in a landslide mass should be determined largely by the orientation of the principal stresses in a slope prior to the development and growth of the failure surface.

IMPACT/APPLICATIONS

The displacement discontinuity boundary element method probably is the modeling technique most widely used by geologists to study fractures. Until now, however, no clear explanation of how to account for effects of gravity and topography with the method has appeared in the geologic literature.

The research completed to date should materially advance the use of boundary element modeling by geologists in the study of near-surface fracture phenomena. It also could be used, for example, in inverse analyses of deformation of volcanoes based on GPS measurements, and in analyses of the stability of boreholes and tunnels. The displacement discontinuity method is a viable alternative to finite element modeling, and in two cases it appears to be superior. First, because fractures are structural discontinuities, a boundary element method based on displacement discontinuities is especially well suited to analyze fractures. Unlike some finite element codes, no special elements are needed to simulate cracks. Second, it naturally avoids pitfalls associated with the zero-vertical displacement basal boundary condition that has been used commonly in FEM analyses.

Four direct applications emerge for avoiding landslide hazards. First, notches in slopes known or suspected to be marginally stable should be avoided; failures probably nucleate there in many cases. Adjacent regions upslope and downslope of prominent notches should be avoided also. Second, displacements monitored at the surface can be used to evaluate the dimensions of a slide plane at depth. Third, formation of arcuate cracks on a slope is evidence that the slope is on the verge of failure (i.e., the slide failure surface is nearly completely developed). Material presented at the NSF workshop on submarine landslides and tsunamis and the observations of Driscoll and co-workers (Driscoll and others, 2000) show that incipient slope failures marked by such fractures exist off the coast of southern California and North Carolina, respectively. Fourth, the results of this project provide a way to estimate the thickness and volume of potential slide masses based on crack patterns on the seafloor, and those estimates could then be used to help assess tsunami hazards if submarine slides were to occur.

TRANSITIONS

The modeling method and its application to slope stability will be presented in a special issue of Pure and Applied Geophysics devoted to landslides and tsunamis. This will expose a broad audience to the method. Given its versatility and simplicity, my expectation is that many other investigators are likely to apply it. A reviewer of one of the journal articles expressed this view as well. The POLY3D results are being used in collaborative work with Kevin Hestir and James Evans of Utah State University to develop an inversion method for fluid flow along faults.

RELATED PROJECTS

A project on the growth of faults and the hydrogeologic implications, supported by the U.S. Department of Energy, continues to benefit directly from the work supported by ONR. A recently completed study on dike propagation, supported by the National Science Foundation division of Ocean Sciences, has relied heavily upon the boundary element method developed through this project.

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ABSTRACTS

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Modeling the failure surface of a landslide as a three-dimensional shear fracture with an elliptical perimeter provides insight into incipient sliding process. The elastic boundary element model developed accounts for failure surface geometry, topographic slope, and gravity. As a region of sliding at depth grows, increasingly large stress concentrations develop near its perimeter. Once the slip surface length becomes several times greater than its depth, tensile stress concentrations near its head help drive the slip surface up towards the topographic surface to form a steep scarp; from there the failure surface "unzips" down along the flanks. The model predicts opening of an arcuate pattern of echelon fractures at the surface at the slide head, normal faulting near the head, and thrust faulting at the toe, as is observed. Three other predictions stand out. First, notches are preferred sites for slide nucleation and should be avoided on slide-prone slopes. Second, arcuate cracks on a slope indicates that it is on the verge of failure. Third, crack patterns on the seafloor can be used to estimate the area, thickness and volume of potential slide masses, parameters important in assessing tsunami hazards due to submarine landslides.

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