EARTHQUAKE SIMULATOR DEVELOPMENT FOR THE C-CORE GEOTECHNICAL CENTRIFUGE

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ABSTRACT
An electro-hydraulic earthquake simulator (EQS) has been developed for use with the C-CORE Centrifuge in St. John's. The EQS applies a one-dimensional prescribed base input motion to a maximum 400 kg payload of 1 m length by 0.5 m width by up to 0.6 m high with a maximum force of 220 kN. The full payload experiences a peak lateral acceleration of 40g under a constant centrifugal acceleration up to 80g within a shaking frequency range of 40-200 Hz. This paper describes the EQS and presents data from preliminary testing involving the replication of the earthquake signal to be used for the centrifuge tests to be undertaken as part of the COSTA-Canada project.

RÉSUMÉ
Un générateur de tremblement de terre (EQS) a été développé pour être utilisé sur la centrifugeuse de C-CORE à Saint Jean de Terre Neuve. Ce EQS applique une excitation imposée unidimensionnelle sur une charge de 400 kg maximum. Les dimensions de la charge utile sont de 1 m de longueur sur 0.5 m. La force maximale appliquée est de 220 kN. La pleine charge peut être sollicitée par une accélération latérale maximale de 40g sous une accélération centrifuge jusqu'à 80g dans la plage de fréquence de 40-200 Hz. Cet article décrit le EQS et présente des données d'essais préliminaires incluant la réplique du signal de tremblement de terre pour les essais en centrifugeuse faisant partie du projet COSTA-Canada.

1. INTRODUCTION

In 1993 C-CORE, on the campus of the Memorial University of Newfoundland, installed the first large geotechnical centrifuge in Canada with a maximum payload capacity of 220 g-tonnes. The Acutronic 680-2 Centrifuge, as shown in Figure 1, has a radius of 5.5 m to the swinging platform and can accommodate a payload of up to 1.1 m by 1.4 m in plan and up to 1.2 m in height over the full platform area with the headroom increasing to 2.1 m at the centre of the platform. The maximum rotational speed of the centrifuge is 189 rpm creating an acceleration of 200g at a radius of 5 m. At an acceleration of 100g the centrifuge carries a maximum payload of 2.2 tonnes, reducing to 0.65 tonnes under 200g, Phillips et al. (1994).

Figure 1. C-CORE Geotechnical Centrifuge

The C-CORE Centrifuge was used during its first 10 years of operation for static and cold regions tests, for example Kosar et al. (1997), Clark & Phillips (2003) and Lau et al. (2002). In 1997 it was decided to increase the Centres capability to include earthquake testing and more studies of liquefaction and its effects, Byrne et al (2000). There are several objectives that must be considered to develop an EQS, as considered by Van Laak et al. (1994):

- capability for producing input motions having arbitrary shape
- base excitation in one direction only, with constraints to prevent uncontrollable vertical and transverse horizontal motions
- easy installation and removal
- low maintenance and high reliability
- capability for multiple successive shakings without stopping the centrifuge.

In addition to these general objectives there were other objectives that were unique to C-CORE's centrifuge, including:

- platform size constraints
- mass constraints
- compatibility with C-CORE's centrifuge systems
- capability of operation at up to 80g centrifugal acceleration
- capability to run the earthquake shaker and acquire data simultaneously
- elimination of rocking moment generated in the slip plane typically caused by classical earthquake actuators

- attenuation of undesirable centrifuge mode shapes
- maintaining centrifuge versatility and quick test turn round

With these objectives, the original engineering team for the C-CORE Centrifuge, Actidyn Systemes of France, were retained to develop their Model QS 67-2 Electro-hydraulic Earthquake Shaker (EQS).

2. CENTRIFUGE EARTHQUAKE ACTUATION

Numerous techniques have been considered for on-arm centrifuge earthquake actuation over the past 25 years. One such technique to deliver earthquake motion was the concept of releasing a cocked spring to produce free, damped vibrations, Morris (1983). The problems related to this method are that the motion of the spring is dependent upon the mass of the model and the stiffness of the spring, variables that cannot be easily altered to meet the requirements of a particular test (Ko, 1994).

Another technique was the bumpy road method as described by Schofield (1981). This method involved the test package making contact with a wavy track mounted on the wall of the centrifuge chamber. However, several problems were identified with this method. Often the motion was contaminated by other frequencies than those desired due to the dynamics of the motion transfer mechanism and also the input frequency is dependent upon the speed of the machine (Ko, 1994).

Several other methods include the use of piezoelectrics to (Arulananadan et al, 1982), the detonation of explosives at the container boundary (Zelikson et al., 1981), and the use of electromagnets (Fujii, 1991).

The electro-hydraulic method has emerged as the most versatile, using servo-controls to deliver any desired motion to the test package (Ko, 1994). This servo-hydraulic technology has been used extensively in centrifuge shaking applications (Figueroa et al. 1998, Imamura et al. 1998, Matsuo et al. 1998, Van Laak et al. 1994, Nagura et al. 1994 and Kutter et al. 1994). This method is an extension of technology that has been used for many years in structural and laboratory testing to great success.

Some centrifuge centres are now developing two-axis electro-hydraulic earthquake simulators, such as at Rensellaer Polytechnic Institute (www.nees.rpi.edu) and University of California at Davis (http://nees.ucdavis.edu).

3. CLASSICAL ELECTRO-HYDRAULIC EARTHQUAKE ACTUATION

Normal electro-hydraulic earthquake shakers feature a model container attached to a slip table carried by the centrifuge platform at the end of the centrifuge arm. When an actuation force is applied to the soil model of mass (M) a moment or torque ($T = M * d$) is applied to the centrifuge platform. This moment is then offset by the inertia of the spinning platform and the overall centrifuge structure itself.

When a dynamic force F_m is applied to a soil model mounted on a classical unbalanced earthquake simulator on a functioning centrifuge the mass of the soil and its container generates a dynamic moment (T_m) that is counteracted by the platform inertia and stiffness as shown in Figure 2, Perdriat et al. (2002)

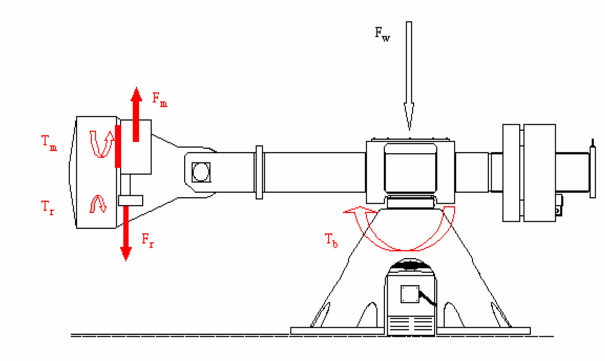

Figure 2. Centrifuge Reaction Forces

Since the earthquake actuator is attached to the centrifuge platform a reaction force (F_r) and reaction moment (T_r) is transmitted to the platform. This configuration typically allows the platform to experience some sort of distortion since T_m and T_r are counteracting moments that do not equal each other due to their geometry. This type of action is then transmitted to the centrifuge bearings through the rotating arm. F_r acts to add or subtract from the self weight of the centrifuge (F_w) and creates a large bending moment (T_b) to be developed in the centrifuge arm.

These dynamic forces and moments when applied to the structure of the centrifuge create significant stress and strain in addition to motions that inhibit the desired motion to be applied to the soil model.

The most significant observed detrimental effect in these classical types of actuation systems is that the centrifuge acts like a spring. The reaction forces drive the platform to rock back and forth with the same frequency of the intended actuation force. This is complicated by the fact that the centrifuge structure is a complex mass spring system that has several resonant frequencies that may be excited by these reaction forces.

4. EQS DYNAMIC BALANCING

To overcome the rocking motion described in Section 3 a new concept was developed by Actidyn for the C-CORE EQS. This concept involves dynamically balancing the shake table through the reciprocal actuation of both the model and a new component – the balancing counterweights (CW). Perdriat et al. (2002) describes the soil model and CW with masses, M_m and M_{cw} respectively, as having centre of masses located at distances d_m and d_{cw} from the platform surface. This setup is shown in Figure 3. If during actuation $F_{cw} * d_{cw} = F_m * d_m$ the torque applied to the centrifuge platform becomes minimal. The two forces, F_{cw} and F_m become balanced when the centres of mass of the CW and the model are the same height above the centrifuge platform. This setup requires complete symmetry along the X and Y axes which is achieved through a close loop control of a parallel pair of actuators for the degree of freedom.

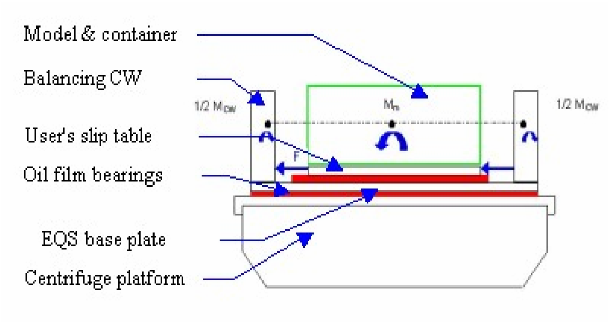

Figure 3. Dynamically Balanced Earthquake Simulator

A distributed hydraulic bearing system was used across the moving and stationary platform surfaces to eliminate any local surface distortion of the base caused by moment distribution.

Overall the EQS was designed to be free of any resonance from 30 to 350 Hz which was the frequency range of interest for possible scaled earthquake input motions. The proposed performance envelope of the C-CORE EQS is given in Figure 4.

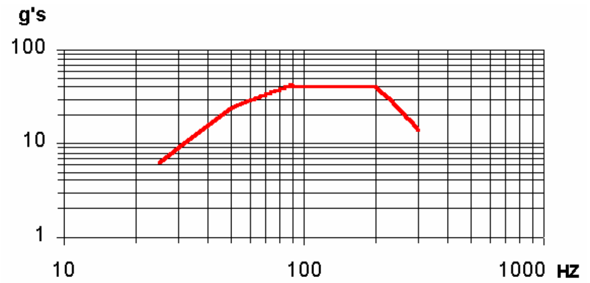

Figure 4. C-CORE EQS Performance Envelope

5. EQS ASSEMBLY

The configuration of the EQS system is shown in Figure 5 and is described in detail by Perdriat et al. (2002). The major components are a flat base (return tank) that supports the dual hydrostatic bearing, the reciprocal hydraulic actuators, the shake table with payload and the balancing CW. The balancing CW and the slip table are the two moving components that reciprocate one another.

The balancing CW is supported by two back-to-back oil film bearings and slides between the slip table and the return tank that is located on the centrifuge platform. The geometrical integrity of the system is supported by a large array of hydraulic bearings. The balancing CW includes the pair of hydraulic actuators, 8 local accumulators, servo-valves, bracing interfaces, and the load balancing counterweights. Some of the highlighted features of the EQS are: the large bandwidth high-g servo-valves to control the axial motion of the shake table; the position of the 100g-rated accumulators to minimise piping and maximise compaction; and the inclusion of manifolds to eliminate piping and minimise hydraulic resonances between the servo valves and the actuators.

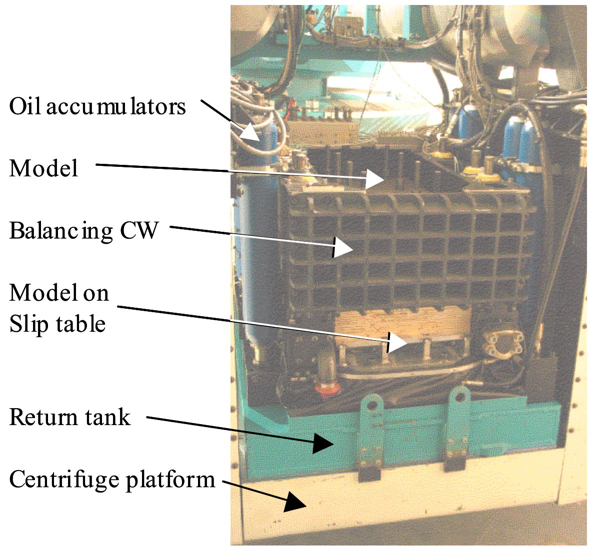

Figure 5. C-CORE EQS Assembly

The EQS is designed to operate several times during the same centrifuge flight. The model payload is mounted securely to the slip table and the counterweights are removable to allow easy access to the model container. The overall structure of the EQS was designed so that all mechanical resonances were out of the frequency range of interest.

The maximum size of the model payload is 1 m by 0.5 m by 0.6 m with a maximum mass of 400 kg up to a 80 g vertical acceleration. This maximum payload can be excited with frequencies of 40 to 200 Hz with a maximum dynamic force of 220 kN. The maximum available payload displacement is 2.5 mm and the maximum velocity is 0.5 m/s.

The EQS is powered from an off-arm 190 bar hydraulic power source (HPS) supplying the hydrostatic bearings, the main actuators and a centering system, which locates the balancing CW on the return tank. The pressure to the main actuators and centering system is boosted to 300 bar by a pump onboard the centrifuge. Oil from these 3 systems is gathered in the return tank and pumped back to the off-arm HPS.

6. EQS CONTROL SYSTEM

The EQS control system is made up of three major parts: a logic controller; a set of hydraulic loop controllers; and a dual axis digital controller and generator. This system is discussed in more detail by Perdriat et al. (2002). Figure 6 illustrates the control system for the single axis using the two actuators.

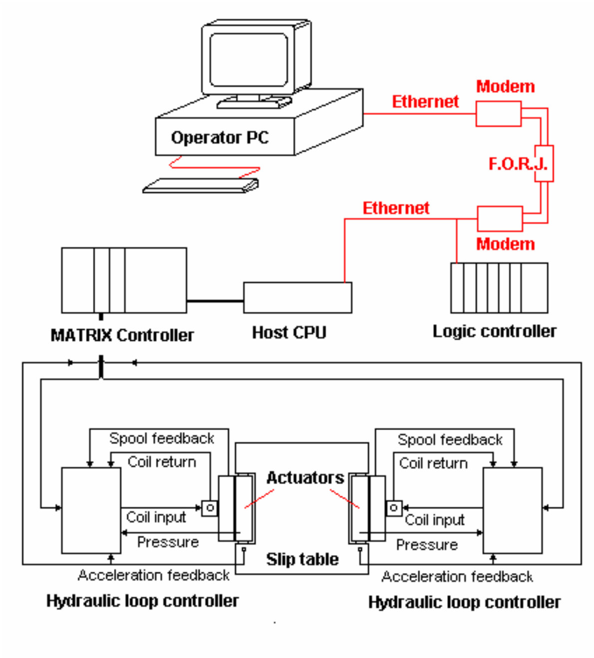

Figure 6. C-CORE EQS Control System

The logic controller is used to perform all logic functions used for proper operation of the hydraulic power supplies, the oil pressure, flow control, safety interlocks, as well as fault detection. This controller interfaces directly with the Data Physics Matrix digital controller and signal generator, which is a dedicated digital control system that can provide the application of sine, random, and shock signals. Control accuracy is kept high through the compensation of the cross-coupled dynamic responses in the multiple inputs simultaneously.

Hydraulic loop controllers are used to provide the servo valves with control power. They operate as cascade closed loops that give feedback signals based upon actuator acceleration and position and servo valve spool position. These loop controllers also compensate for the hydraulic circuit resonance frequency. Acceleration feedback is observed through piezoelectric accelerometers located on either side of the shaking table. Position feedback signals are gathered through the use of LVDT sensors.

7. DATA ACQUISITION SYSTEM

The data acquisition system acquires data simultaneously with the operation of the EQS. The Matrix system includes 8 analogue data inputs filtered at 1 kHz and sampled at 2.56 kHz per channel using VXI hardware. This hardware has a further 24 channels of analogue inputs controlled by Data Physics 620 data acquisition software. These 24 inputs are typically filtered at 2 kHz and sampled at 5.12 kHz/channel for a 16 second period before, during and after the earthquake event.

8. EQS OPERATION

The EQS is tuned over a two hour period prior to each geotechnical model test. A dummy payload similar in mass and centre of mass to the geotechnical model is mounted on the EQS. At the desired centrifugal acceleration level, the dummy payload is subjected to a pretest comprising about 8 random bursts of uncorrelated accelerations in the range 40 to 400Hz to each actuator. The pretest acceleration magnitude is set to a similar rms value to that of the target earthquake. The actuators gain and phase transfer functions are assessed from the average system response to these bursts, Figure 7.

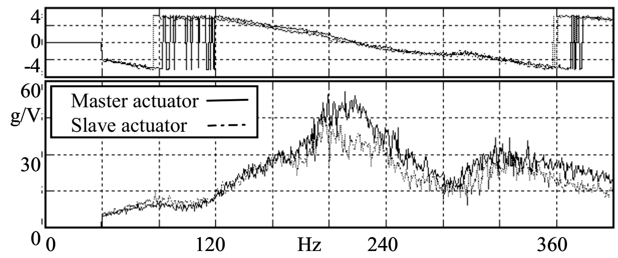

Figure 7. Typical Actuator Transfer Functions

The target earthquake motion is assessed from the prescribed earthquake motion defined in prototype terms. The prescribed motion is scaled in amplitude and time according to centrifuge similitude laws. The scaled motion is passed through a 40-200 Hz band pass filter to fit the EQS frequency and amplitude specification. The filtered motion is base line corrected to remove any residual displacement or velocity at the end of the record to give the target earthquake.

The target earthquake is imposed on the dummy payload. The actuator drive signals are improved over about five iterations to reproduce the target frequency content and phase relationships. The geotechnical model then replaces the dummy payload. The saved drive signals are replayed to conduct the geotechnical earthquake test.

9. COSTA-Canada PRELIMINARY TEST RESULTS

One of the first applications of this new EQS is to the COSTA-Canada Project. This is a collaborative project with Canadian, American and European partners to study the stability of submarine slopes, Locat et al. (2001). One of the objectives of this project is to model the forces and mechanical processes that control the initiation of slope instabilities. This is being investigated at C-CORE primarily by investigating the effect of stratified layers on the stability of submarine slopes. It is expected that the presence of lower permeability silt layers in sand slopes will effect both pore pressure generation and its subsequent dissipation.

COSTA-A was the first test to be performed with this stratified silt profile in the spring of 2004 using the techniques described by Coulter & Phillips (2003). The configuration of this centrifuge model is illustrated in Figure 8. A gravel layer is included at the bottom of the model to aid in the vacuum saturation of the model with a substitute viscous pore fluid used to reconcile dynamic and static scaling laws. All dimensions are shown in model scale in millimetres.

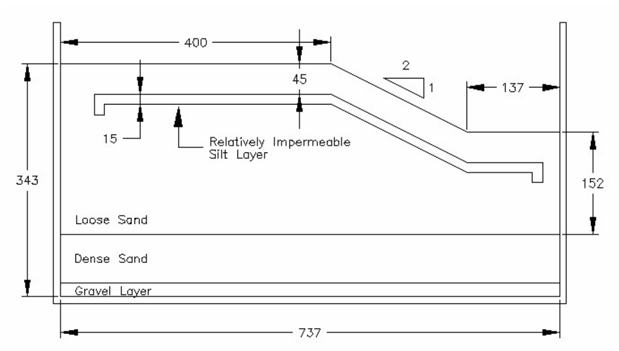

Figure 8. COSTA-A Centrifuge Test Geometry

P-wave velocities of around 1250m/s were measured in the model indicating a degree of saturation significantly more than 99%.

The target earthquake was replayed on the geotechnical model as shown in Figure 9. There is excellent reproduction of the target in both actuators in terms of amplitude and phase.

The frequency content of the target and measured accelerations are compared in Figure 10. The reproduction is excellent. The measured accelerations exceed that targeted at 120 Hz due to a slight resonance in the dummy payload configuration, Figure 7. Frequencies between 160 and 200Hz are slightly attenuated. There is no target motion above 200Hz.

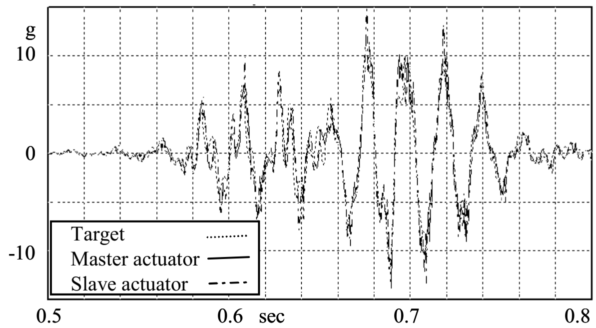

Figure 9. COSTA-A Earthquake Time Record

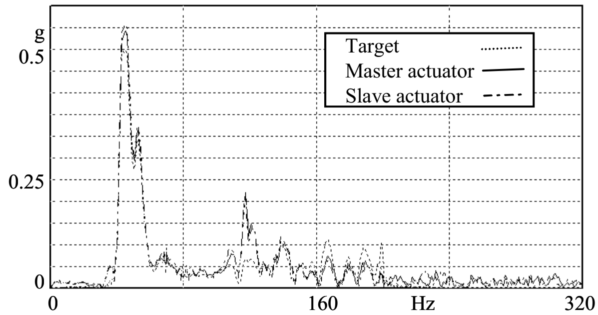

Figure 10. COSTA-A Earthquake Frequency Content

Some typical responses observed during the shaking of this model are shown in Figures 11 and 12, all measurements are given in model scale. Figure 11 displays the typical response of pore pressure directly below and above the lower permeability silt layer, in this case at the toe of the slope. This response shows how the silt layer impedes the dissipation of pore pressures generated during earthquake shaking. Above the silt layer pore pressure is generated and dissipated quite quickly. However, beneath the lower permeability silt layer long-term pore pressure measurements indicate a capturing of the generated pore pressure for a much longer period of time, which should contribute to slope instability.

Figure 12 demonstrates the typical results observed in the COSTA-A test with respect to the observed acceleration in the direction of shaking both directly beneath and above the silt layer at midslope. In the case of significant failure in the localized area of measurement one would expect to observe a larger magnitude of acceleration in the failed area as the soil becomes closer to liquefaction and thus closer to failure. However, in the case of this set of accelerometers there is no significant difference in the magnitude in the acceleration observed beneath and above the silt layer.

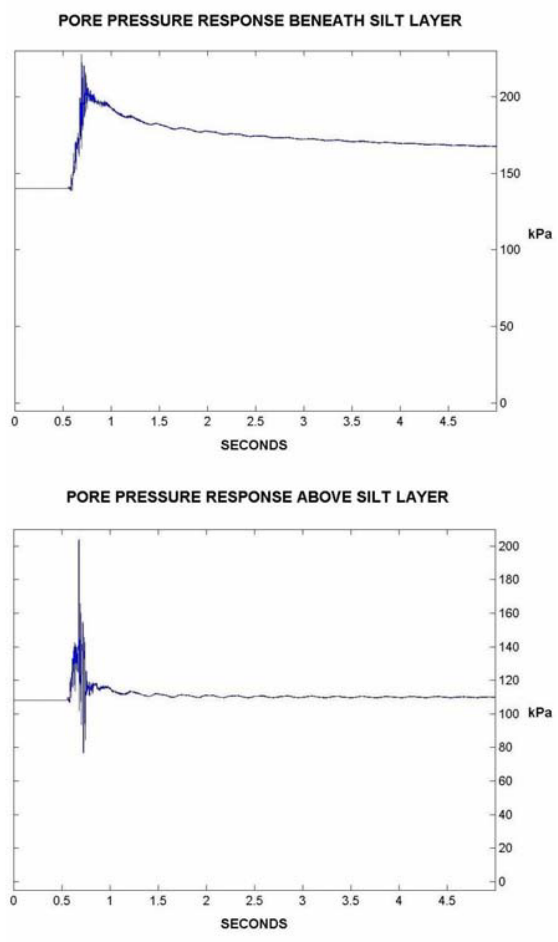

Figure 11. COSTA-A Pore Pressure Response

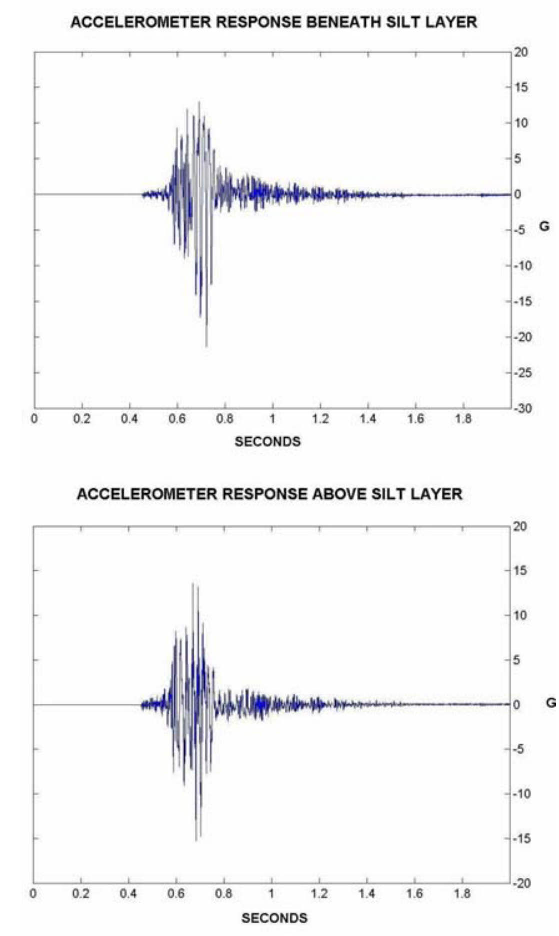

Figure 12. COSTA-A Accelerometer Response

These types of tests will continue for the remainder of 2004 under the COSTA-Canada program in order to observe the behaviour of various types of configurations of submarine slopes featuring lower permeability layers. At the time of publication the preliminary design for the COSTA-B centrifuge test was being completed, with the basic test geometry shown in profile in Figure 13, again with all dimensions in model scale in millimetres. This test is to feature a 5:1 inclined silt barrier extending most of the length of the model. This test is similar to COSTA-A in that it features a 2:1 sand slope and has the same upslope height above the bottom of the model container.

In the past year, C-CORE has also assisted in an earthquake centrifuge model test program for the George Massey tunnel in Vancouver, Adalier et al (2003) and is conducting model tests in collaboration with University of British Columbia as part of a liquefaction remediation initiative, www.civil.ubc.ca/liquefaction/.

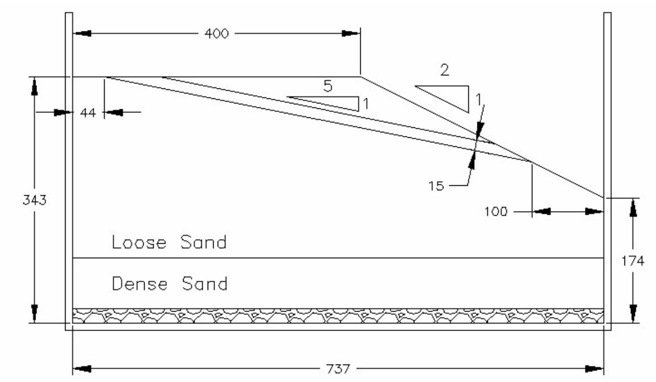

Figure 13. COSTA-B Centrifuge Test Geometry

10. CONCLUDING REMARKS

An electro-hydraulic earthquake simulator (EQS) has been developed for use with the C-CORE Centrifuge in St.

John's. A 400kg payload can be subjected to a peak lateral acceleration of 40g under a constant centrifugal acceleration up to 80g within a shaking frequency range of 40-200 Hz. Preliminary centrifuge test data has well reproduced the target earthquake motion as part of the COSTA-Canada project funded by NSERC.

The EQS is available for Canadian academic use through an existing NSERC major facility access grant and for industry usage. Ongoing earthquake centrifuge tests can be viewed remotely using a new webpresence capability from www.c-core.ca/expertise_geo.htm.

11. ACKNOWLEDGEMENTS

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