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SIMULATING SUBMARINE SLOPE INSTABILITY INITIATION USING CENTRIFUGE MODEL TESTING

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ABSTRACT
COSTA is addressing the questions of why seafloor slope failures occur where they do, and with what frequency they occur. The original program has been complemented by COSTA-Canada. One of the tasks involves the study of the initiation of slope instability through numerical and centrifuge modelling.

This paper reviews previous centrifuge studies related to submarine slop failure and presents the preparations for this task. The initiation of submarine slope instability has been attributed to triggers such as earthquakes, erosion, oversteepening, wave loading, gassy soils and sedimentation. Centrifuge modelling has been used to simulate most of these loading conditions in similar boundary value problems.

RÉSUMÉ
COSTA adresse les questions de pourquoi les échecs de pente de seafloor se produisent où ils , et avec quelle fréquence ils se produisent. Le programme original a été complété par COSTA-Canada. Un des tâches implique l'étude du déclenchement de l'instabilité de pente par modeler numérique et de centrifugeuse.

Cet article passe en revue des études précédentes de centrifugeuse liées à l'échec submersible de slop et présente les préparations pour cette tâche. Le déclenchement de l'instabilité submersible de pente a été attribué aux déclenchements tels que des tremblements de terre, l'érosion, le chargement de vague, des sols grisouteux et la sédimentation. Modeler de centrifugeuse a été employé pour simuler la plupart de ces conditions de charge dans les problèmes de valeur semblables.

1. INTRODUCTION

Submarine slope stability has been identified as a major concern in offshore resource development. Research programs have attempted to characterise and understand submarine failures worldwide. These programs have included the Arctic Delta Failure Experiment (ADFEX) 1982-1992, Geological Long Range Inclined Asdic (GLORIA) 1984-1991, Sediment Transport on Atlantic Margins (STEAM) 1993-1996, ENAM II 1996-1999, STRATAFORM 1995-2001 and Continental Slope Stability (COSTA) 2000 to present.

The original COSTA program on seafloor stability has been complemented by COSTA-Canada, Locat and Héroux (2001) and http://www.costa-canada.ggl.ulaval.ca. One of the 6 tasks in this complementary study involves the initiation of slope instability through numerical and centrifuge modelling.

The initiation of submarine slope instability has been attributed to triggers such as earthquakes, waves, tides, sedimentation, gas, erosion and diapirism, Hampton et al (1996). Centrifuge modelling has been used to simulate many of these loading conditions and relevant soil conditions in similar seafloor stability studies. Figure 1 shows a submarine slope failure model of a submerged 8^{o} slope which flowed to an angle of 2^{o} in normally consolidated silty clay due to an increase of excess pore water pressure in the slope. Following an overview of centrifuge modelling, other examples reviewed in this paper include submarine failures from:

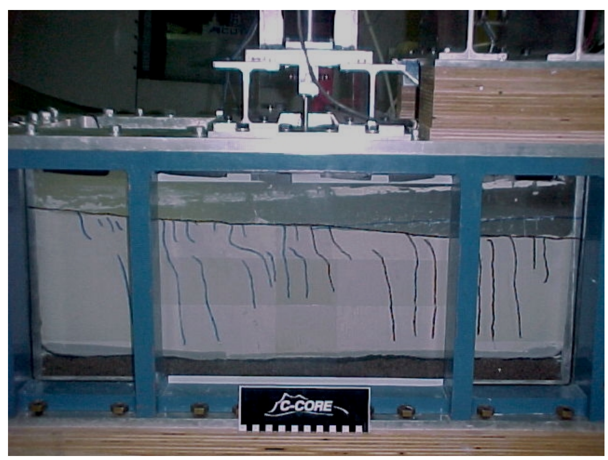

Figure 1 - Submarine Slope Failure in Silty Clay.

a) Material softening,
b) Sedimentation,
c) Wave loading, and
d) Earthquakes.

2. CENTRIFUGE MODELLING

Centrifuge model testing is a physical modelling tool for geotechnical engineers. Analogues to this technique exist in other branches of civil engineering, such as wind tunnel testing in aeronautical engineering and flume testing in hydraulic engineering. To achieve mechanical similitude in geotechnical models it is necessary to reproduce the material behaviour both in terms of strength and stiffness. This behaviour is primarily a function of the effective stress resulting from self-weight and other external forces.

Centrifuge modelling then is a technique for investigating gravity dependant phenomena, such as soil slope behaviour, using reduced-scale physical models. As a full-scale soil structure is in equilibrium under earth's gravitational field, g, a reduced-scale model on a centrifuge, at radius R, is in equilibrium under an acceleration field of $R\omega^2$, where ω is the rotational speed of the centrifuge. The model will then have its weight increased N times, where $N = R\omega^2/g$.

For a typical value of N = 100, if a model is made at 1/100th scale and is accelerated to 100g, the stresses due to self-weight will be similar to the stresses in the prototype at homologous points. The model can then reproduce the phenomena of cracking, rupture or flow that would be observed in the prototype because the stress dependency of soil behaviour has been correctly simulated. The principles, scaling laws and some applications of centrifuge modelling are more fully described by Murff (1996) and Taylor (1995).

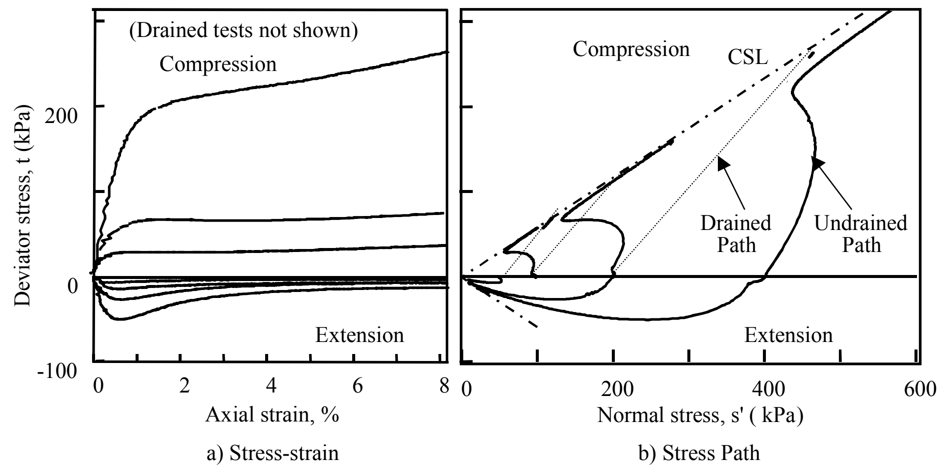

Figure 2 – Oil Sand Triaxial Response from Initial D_r of 40%

3. MATERIAL SOFTENING

The Canadian Liquefaction Experiment (CANLEX) by Robertson et al (2000) investigated the liquefaction potential of loose sand deposits under monotonic shear stress increments. The program included high quality soils testing, numerical analyses and a full-scale field event designed to cause a flowslide. Centrifuge model tests were added to the CANLEX program to provide additional physical data and to simulate the physical response of the field event. The oil sand tailings from the field site used in the model tests were strain softening under triaxial extension, Figure 2. One centrifuge model simulated the failure of a 16°, 8.8m high loose sand submerged slope, Phillips and Byrne (1994). Surcharging the slope crest caused the model slope to liquefy and flow with deep-seated lateral movements to an angle of 7°, Figure 3. This submarine slope failure occurred primarily due to the strain softening response of the sand at the toe of the slope that caused pore pressure increases and destabilisation of the slope.

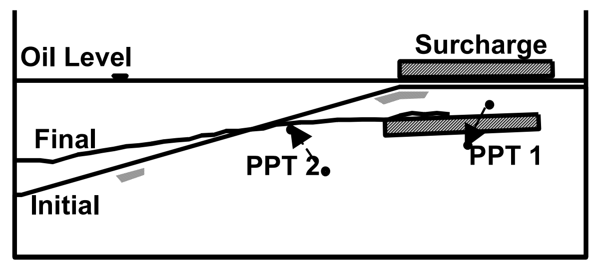

Figure 3 - CANLEX Submerged Slope Flowslide Failure

4. SEDIMENTATION

There are other external loading conditions that can cause pore pressure increases in the vicinity of slopes. Continuous sedimentation has been identified as one such loading condition. Hurley (1999) has modelled the sedimentation and primary consolidation of a highly permeable cohesive kaolin sediment from 580% water content. The equivalent of 10m depth of aqueous slurry sedimented and consolidated into a 2m thick silty clay layer, Figure 4. Continuous measurements of bulk density (from gamma ray attenuation), pore pressure and shear and compression wave velocities were made at 100g. The excess pore pressures generated by this sedimentation process may be sufficient to destabilise a submarine slope, Figure 5. The excess pore pressure at

PPT6 5m down in the consolidating clay layer was 30kPa at the equivalent of 2 years (100 mins.) after commencement of sedimentation. This is equivalent to an excess pore pressure ratio, r_u, of about unity. The associated effective shear strength is low. If sufficient material is subject to such pore pressures then seafloor instability can ensue.

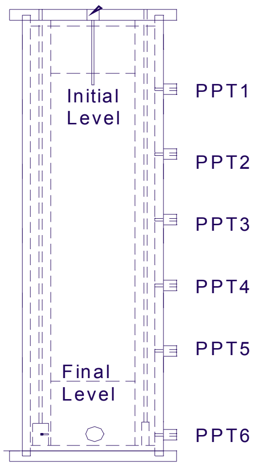

Figure 4 - Sediment column test setup

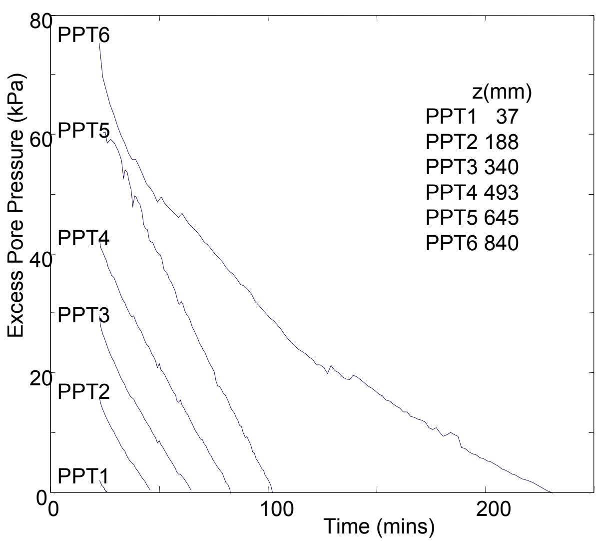

Figure 5 - Excess Pore Pressures in Slurry Sediment

5. WAVE LOADING

Wave loads can also cause excess pore pressures leading to seabed mobility and liquefaction. The techniques for modelling wave seabed interaction were developed by Phillips and Sekiguchi (1992). Sekiguchi et al (2000) simulated at 50g the response of a 4.5m thick sand layer under 4m water depth subjected to 0.3m high waves with a 6 second period, Figure 6. A 50-centistoke pore fluid was used to allow simultaneous time scaling of diffusion and inertial processes.

Significant seabed mobility and liquefaction was observed to propagate down from the seafloor to base of the sand layer. Figure 7 shows the excess pore pressure response, u_e, at the sand base to pressure cycles at the

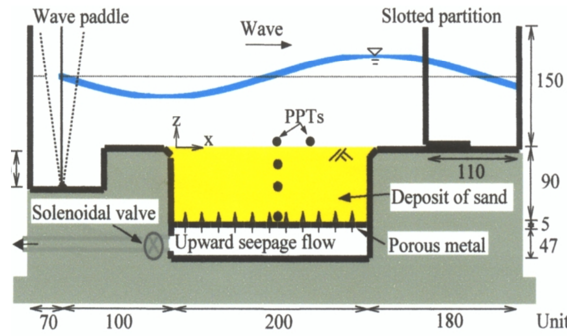

Figure 6 - Wave Loading Model Test Setup

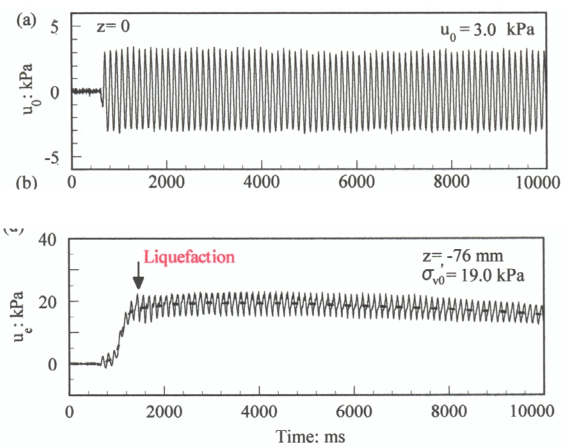

Figure 7 Excess Pore Pressure Response in Seabed

seafloor. Three additional configurations were modelled with a gravel cap of various lengths on the seabed to develop a mitigation strategy to minimise damage to the seafloor.

6. EARTHQUAKE EFFECTS

6.1 VELACS

The VELACS (Verification of Earthquake Liquefaction Analysis by Centrifuge Studies) program considered the effects of earthquake-like loading on a variety of soil models, Arulanandan and Scott (1993 &1994) and http://ceor.princeton.edu/~radu/soil/velacs/. VELACS was aimed at better understanding the mechanisms of soil liquefaction and at acquiring data for the verification of various analysis procedures. The response of each of nine boundary value configurations was predicted by between 4 to 16 numerical analysts. The Class-A predictions were then compared to the measured response from nominally the same physical model test conducted at between 1 to 3 centrifuge centres.

Model 2 involved the simulation of lateral spreading of a submerged slope due to earthquake effects, Figure 8. The submerged 2° slope comprised a saturated 10m

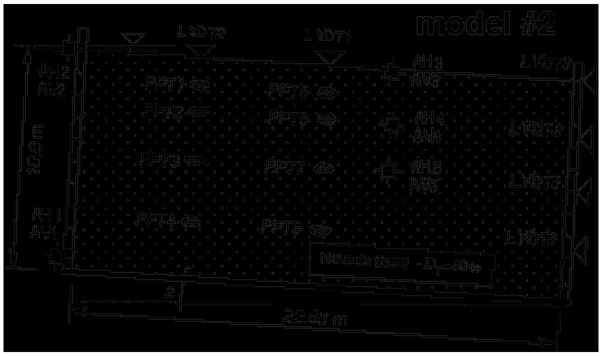

Figure 8 - VELACS Model 2 test setup

deep layer of Nevada sand at 40% relative density. The base of the layer was subjected to about 22 cycles to 0.1g lateral acceleration at 2Hz. The toe of the slope at the seafloor, LVDT 3 was observed to move downslope a distance of 0.5m due to this earthquake, Figure 9.

6.2 Earthquake Simulation

C-CORE will commission a C$0.5m earthquake simulator (EQS) on its 5.5m radius centrifuge before the end of 2002. This single axis EQS shown in Figure 10 will excite a 400kg moving payload of 1m length by 0.5m width by up to 0.6m high with a maximum force of 200kN. The peak lateral acceleration of the full payload will be 40g under a constant (centrifugal) acceleration of 80g. The lateral acceleration envelope is shown in Figure 11 over the frequency range of 40 to 200Hz.

6.3 COSTA Canada

This EQS will be used from late 2001 in the COSTA-Canada program to conduct tests similar to those shown in Figure 8. Lower permeability silt layers will be introduced into the sand layer to simulate a stratified profile. The effect of these layers on pore pressure generation and subsequent dissipation will be examined. The silt layers will impede drainage of the sand. The

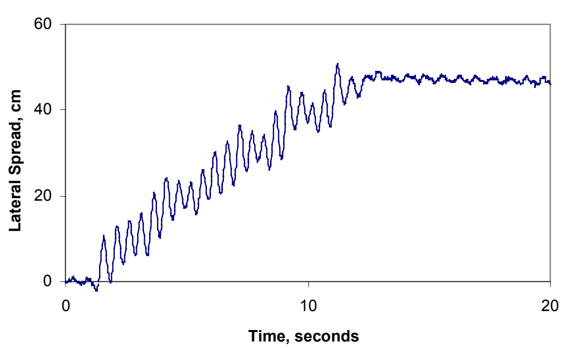

Figure 9 - VELACS Model 2 Lateral Spread

migration of pore pressure towards potential drainage boundaries is also expected to cause continued movement of the slope after cessation of the earthquake.

The preliminary results of this study will be presented to the next Canadian Geotechnical Conference in 2002.

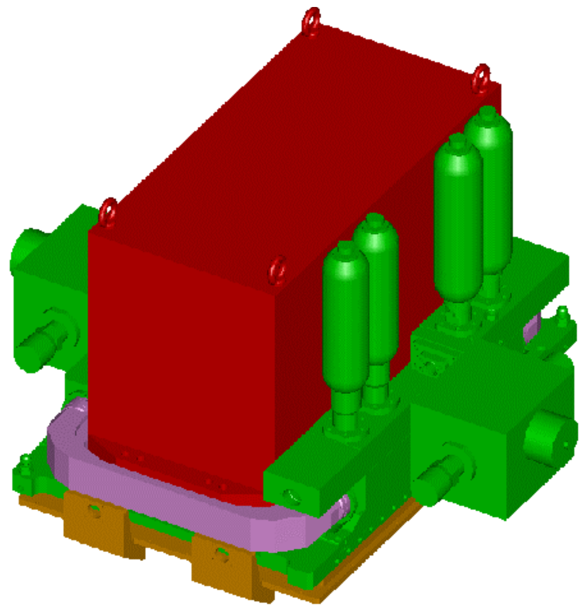

Figure 10 - C-CORE Earthquake Simulator Layout

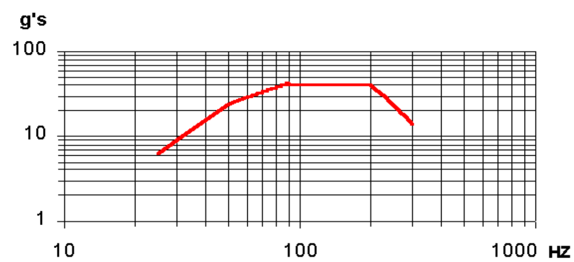

Figure 11 - EQS Performance Envelope

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