Quantitative Fracture Model for Initiation of Submarine Landslides

Stephen J. Martel
Department of Geology and Geophysics
University of Hawaii
2525 Correa Road
Honolulu, HI 96822
phone: (808) 956-7797 fax: (808) 956-5154 e-mail: martel@soest.hawaii.edu
Award#: N00014-96-1-0353, modification # A00003
http://www.soest.hawaii.edu/martel/Stevem.html

LONG-TERM GOAL

My long term goals are to develop, test, and clearly present new quantitative methods for evaluating stresses in the earth's crust and 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 quite 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 two 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.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1998**	2. REPORT TYPE	3. DATES COVERED **00-00-1998 to 00-00-1998**
4. TITLE AND SUBTITLE **Quantitative Fracture Model for Initiation of Submarine Landslides**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Hawaii,Department of Geology and Geophysics,2525 Correa Road,Honolulu,HI,96822**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM002252.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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. Completion of the fault modeling work satisfied the remaining M.S. requirement for Mr. William Boger.

Three journal papers on the research have been published or are in-press in leading journals. The two papers in-press address boundary element modeling with body forces and its application to landslides; these were invited papers for a special issue of Pure and Applied Geophysics on landslides and tsunamis. The published manuscript, in the Journal of Geophysical Research, addresses three-dimensional aspects of faulting.

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.

The model formulation shows 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 should differ 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 the following 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. 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.

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. The method is being extended to three dimensions.

Three 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).

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, many other investigators are likely to apply it. 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 three-dimensional hydrogeology of faults, supported by the U.S. Department of Energy, continues to benefit directly from the work on POLY3D. A study on dike propagation, supported by the National Science Foundation division of Ocean Sciences, relies heavily upon the boundary element method developed through this project.

REFERENCES

Crouch, S.L., and Starfield, A.M.. 1983: Boundary element methods in solid mechanics, Allen and Unwin, London.

Fleming, R.W., and Johnson, A.M. 1989: Structures associated with strike-slip faults that bound landslide elements, Engineering Geology, 27, 39-114.

Savage , W.Z., Swolfs, H.S. and Powers, P.S. 1985: Gravitational stresses in long symmetric ridges and valleys, International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, 22, 291-302.

Thomas, A.L. 1993: Poly3D: a three-dimensional, polygonal element, displacemement discontinuity boundary element computer program with applications to fractures, faults, and cavities in the Earth's crust, M.S. thesis, Stanford University.

PUBLICATIONS

Muller, J., and Martel, S.J., 1999: Numerical models of translational landslide failure surface growth: Pure and Applied Geophysics [in-press].

Martel, S.J., and Muller, J., 1999: A two-dimensional boundary element method for calculating elastic gravitational stresses in slopes: Pure and Applied Geophysics [in-press].

Martel, S.J. and Boger, W.A. 1998: Geometry and mechanics of secondary fracturing around small three-dimensional faults, Journal of Geophysical Research, 103, 21,299-21,314.

Martel, S.J., and Boger, W.A., 1997: Mechanics of secondary fracturing in three dimensions around small faults:American Geophysical Union Transactions, v. 78, p. F695.

Muller, J., and Martel, S.J., 1997: Nucleation and growth of landslide failure surfaces:American Geophysical Union Transactions, v. 78, p. F695.