Factors Influencing Occurrence, Scale, Mobility, Runout, and Morphology of Mass Movements on the Continental Slope

Jacques Locat
Department of Geology and Geological Engineering, Laval University
Sainte-Foy, Québec, CANADA G1K 7P4
phone: (418) 656-2179, fax: (418) 656-7339, email: locat@ggl.ulaval.ca

Award Number: N00014-98-1-0073
http://www.ggl.ulaval.ca

Thrust Category: Marine Geotechnics

LONG-TERM GOALS

Achieve an improved understanding of the relationships between sedimentation, environment, and the morphology of continental slopes. This goal will be accomplished primarily through investigations within the northern California (Eel River) and New Jersey study areas and incorporation of data from around the World. An underlying assumption of our work is that the occurrence and morphology of mass movement features on the continental slope depend upon a combination of characteristics, each of which varies over the region in a consistent manner. The various components of this project are part of a concerted effort between the geotechnical groups at the USGS and Laval University. Their activities are very much interwoven but, for administrative reasons, annual reports are provided seperately.

OBJECTIVES

Identify factors that can be mapped regionally and that determine where and how slope failures occur; derive a basis for producing regional maps that indicate relative landslide susceptibility. Model shear strength development with depth and incorporate this model into continental slope stability, post-failure behavior, and bedform processes. Observe and model pore pressure development in continental slopes. Analyze the relationship between seismic intensity, sediment instability and slope processes. Integrate these elements into geo-hazards asssessment.

APPROACH

Our research focuses on the factors that lead to variations in the sedimentological and environmental conditions determining slope failure. We develop improved correlation between engineering classifications and strength factors. We relate compressibility, physico-chemical properties and strength to sediment microstructure, observed using SEM techniques. We simulate sediment accumulation in specially designed large cells. We measure sediment rheological properties in a viscometer. Geotechnical properties are related to sediment density state, obtained from detailed logs of downcore variability of sediment density and sound velocity. Basic strength parameters are obtained using triaxial drained and undrained tests and undrained cyclic tests. Using available bathymetry, and seismic profiles, we develop models tested for stability and mobility. Seismic shaking variations are evaluated probabilistically by seismologists. Pore pressures are either determined *in situ* by means of the Excalibur probe (AGC-Atlantic) or estimated using sedimented rates and consolidation theory. If

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2001		**00-00-2001 to 00-00-2001**

4. TITLE AND SUBTITLE **Factors Influencing Occurrence, Scale, Mobility,Runout, and Morphology of Mass Movements on the Continental Slope**	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) **Department of Geology and Geological Engineering, Laval University ,Sainte-Foy, Quebec, CANADA G1K 7P4, , ,**	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

14. ABSTRACT
Achieve an improved understanding of the relationships between sedimentation, environment, and the morphology of continental slopes. This goal will be accomplished primarily through investigations within the northern California (Eel River) and New Jersey study areas and incorporation of data from around the World. An underlying assumption of our work is that the occurrence and morphology of mass movement features on the continental slope depend upon a combination of characteristics, each of which varies over the region in a consistent manner. The various components of this project are part of a concerted effort between the geotechnical groups at the USGS and Laval University. Their activities are very much interwoven but, for administrative reasons, annual reports are provided seperately.

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)**	**6**	

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

there is charging by bubble-phase gas, or if earthquake shaking disrupts the sediment fabric and causes it to collapse with a resulting increase in the pressure of interstitial fluids. Driving stresses are balanced against strength variations in a geographic Information System (GIS) to obtain a regional estimate of relative slope stability.

Key individuals at Laval are: Jacques Locat, Jean-Marie Konrad, Serge Leroueil, and Priscilla Desgagnés: strength and compressibility measurements, SEM studies, rheology measurements, and simulation of sediment accumulation. At the USGS they are: Homa Lee, Kevin Orzech, Dianne Minasian, and Pete Dartnell: physical property logs of sediment cores and relations between geotechnical and classification properties, algorithms relating sediment properties, environmental factors, and slope stability within the framework of a GIS.

WORK COMPLETED

During FY 01, our research involved mostly one of the two main areas of STRATAFORM: the New Jersey Margin, the Hudson Apron in particular. We continued the laboratory testing and analysis of tests carried out on various cores obtained from the 1999 Marion Dufresne cruise on the New Jersey Margin (Desgagnés *et al.* 2000). Further tests conducted at Laval included five triaxial tests, 10 oedometer tests, 3 SEDCON tests, Atterberg's limits, grain size, mineralogy, microstructure and rheology. A total of 3 long cores were collected (MD992-211, 212, and 213), of which one is kept at Laval. All cores were logged, onboard the ship, at 1-cm resolution for density, sound velocity, and magnetic susceptibility. In addition, core MD992-213 was completely logged with a CATSCAN at a resolution of 1cm. The rheological tests were carried out on mixtures at various water content with a liquidity index from about 1.5 to 4.0. The slope stability analysis of two slides identified on the Hudson Apron were carried out using SLOPE/W. Mobility analyses was carried using BING. Work completed at Laval has been integrated with available data from other projects, mostly ODP related from which strength, water content and density data could be used and compared to our results.

RESULTS

Advanced geotechnical testing of the Hudson Apron sediments indicates that they are normally consolidated, at least in the section investigated (*i.e*. to a depth of 38m). The strength parameters, obtained on reconstituted samples, are defined by a failure envelope with a friction angle of 27˚ and a cohesion of about 0 kPa (Figure 1). Our analysis of the Hudson Apron area indicates that there are at least two mass movements in the area. They are part a about 100 mass movements mapped by Booth *et al.* (1993). The first one shows a failure plane extending over a distance of about 3 km at a depth of about 50m. It is located near the crest of the slope at a water depth less than 600m. The second one is deeper and extends down to a depth of more than 1000m. Both of these slides took place on a slope of about 4˚. Limit equilibrium analyses indicate that the slope is very stable under normal hydrostatic conditions. A high pore pressure is required for the slope to fail. It is speculated that possible source of pore pressure generation could be related to high sedimentation rate or gas hydrates. The implication of either causes is being currently investigated. The rheological properties of the Hudson Apron sediments are quite similar to those of other sediments and follow the general relationship proposed by Locat (1997). The mobility analysis of the Hudson Apron is being investigated using BING. Initial use of the geotechnical characterization of mass movements (Leroueil *et al.* 1996) has been attempted for the New Jersey area (Locat *et al*. 2001a) in the view of providing some insight on regional geo-hazard assessment. This approach enables us to consider all component of the phenomena, from its initiation to the final deposit and by integrating soil or rock mechanics with fluid mechanics. A general framework for submarine landslides risk assessment is shown in Figure 2. Another major component of the work completed has been the integration of slope stability consideration at a regional scale (Lee *et al.* 2000 and 2001, see also Locat and Lee 2002).

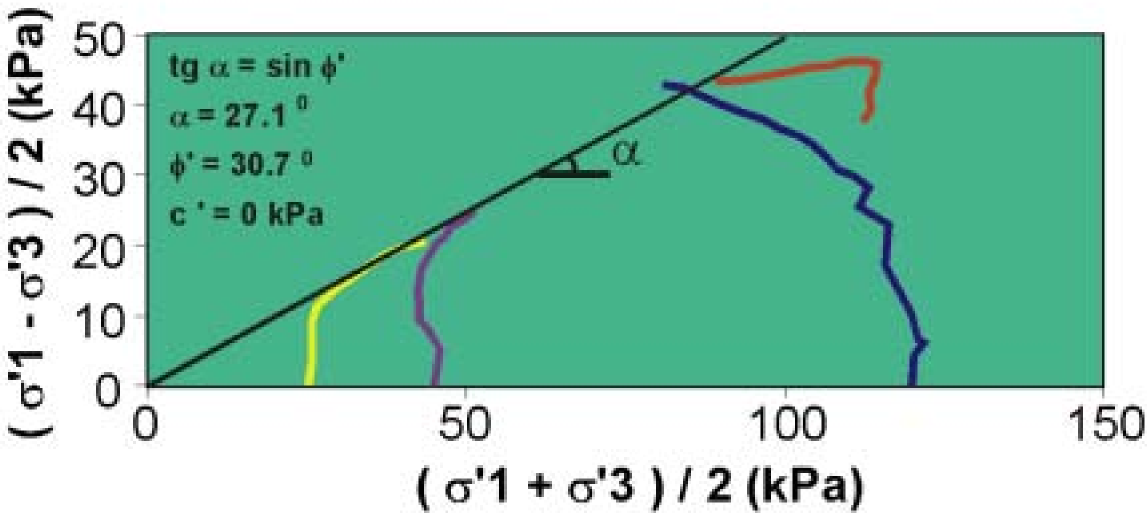

Figure 1. Triaxial tests results showing various stress path grouped around a failure envelope corresponding to a friction angle of 27 and a cohesion of about 0 kPa (Desgagnés et al. 2001).

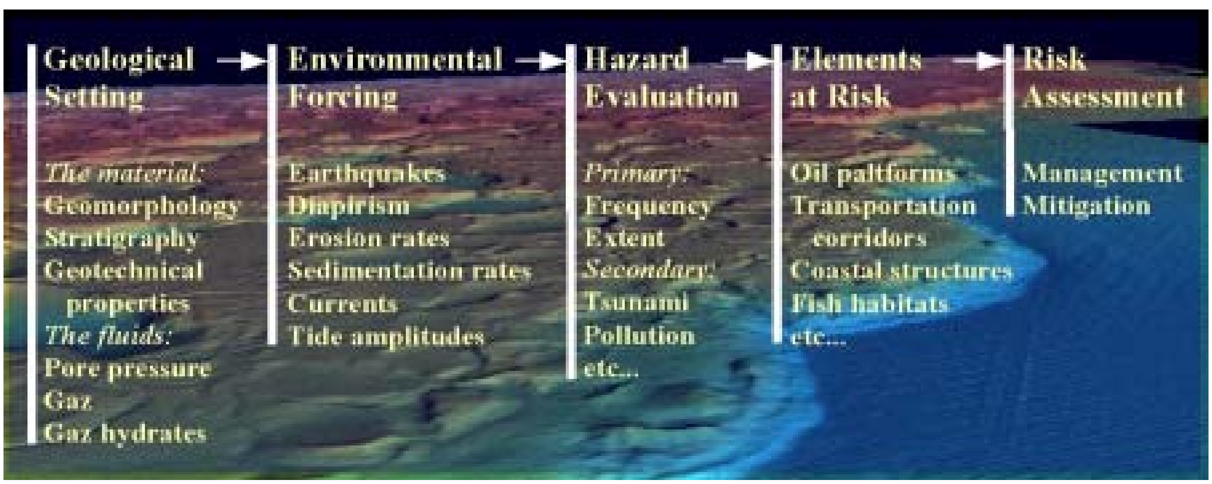

Figure 2. General framework for submarine slide risk assessment (Locat 2001)

IMPACT/APPLICATION

Relationships developed in this project show the importance of sediment liquidity index and seabed density profiles in representing the behavior of marine sediment. These values can be used to predict regional slope stability and the rheological behavior of debris flows. General strength-density relationships can be used for modeling sediment accumulation and stability (Locat *et al.* 2001b). It is also now feasible to intregrate geomorphological and geotechnical data into a regional analysis of submarine landslide risk assessment.

TRANSITIONS

Geoacoustic properties are being used by mappers and acousticians to identify lithologies acoustically. Rheological properties are being used by modelers to represent debris flows (Imran *et al*. 2001). Landslide generation models are being used by landscape evolution modelers. Offshore research groups interested in margin (January 1999 Paris Workshop, see Locat 2001) and in oil and energy development were used as a platform to present our knowledge on submarine slope stability and hazard acquired as part of STRATAFORM . a major opportunity was also provided in June 2000 when we were invited to give a keynote lecture oln submarine mass movements at the 8th International Symposium on Landslides in Cardiff (Locat and Lee 2002). Our knowledge on subamrine mass movement, developed as parto of STRATAFORM, has been put to use in the analysis of tsunami generation. There appears to be more and more cases of tsunamis which are believed to result from submarine mass movements. This is particularily important for coastal cummunities like in the Los Angeles area (Locat *et al.* 2001c)

RELATED PROJECTS

Lee has developed a USGS project to investigate sediment and pollutant transport on the Los Angeles margin that uses techniques produced by STRATAFORM. Locat is investigating the behavior of a newly formed sediment layer acting as a natural cap over contaminated sediment in Canada (Saguenay Fjord). The development of this project benefited from approaches developed within STRATAFORM. Recently, a group of Canadians led by J. Locat, and H. Lee developed a new project called COSTA-Canada (COntinental Slope STAbility) which has been linked to its European counterpart COSTA-Europe. These projects should last at least until 2003.

REFERENCES

Booth, J.S., O'Leary, D.W., Popenoe, P., and Danforth, W.W., 1993. U.S. Atlantic continental slope landslides: their distribution, general attributes, and implications. U.S. Geological Survey Bulletin, v. 2002, pp.: 14-22.

Desgagnés, P., Locat, J., Lee, H.J., Leroueil, S., Alexander, C., Mountain, G., and Pratson, L., 2000. Geotechnical properties of a mass flow deposit on the Hudson Apron, off New Jersey, U.S.A.. Comptes rendus, 53^{e} Conférence canadienne de géotechnique, Montréal, vol. 1: 137-144.

Desgagnés, P., Locat, J., Lee,. H., and Leroueil, S., 2001b. Le glissement du Hudson Apron : un exemple d'application de la caractérisation géomécanique des mouvements de masse. Comptes rendus de la 54e Conférence canadienne de géotechnique, Calgary. In press.

Imran, J., Parker, G., Locat, J., and Lee, H., 2001. A 1-D numerical model on muddy sub-aqueous and sub-aerial debris flows. Submitted to ASCE Journal of Hydraulic Engineering. Accepted for publication.

Lee, H.J., Locat, J., Dartnell, P., Minasian, D., and Wong, F., 2000. A GIS-based regional analysis of the potential for shallow-seated submarine slope failure. Proceedings, 8th International Symposium on Landslides, Cardiff, England, v. 2, p.913-922.

Lee, H., Locat, J., Dartnell, P., Minasian, D., and Wong, F., 2001. Regional variability of factors that influence offshore slope stability, sybthesis within a GIS. XI European Union of Geosciences meeting, Strasbourg, Session RCM4, p739.

Leroueil, S., Locat, J., Vaunat, J., Picarelli, L., and Lee, H., and Faure, R., 1996. Geotechnical characterization of slope movements. Keynote paper**,** 7th International Symposium on Landslides, Trondheim, Norway, . vol. 1, pp.: 53-74.

Locat, J., 1997. Normalized rheological behaviour of fine muds and their low properties in a pseudoplastic regime. ASCE, First Conference on Debris Flows Hazards Mitigation, Mechanics, Prediction and assessment, pp.: 260-269.

Locat, J., 2001. Instabilities along Ocean Margins : A Geomorphological and Geotechnical Perspective. Marine and Petroleum Geology, 18: 503-512.

Locat, J., Desgagnés, P., Leroueil, S., Lee, H., and Héroux, M.-C., 2001a. The geotechnical characterization of mass movements as o component of submarine landslides risk assessment : an application to the New Jersey Margin. XI European Union of Geosciences meeting, Strasbourg, Session RCM4, p735.

Locat, J. Lee. H.J., Kayen, R., Israel, K., Savoie, M.-C., and Boulanger, É., 2001b. Shear strength development with burrial in recent Eel River Margin slope sediments. Accepted: Marine Geotechnology and Resources.

Locat, J., Lee, H., and Locat, P., 2001c. Analysis of Submarine Mass Movements and its Implication for the Generation of Tsunamis, with a Particular Reference to the Palos Verdes Slide, California. *In:* Proceedings of the Workshop on the Prediction of Underwater Landslide and Slump Occurrence and Tsunami Hazards off Southern California, Los Angeles, March 10-11 2000, In Press.

Locat, J., and Lee, H.J., 2002. Submarine landslides : advances and challenges. Keynote presentation, 8th International Symposium on Landslides, Cardiff, U.K., June 2000. Canadian Geotechnical Journal, vol. 39, no. 2.

PUBLICATIONS

Locat, J. Lee. H.J., Kayen, R., Israel, K., Savoie, M.-C., and BOULANGER, É., 2001. Shear strength development with burial in recent Eel River Margin slope sediments. Submitted to: Marine Geotechnology and Resources.

Urgeles, R., Locat, J., Lee, H. and Martin, F. (2001): The Saguenay Fjord, Québec, Canada: Integrating marine geotechnical and geophysical data for spatial seismic slope stability and hazard assessment. Accepted, Marine Geology, in press.