SEISMIC STRENGTHENING, A CONDITIONING FACTOR INFLUENCING SUBMARINE LANDSLIDE DEVELOPMENT

Homa J. Lee, U.S. Geological Survey, Menlo Park, California
Kevin Orzech, U.S. Geological Survey, Menlo Park, California
Jacques Locat, Laval University, Quebec, Quebec, Canada
Eric Boulanger, Laval University, Quebec, Quebec, Canada
Jean-Marie-Konrad, Laval , University, Québec, Québec, Canada

ABSTRACT
Slopes in seismically active areas seem to show a higher level of stability than would be expected. A possible explanation for the lower than expected abundance of landslides in seismically active areas may be "seismic strengthening." This is a process that involves gradual densification of sediment following earthquake events. Continental slope morphology, measured strength properties on submarine slopes, and laboratory simulations all support this mechanism.

RÉSUMÉ
Les pentes dans les secteurs sismiquement actifs semblent montrer un niveau de stabilité supérieur à ce que serait prévu. Une explication possible du faible nombre de glissements sous-marins y est possiblement causé par un gain de résistance du à une sorte de compaction dynamique. Il s'agirait d'un processus par lequel la densité du sédiment augmente à la suite de tremblements de terre successifs. Les données sur la morphologie du talus continental, la résistance au cisaillement ainsi que les simulations en laboratoire viennent appuyer cette hypothèse.

1. INTRODUCTION

At least five decades of research has documented that landslides are a common phenomenon on submarine slopes and that they tend to occur preferentially in certain environments such as fjords, river deltas, submarine canyons, volcanic islands and the open continental slope. Likewise, triggers causing submarine landslides have been identified and include oversteenpening from erosion or deposition, storm waves, and earthquakes. Earthquakes are often considered to be a particularly important trigger and the occurrence of earthquake-induced failures on submarine slopes has been well-documented. However, as will be seen below, many continental slopes in highly seismically active areas have not failed whereas slope failures in less seismically active areas actually seem to be more prevalent.

We speculate in this paper that one of the factors that may contribute to the relatively low occurrence of slope failures in some seismically active environments may a response to cyclic loading history. That is, sedimentary bodies that are exposed to a long history of seismic loading from small to moderate earthquakes may strengthen themselves as a result of this history and become better suited for withstanding future earthquake shocks.

2. THE PREVALENCE OF CONTINENTAL SLOPE FAILURES

McAdoo et al. (2000) evaluated large sections of the U.S. continental slope using Geographic Information System (GIS) software. Based on multibeam bathymetric data and GLORIA sidescan surveys of these areas, their analysis identified a total of 83 mass flows, slides, and slumps. The methodology of McAdoo et al. (2000) was based solely on surficial morphology and reflectivity. They measured various aspects of the failures, including landslide area, runout distance, and headscarp height, along with the slope gradient of the runout zone, the failure's scar, headscarp, and adjacent slopes.

The morphometric analysis of McAdoo et al. (2000) considered four distinctly different tectonic environments on the continental slopes of Oregon. central California. Texas, and New Jersey. The analysis showed that the slope in the Gulf of Mexico has the highest percentage (27%) of its surface area covered with failures. The next highest percentage is for New Jersey (9.5%), followed by California (7.1%) and Oregon (3%). Interestingly there is a rough inverse relation between the area covered by landslides with the seismicity.

Within smaller sections of the highly active California margin, several areas have been mapped in detail using multibeam bathymetric mapping techniques (Locat et al. 1999). These maps show enough bathymetric detail to identify all large landslides and many medium and small failures. Three sections of the California margin are shown in Figs. 1 to 3. The northernmost section, the STRATAFORM study area off Eureka, California, is shown in an oblique view from the NW in Figure 1. The image shows a generally smooth slope (steepness of about 4°) containing small regularly spaced gullies. Field et al. (1999) showed that this pattern of gullies extends at

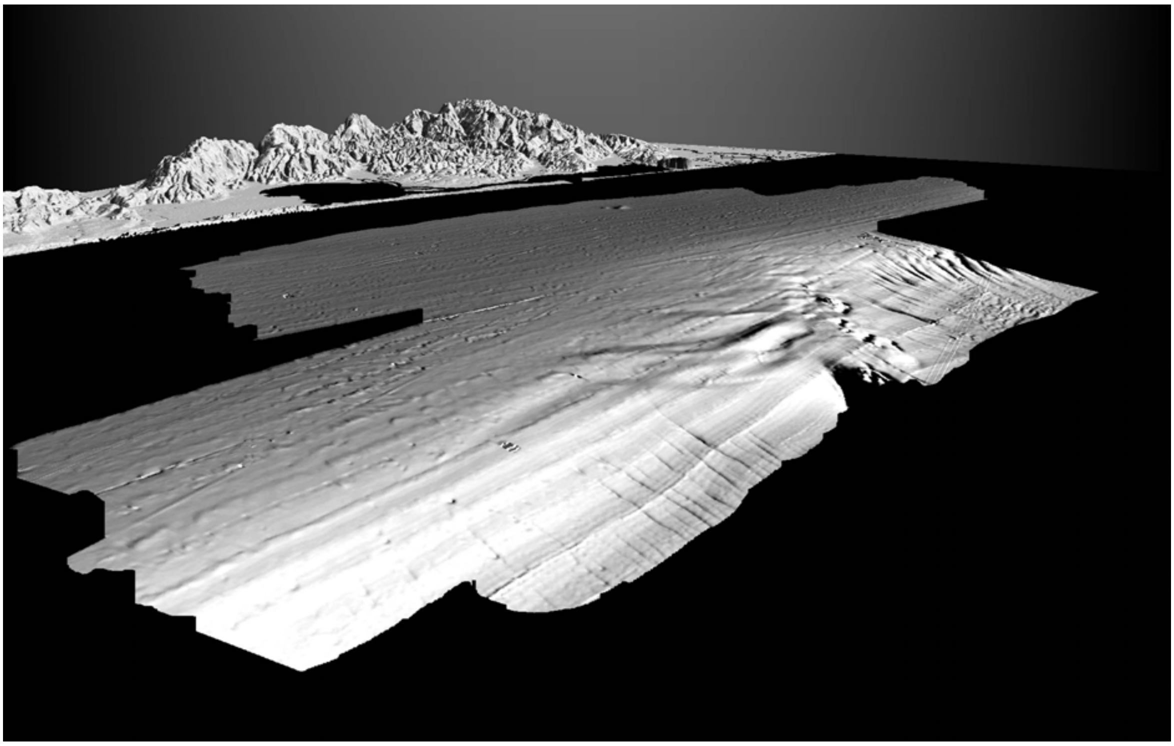

Figure 1. Oblique view of multibeam imagery of the Eel margin, northern California. The center and lower left foreground show the shelf break and upper continental slope. The figure show a gullied area on the upper continental slope that shows that the slope has been stable for considerable time.

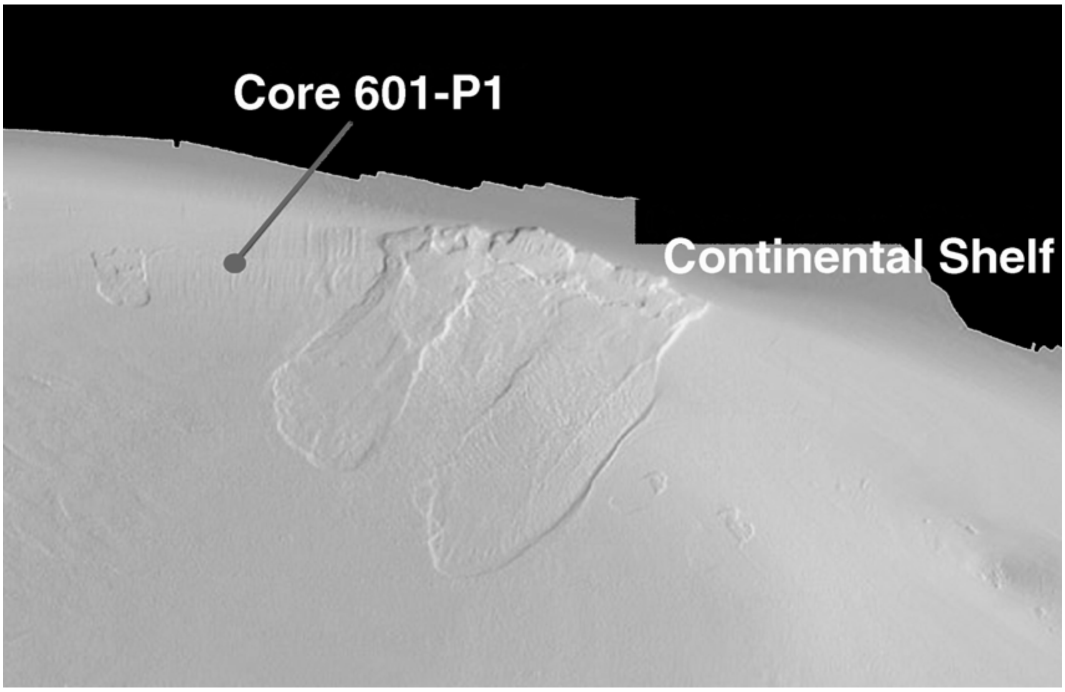

Figure 2. Oblique view of multibeam imagery in the Santa Barbara Channel, southern California (after Eichhubl et al. 2002). The Figure shows a large landslide complex near the center (Goleta Slide, about 10 km x 10 km) and a smaller landslide near the left margin (Gaviota mudflow, 2 km x 2 km). The space between the failures has not failed. Properties of a sediment core in the stable area were obtained on Piston Core 601-P1.

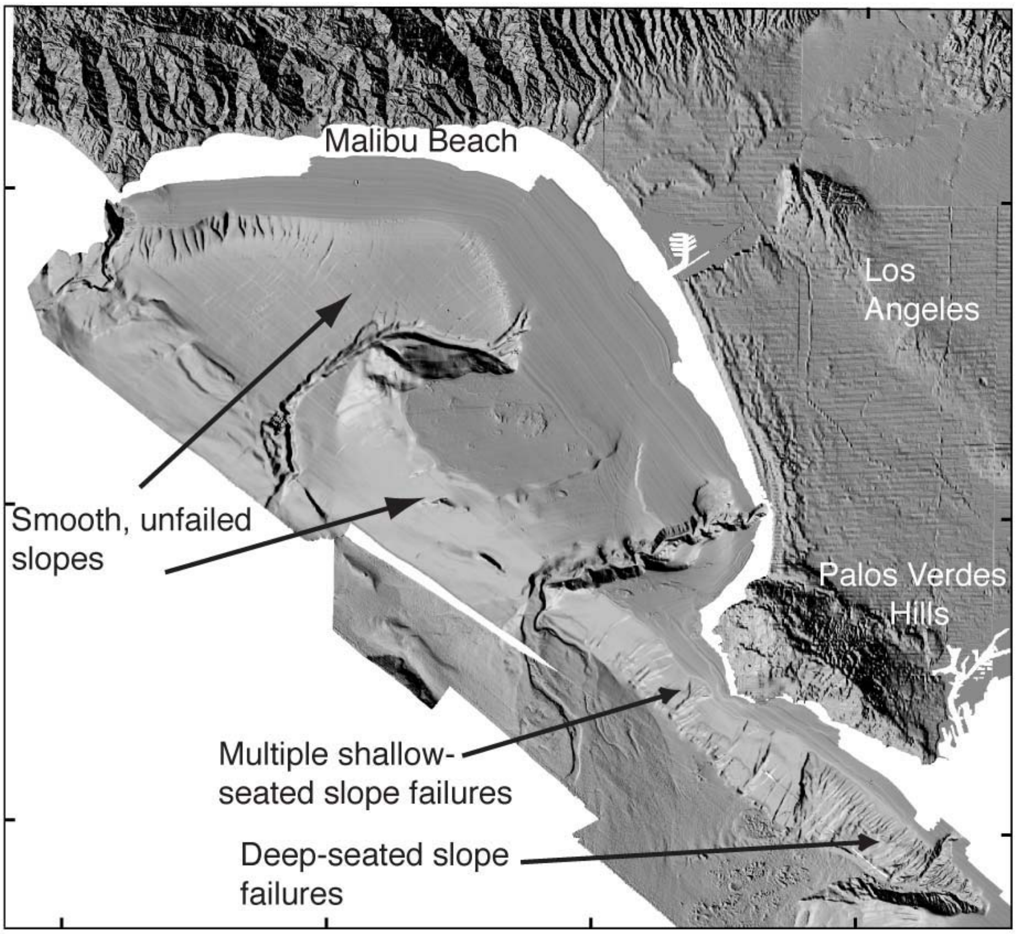

Figure 3. Multibeam imagery of the continental margin off Los Angeles California showing a slope dominated by landslide activity south of the Palos Verdes Hills and other slopes to the northwest that do not show indications of failure (after Lee et al. 2000).

least 10 to 20 m below the present seafloor, corresponding to at least 5,000 years of geologic history according to accumulation rates measured by Alexander and Simmoneau (1999). These gullies are not disturbed by landslide deposits either on the sediment surface or in the subbottom, indicating that this slope has been stable for many thousands of years. Note that this section of margin is subjected to magnitude 7.0 earthquakes approximately every 10 years implying exposure of this slope to hundreds of large earthquakes without failing.

Farther to the south in Santa Barbara Channel, several large and a number of smaller slope failures are apparent on multibeam imagery obtained by the Monterey Bay Aquarium Research Institute (Fig. 2, Eichhubl et al. 2002). At least one of the smaller failures may only be a few hundred years old (Lee et al. 2004) but the large failure near the center of the image is about 5000 years old. Other ancient failures have occurred at the location of the large failures as recorded in in subbottom profiles. These failures likely have a recurrence interval of about 15,000 years (Lee et al. 2004). Unfailed smooth slopes, lying to the west of the major failures (for example in the area of core 601 P1), have apparently been stable for long periods of geologic time, certainly in the range of thousands of years. Again, during this period of stability, hundreds of large earthquakes must have occurred without causing the slope to fail.

Finally, Figure 3 shows a section of the southern California margin off the coast of the City of Los Angeles. One part of this image from the continental slope off the Palos Verdes Peninsula shows multiple shallow- and deep-seated slope failures. However, as noted in the figure, many sections of the slope are smooth, sediment-covered and apparently unfailed.

These three figures show several dramatic slope failures but a general paucity of landslides in one of the most seismically active margins of the United States. These figures support the general findings of McAdoo et al. (2000) that the west coast of the United States has a relatively lower concentration of continental slope submarine landslides than do other U.S. continental margins.

3. ANALYSIS

Lee and Edwards (1986) used a modified form of Morgenstern's (1967) infinite slope analysis for seismic loading of submarine slope. Earthquake loads are represented by a pseudo-static acceleration. For a factor of safety of 1, the critical pseudo-static acceleration, k_c, is:

$$K_c = (\gamma'/\gamma)\ [S\ (OCR)^m - \sin \alpha] \qquad [1]$$

where (γ'/γ) is the ratio of buoyant to total unit weight (typically about 1/3), S is the ratio of undrained shear strength to overburden effective stress for normal consolidation (typically about 0.3), OCR is the overconsolidation ratio, m is a soil constant (typically = 0.8) derived from a normalized soil parameter approach (Ladd and Foott 1974) and α is the slope steepness. Accordingly, for typical values, normal consolidation, and no slope, the critical acceleration is 0.1 *g*. For a typical slope of 4°, K_c becomes 0.076 *g*. Such low values of acceleration would likely be exceeded frequently along the coast of California. Only with some level of OCR can higher critical accelerations be obtained, allowing submarine slopes to withstand repeated seismic shaking.

4. THE IMPACT OF SEISMIC SHAKING

We generally think of seismic shaking as contributing to a reduction in sediment shear strength. In fact in the case of loose, cohesionless soils, we know that seismic shaking can lead to liquefaction, loss of bearing capacity, and collapse of engineering structures. For cohesive sediment we have found that there is also a loss in shear strength during cyclic loading. For example, based on an extensive series of cyclic triaxial tests on sediment from off the coast of southern Alaska, we found that the cyclic strength (defined as cyclic stress level necessary to cause 20% axial strain in 10 cycles) ranged between 40% and 105% of static strength, depending upon plasticity (Lee and Edwards 1986).

One of the reasons that cyclic loading causes a reduction in shear strength, or even liquefaction, is that cyclic loads transfer overburden stress from interparticle contacts to the interstitial water. This transfer causes an increase in pore water pressure and a decrease in effective stress. Such changes cause an immediate decrease in strength.

If the sediment column does not fail during an earthquake, some of the excess pore water pressures generated by seismic shaking will remain and slowly dissipate with time. Such dissipation will result from pore water drainage out of the sediment fabric and associated compaction. Although not necessarily so, this densification can result in apparent overconsolidation, a net gain in undrained shear strength and an enhanced ability of the sediment fabric to resist cyclic loads in the future. One would expect that future earthquakes of the same magnitude would have a similar effect, although perhaps with decreasing amounts of densification and strength gain. At some point, after many episodes of cyclic loading and perhaps corresponding to the steady state of deformation (Poulos 1981), cyclic loading would no longer induce positive pore water pressures (contractive behavior) and might begin inducing negative pore water pressures (contractive behavior). This would relate to the maximum amount of strength gain possible by the seismic strengthening mechanism.

Many submarine slopes are depositional environments. For these situations, one might expect there to be a tradeoff between continuing deposition and cyclic strengthening. That is, earthquakes, pore pressure generation, and subsequent pore water drainage would lead to densification and the development of apparent overconsolidation. Continued deposition would drive the sediment toward a state that would be more nearly normally consolidated. We expect that, ultimately, models can be developed that relate levels of seismic strengthening, sediment accumulation rates, earthquake loading recurrence intervals, and steady-state strength behavior. The present paper presents preliminary data that can ultimately be directed toward this model.

5. FIELD EVIDENCE

A piston core sample was recently obtained in the Santa Barbara Channel of southern California on an apparently stable slope between the remains of two large slope failure deposits (Figure 2, Core 601P1). Several of the core sections were split and fall cone penetrometer tests were conducted downcore to determine the undrained shear strength profile. Figure 4 shows these results as well as an estimate of what the strength profile would be if the sediment were normally consolidated (S assumed equal to 0.3, Lee and Edwards, 1986). As may be seen the measured shear strengths exceed the normally consolidated values by a factor of 2 or more, indicating some level of apparent overconsoldiation. As an indication of age control and seismicity, the accumulation rate in this region is about 1 mm/yr (Lee et al. 2004) and the last major earthquake in this area occurred in 1812 (corresponding to a depth in core of about 20 cm). If large earthquakes occur every few hundred years, then the 5 m long sequence shown by Core 601P1 represents perhaps 20 large earthquakes.

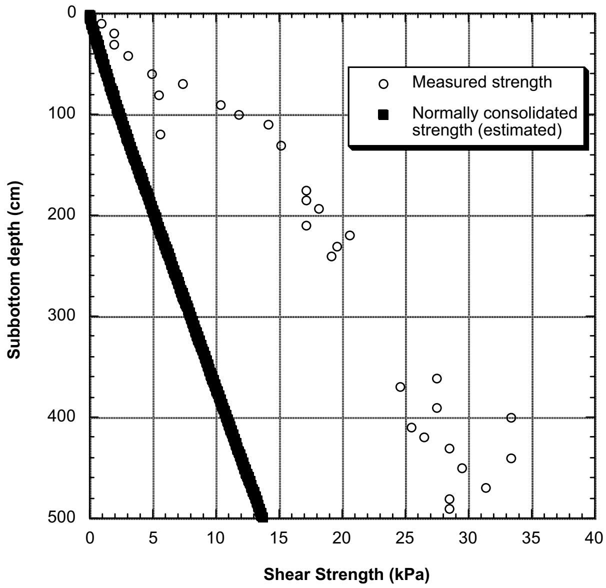

Figure 4. Shear strength of Piston Core 601 P1 compared with an estimated normally consolidated strength profile.

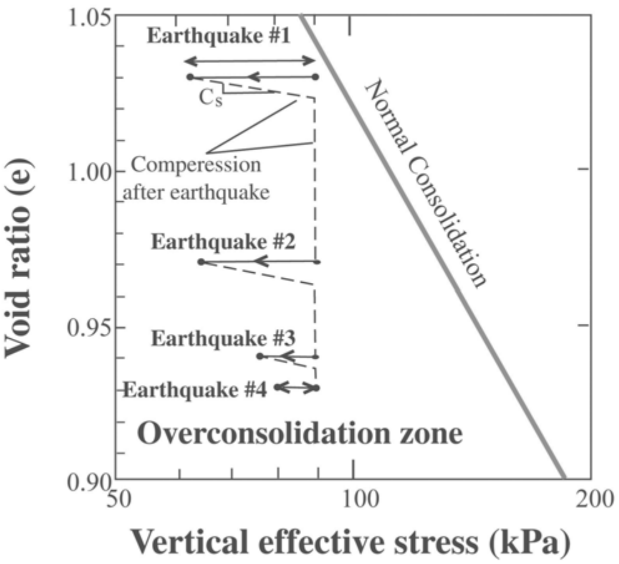

Figure 5. Void ratio-effective stress data showing the response of sediment to four bursts of cyclic loading (simulated "earthquakes") applied in a testing program at Laval University. The "normal consolidation" line corresponds to a SEDCON test conducted on a comparable sample.

6. LABORATORY SIMULATIONS

Laboratory simulations of seismic strengthening were conducted at Laval University (Boulanger et al. 1998, Boulanger 2000) and recently at the USGS. In both simulations, sediment samples were consolidated in a direct simple shear device to a predetermined vertical consolidation stress level, σ_{vc}'. Next the samples were subjected to a series of simulated earthquakes. A set of shear stress cycles was applied to the samples under undrained loading and the amount of pore pressure development was measured. The drainage valve leading to the samples was then opened, water was allowed to flow and the generated excess pore water pressures were allowed to dissipate. Additional bursts of cyclic loading were then applied, again followed by a period of full pore pressure dissipation and drainage. The overall response of the sediment samples was compared with one-dimensional consolidation tests of comparable samples so that the degree of induced overconsolidation could be determined. In the case of the USGS testing, the seismically-strengthened sample was finally failed by monotonic simple shear loading under undrained conditions. A control sample was also prepared that was consolidated normally and then failed under undrained conditions.

Fig. 5 shows the results of a simulation at Laval University. A reconstituted sample of sediment from the Eel margin, northern California (Locat et al. 2002) was consolidated to a vertical effective stress of 90 kPa. A total of four bursts of undrained cyclic loading were applied with a cyclic stress ratio (cyclic stress level divided by vertical consolidation stress) of 22%, The number of cycles per burst was 10 for the first burst and 20, 40, and 210 for the subsequent bursts. As can be seen in Fig. 5, each cyclic burst/reconsolidation cycle caused a reduction in void ratio although the amount of reduction became smaller with each burst. Likewise the amount of pore pressure generated also decreased with each burst, even though the number of cycles applied was increasing. For comparison a SEDCON test (Locat 1982, Locat et al. 2002) was conducted on similar reconstituted sediment (Fig. 5). Such a test is used to simulate natural sedimentation and sediment fabric development and defines the consolidation path that would be followed under truly normal consolidation. Fig. 5 shows that the bursts of cyclic loading have produced lower void ratios than would be expected for normal consolidation. Overconsolidation ratios (OCR) can be obtained for the sediment after each cyclic burst by constructing parallel recompression curves. An estimate of static shear strength, s_u, can then be obtained using normalized soil parameters (Ladd and Foott 1974; Lee and Edwards 1986) with S = 0.3 and m = 0.8 as discussed previously:

$$s_u = S\ OCR^m \qquad [2]$$

Fig. 6 shows how estimated undrained shear strength increases as a function of number of simulated earthquakes (bursts of cyclic loading followed by reconsolidation). For this particular test the estimated shear strengh increases by 67% after only 3 "earthquakes."

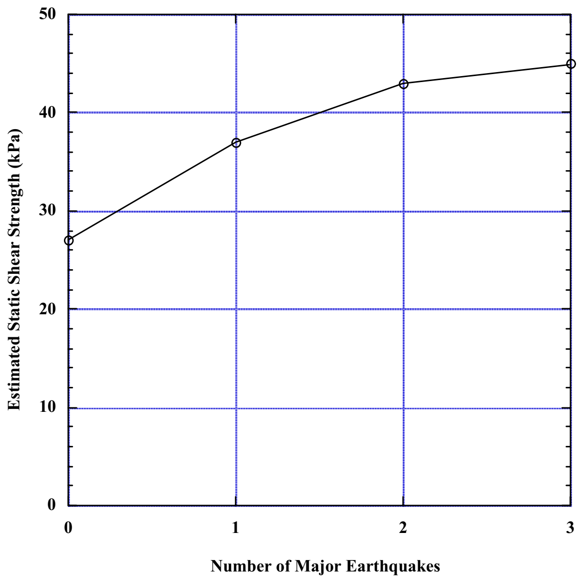

Figure 6. Estimated shear strength increase related to the simulated earthquakes shown in Fig. 5. Shear strength was estimated from OCR using Eq. 2.

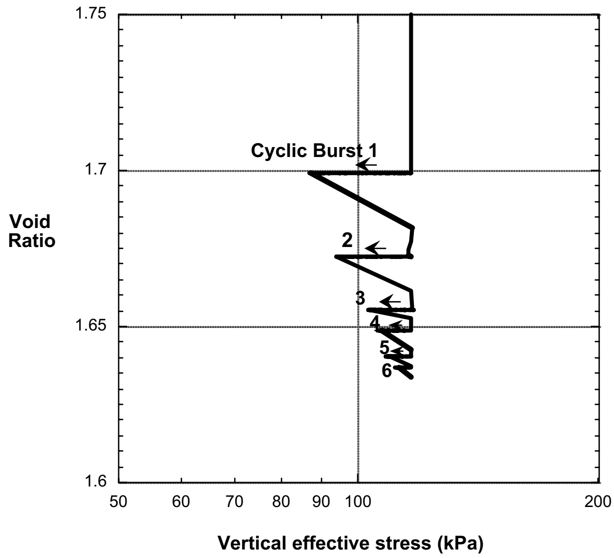

Figure 7. Void ratio-effective stress data showing the response of San Francisco Bay mud to six bursts of cyclic loading (simulated "earthquakes") applied in a testing program at the USGS.

At the USGS we tested natural samples from San Francisco Bay. We consolidated the samples in a direct simple shear cell to a vertical effective stress of 116 kPa. We then applied a series of 6 bursts of cyclic loading, each followed by a period of drainage and reconsolidation. The cyclic stress ratio for these bursts was 32%. In contrast with the tests at Laval University, we applied the same number of cycles for each burst: 23 cycles. We found a similar response (Fig. 7) to the Laval tests. The void ratio decreased with each burst but the change in void ratio per burst became smaller with each successive burst. The San Francisco Bay mud is more plastic and has a higher void ratio than the Eel margin sediment. This is reflected in a generally higher void ratio scale for the USGS tests and a smaller pore pressure response for each burst of cyclic stresses.

To determine the effect on shear strength of San Francisco Bay mud, we failed the sample that had been "seismically strengthened" with 6 bursts of cyclic loading. We also failed a control sample consolidated to the same effective stress level (116 kPa) but with no cyclic loading history. We found that the cyclically strengthened sample was 11% stronger than the control sample. The smaller increase in strength for the USGS tests perhaps reflects a difference in sediment type or a difference in the test approach. In any case, for both Laval and USGS simulations, we found that a history of cyclic ("seismic") loading strengthens marine sediment and has the potential to enhance the stability of marine slopes.

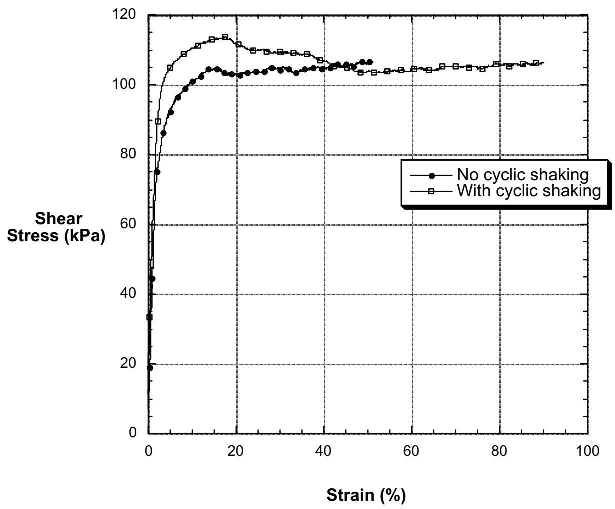

Figure 8. Results of static direct simple shear tests on two samples of San Francisco Bay mud. Samples were treated identically except one sample (higher strength) was subjected to 6 simulated "earthquakes" and the other was not.

7. CONCLUSIONS

The morphology of slopes in seismically active areas shows fewer deposits from submarine landslides than one might expect given the apparent severity of loading that earthquakes produce on the seafloor. In fact a comparison of continental slopes around the margins of the United States shows an almost inverse relation between landslide occurrence and seismicity. Within individual study areas off the coast of California, where highly accurate multibeam bathymetric maps have been prepared, dramatic landslide deposits are observed but so are large areas of unfailed slopes.

Within an area of unfailed slope between two large slope failures in Santa Barbara Channel, we found that the sediment shear strength is at least twice as large as we would expect for normally consolidated sediment. We suggest that the sediment is unusually strong because of the process of "seismic strengthening." With each passing earthquake the sediment's excess pore pressure is increased. If the sediment does not fail immediately, the pore pressures will dissipate as pore water drains, and the sediment will densify. In time, the sediment will become strong enough to withstand most earthquakes.

Laboratory simulations show that the process of seismic strengthening is effective and leads to significant strength gains, as large as 67%. We expect that the amount of strength that can be gained is a function of level of seismic shaking, recurrence intervals of major earthquakes, sedimentation rate, and sediment properties such as plasticity and the character of the steady state line.

8. ACKNOWLEDGEMENTS

The authors gratefully acknowledge support from the Geology and Geophysics Program of the Office of Naval Research, the U.S. Geological Survey, and the Conseil de Reecherche en Sciences Naturelles et en Génie du Canada (CRSNG). The authors thank Robert Kayen, and Brad Carkin for their helpful comments and support in conducting the laboratory testing programs.

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