Sediment Formation in Nearshore Environments: Strength, Rheology, Microstructure, and Stability

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LONG-TERM GOALS

Our long term goals are to understand how geotechnical and physical properties develop in marine sedimentary deposits on continental margins as a result of various biological, geochemical and mechanical processes. From these considerations we advance our ability to understand how these properties influence sediment deformation and transport processes and the development of final geomorphology. Our studies include predicting the stability of slopes within the continental terrace and distinguishing morphologic features caused by slope failure from those caused by other gravity-driven processes, including turbidity-current flow. A major component is the development of mobility so that we can understand the transition from initial slope failure to the development of debris flows and turbidity currents. Another component is predicting the rheological properties that determine the dynamics of such flows. We are applying our studies to the EuroSTRATAFORM project, within which we collaborate with scientists seeking to model the formation and alteration of nearshore sedimentary bodies.

OBJECTIVES

Our objectives for FY04 were: (1) to understand the ways sediment bodies develop shear strength, rheological properties and structure; (2) to test shear strength development models in controlled environments, (3) to further the development of the concept of seismic and biologic strengthening; (4) to relate regionally distributed geotechnical properties to index properties that can be determined easily or, potentially, mapped remotely; and (5) to assess the signatures of catastrophic events to determine whether they are produced by deformational (landsliding) or depositional (turbidity current sediment waves) processes.

APPROACH

Our research focuses on the geotechnical changes that occur to sediment as it is buried under the seafloor. These changes include the direct influence of burial, the impact of repeated seismic shaking (seismic strengthening), and the effects of biological activity (biological strengthening). We make detailed measurements of the geotechnical properties (shear strength, compressibility, Atterberg limits, P-wave velocity, density) of marine sediment within the field studies of the EuroSTRATAFORM project (Adriatic Sea and Gulf of Lions). For comparison we simulate the changes in geotechnical properties that occur as a result of known factors. We simulate the effects of compaction of non-bioturbated, non-seismically loaded sediment using the SEDCON (SEDimentation-CONsolidation)

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test performed on synthetic sediment and reconstituted field samples. These results serve as a reference, enabling us to evaluate the relative influence of either bioturbation or seismic strengthening. We also determine the sediment microstructure using SEM techniques and mercury microporosimetry. Seismic strengthening is evaluated by subjecting sediment samples to a series of simulated earthquakes in a cyclic direct simple shear device. Cyclic loads induce positive pore pressures that dissipate with time between events. The resulting densification leads to higher strength than that of comparable sediment not subjected to cyclic (earthquake) loading. Seismic strengthening is modeled within the context of critical state soil mechanics so that this influence can be predicted if certain basic parameters are known (sediment accumulation rate, recurrence rate of particular magnitude earthquakes, plasticity). The bioturbation contribution to sediment characteristics is evaluated by measuring the bio-porosity using CATSCAN imaging. Using available bathymetry, and seismic profiles, we develop models for stability, mobility, and risk (Leroueil et al. 2003). Driving stresses are balanced against strength variations in a geographic Information System (GIS) to obtain a regional estimate of relative slope stability.

Our work is fully coordinated with a matched project at Laval University directed by Jacques Locat. Key individuals, at Laval: Jacques Locat, Jean-Marie Konrad, Serge Leroueil, Marie-Claude Lévesque and Pierre Therrien: strength and compressibility measurements, CATSCAN measurements, SEM studies, rheology measurements, and simulation of sediment accumulation.; at the USGS: Homa Lee, Dianne Minasian, Pete Dartnell, and Kevin Orzech: 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, and strength development from seismic shaking. Partners in Europe are N. Sultan (France), M. Canals and R. Urgeles (Spain), and F. Trincardi (Italy). NA-EuroSTRATAFORM partners who have been involved in FY04 research include D. Orange, R. Wheatcroft and T. Milligan

WORK COMPLETED

During FY 04, we completed EuroSTRATAFORM-related work in the Adriatic Sea. The work included detailed physico-chemical, mineralogical and geotechnical analyses of 11 cores from the shallow shelf off the Po delta. Three cores were selected for a detailed analysis of the bio-porosity, including one from the Saguenay Fjord. Detailed 3D CATSCAN was also carried out on the two SEDCON samples. These results were discussed in greater detail by Lévesque et al. (2004). We continued to perform simulated seismic strengthening experiments in the laboratory. We are varying the input parameters (seismic intensity, burial depth, degree of consolidation, sediment plasticity) to quantify a model for seismic strength development that can be used in regional slope stability models. At the end of the FY we are participating in a sediment sampling cruise in the Gulf of Lions.

In addition to contributing papers to various workshops (ComDelta, Lee, 2004a) and special sessions (Lee, 2004b, Lee et al., 2004b, Lévesque et al. 2003, Locat et al. 2003), the work completed in FY04 also included the completion of major contribution to two books: the Master Volume of STRATAFORM (Lee et al., 2004a, Ch. 6) and another volume on debris flows (Locat and Lee, 2004, Ch. 9).

RESULTS

Detailed analysis of cores from the Po Delta has shown that the consolidation process has been largely influenced by bioturbation resulting in a significant decrease in the in situ water content to a point well below a normally consolidated reference curve. Using the CATSCAN, we developed a method for defining the bio-porosity. Results from one core indicate that the bioporosity can be as high as 40% whereas the total bulk porosity is 80%. This is a very significant contribution and has an impact on the measurement of water content in samples. Comparison of measurements of shear strength on cores in seismically active areas with estimated normally consolidated profiles (Fig. 1) shows that the shear strength can be anomalously high by a factor of 2 or more. Simulations of seismic shaking in the laboratory (Fig. 2) illustrate the mechanism of seismic densification that can cause strength increase. The experiments show that there is "point of diminishing return," with respect to seismic strengthening. Each succeeding earthquake has a proportionally smaller effect than the previous one.

IMPACT/APPLICATION

Relationships developed in this project show the importance of sediment liquidity index and seabed density profiles in representing the physical behavior of marine sediment. These values can be used to predict regional slope stability, rheological behavior of debris flows, and resistance to object penetration. General strength-density relationships can be used for modeling sediment accumulation and stability. We

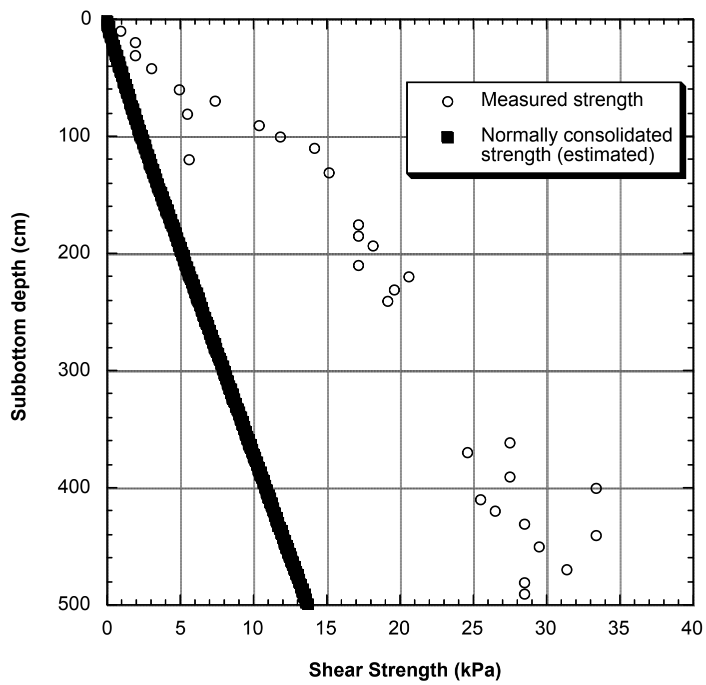

Figure 1. Results of shear strength measurements made on sediment from a seismically activee area compared with estimated strength of normally-consolidated sediment. Higher measured strengths may be a result of exposure to repeated earthquakes (seismic strengthening).

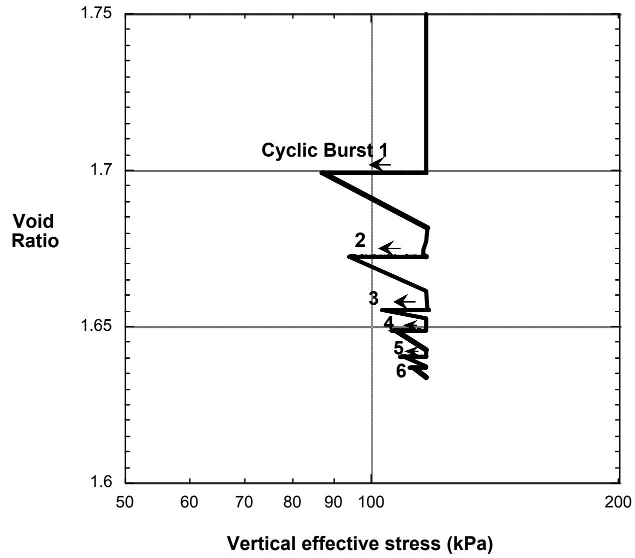

Figure 2. Results of simulated "seismic strengthening" in the laboratory. Each cyclic burst represents a strong earthquake. Decreases in void ratio correspond to an increase in shear strength. Short term decreases in vertical effective stress result from development of pore pressures during shaking. The results show that repeated earthquakes cause an increase in strength but that the impact of each earthquake becomes smaller as the number of earthquakes increases.

are also currently working on the definition of a bio-porosity index to include in the measurement of the shear strength of near surface sediments. We are developing a model whereby shear strength profiles are related to seismicity levels and accumulation rates. By understanding the influence of seismic strengthening, we can better explain the relative lack of slope failures in seismically active environments. Models of strength development for these environments can be used to forecast object penetration and other engineering issues.

TRANSITIONS

Geoacoustic properties are being used by mappers and acousticians to identify lithologies acoustically (Locat and Sanfacon, 2002). Rheological properties (Locat, 1997) 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 oil and energy development were used as a platform to present our knowledge on submarine slope stability and hazard acquired as part of STRATAFORM. We have also contributed to a major effort in assembling all the existing knowledge on submarine mass movements and their consequences by publishing a book containing refereed papers on the topic (Locat and Mienert 2003) including papers by Lee et al. (2003) and Locat et al. (2003a) related to STRATAFORM. We also transfered our knowledge developed as part of STRATAFORM to those interested in tsunami modeling (Locat et al. 2003b, Lee, 2004b).

RELATED PROJECTS

Lee has developed a USGS project to investigate sediment and pollutant transport on the Los Angeles margin that uses the methodology developed in STRATAFORM and EuroSTRATAFORM. Recently, a group of Canadians led by J. Locat and H. Lee developed a new project with project COSTA (COntinental Slope STAbility) in Europe that will last until 2005.

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