Since one of the major applications of piezocone testing is assessing properties of soft and very soft clays, a main concern is the sensitivity of the load cells. Considering this fact, the CUB1 primary load cell was designed to measure the relatively low penetration resistance of soft clays. It has a resolution of 0.0005 kN for the range 0-0.5 kN. The high sensitivity is achieved by using semiconductor strain gages. The CUB2 and CUB3 penetrometers, intended to perform penetration tests in cohesionless soils, are provided with off-the-shelf higher capacity load cells.

The piezocone pore pressure transducer is provided with a silicon diaphragm, which ensures very fast response time. The pressure transducer is placed inside the primary load cell, as shown in Figure 1. The filter is located at the cone shoulder. Whereas the piezocone shaft and the load cells are made of 7075-T6 aluminum, the cone is made of stainless steel, and the filter is made of sintered stainless steel. The filter element is obtained from cutting slices from a 10-micron porosity filter cup, with an external diameter of 12.7 mm and an internal diameter of 9.5 mm.

THE PENETRATION TESTING APPARATUS

The basic framework of the penetration testing apparatus consists of a steel base, two welded steel support frames, one main frame and one auxiliary frame, and a rotary stand, which supports the model container. The steel frames are used to support the pneumatic loading system during the consolidation process, to help placing the whole apparatus on the centrifuge platform, and to support the piezocone driving device (Fig. 2).

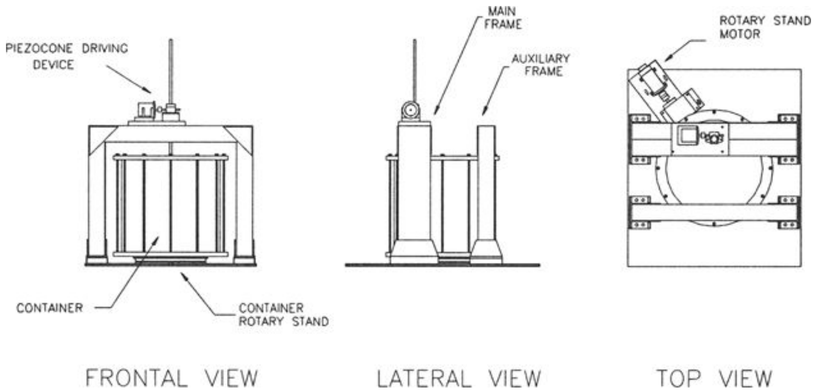

Fig. 2. Penetration Testing Apparatus

The purpose of the container rotary stand is to allow different penetration tests at different sites in the same tub of soil, without stopping the centrifuge to change the position. The rotary stand consists of a steel disk pivoted in the center and supported by hard metal ball bearings. The rotary stand is driven by a servomotor, through a gear reducer (1:60), a chain and sprockets.

The piezocone driving device consists of a linear mechanical actuator, which is driven by a servomotor. The position and the motion of the piezocone are controlled from a computer located in the centrifuge control room.

MOTION CONTROL SYSTEM

A modular motion control system remotely controls the operation of the piezocone driving device, the container rotating stand and the vane apparatus. The basic system is made up of four components: (1) the host computer, from which the commands to the drive system originate; (2) the indexer, which receives commands from the host computer and generates the pulse stream required to control the motor and drive systems; (3) the servo amplifier, which provides the necessary power amplification to maintain the operation of the motors; and (4) DC servo motors and optical encoders with two channels in quadrature. The optical encoders connected to the motors, provide feedback signals to control position, speed, acceleration, direction and range of the movement. The menu-driven program MOTOP is used to operate the motion control system. Through this software, the user selects the option to be executed and is prompted for inputs that define the direction, range and speed of motion.

PENETRATION TESTS IN CLAY

A series of piezocone penetration tests were performed in soil specimens prepared by consolidating a slurry made of Speswhite fine china kaolin. For reference, the physical index properties of this material are listed in Table 1. The specimens were prepared to represent typical soil profiles. Each specimen was prepared in such a way as to obtain a specified overconsolidation ratio at the gravity level under which the penetration tests were performed.

Table 1. Index Properties of Speswhite China Kaolin.

Percent finer than 2 microns (by weight)	75%
Specific gravity, G_s	2.66
Liquid limit, W_l	53.1
Plastic limit, W_p	31.9

The penetration tests were performed at seven different sites along a circumference with a radius of 180 mm and 45° apart. In this way, the distance between two adjacent penetration sites was 130 mm, which corresponds to 10.8 piezocone diameters. The shortest distance from any penetration site to the container wall was 106 mm.

The obtained resistance profiles showed good repeatability, meaning that any eventual boundary effect or interference from adjacent tests can be neglected while interpreting penetration test data.

Figures 3, 4, 5 and 6 show the plots of the corrected penetration resistance (q_T) versus depth for four different soil samples. Each curve represents the penetration resistance profile for one penetration site. Also, are shown the plots of the pore pressure generated at the cone shoulder (u_T) during the penetration. The corrected penetration resistance was obtained with the aid of the following expression (Lunne et al., 1997):

$$q_T = q_c + u_T\,(1\text{-}a)$$

where q_c is the total penetration resistance, and a is the net area ratio (a = 0.56). It can be noticed that for each specimen, the curves representing each tip resistance profile are close to each other, meaning that the tests show a good degree of repeatability.

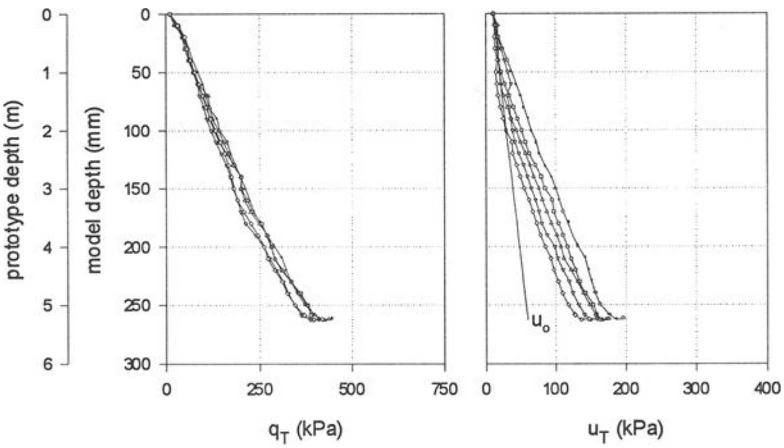

Fig. 3. CPTU Performed in Overconsolidated Clay (6<OCR<14, g-level=20).

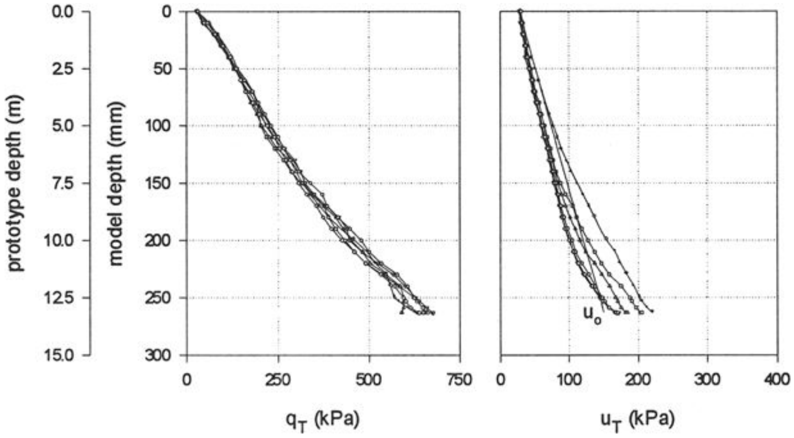

Fig. 4. CPTU Performed in Overconsolidated Clay (4<OCR<10, g-level=50).

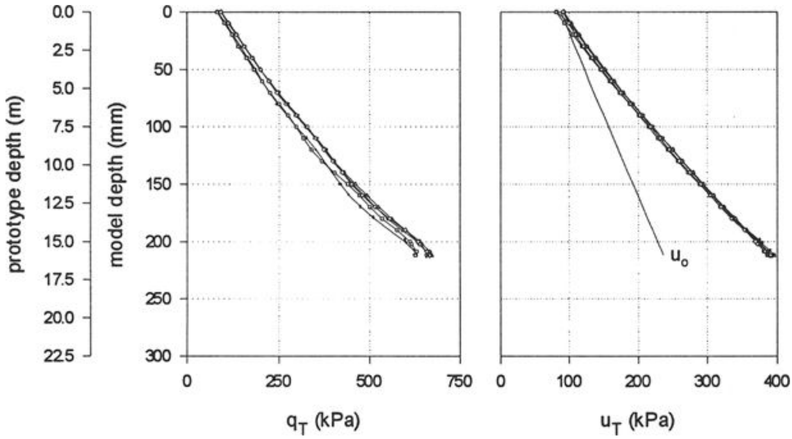

Fig. 5. CPTU Performed in Normally Consolidated Clay (g-level=75).

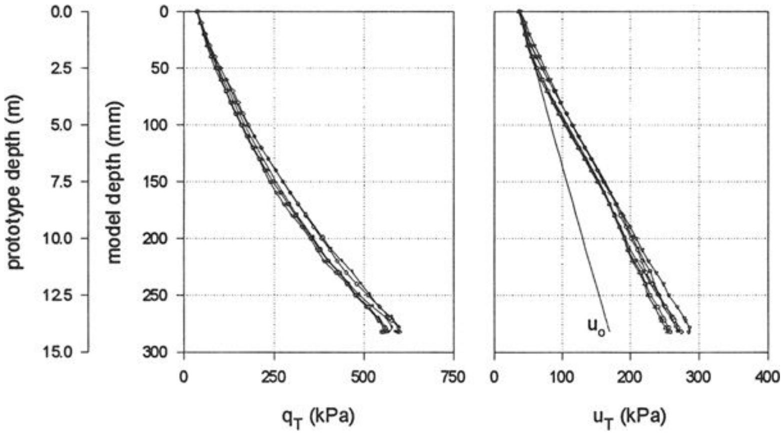

Fig. 6. CPTU Performed in Normally Consolidated Clay (g-level=50).

PENETRATION TESTS IN SAND

Ideally, the cone penetration testing in cohesionless soil models should be performed under no influence of *boundary effects* and *scale effects*. The boundary effects can be caused by the following factors: development of shear stresses in the contact between the sand specimen and the container wall; arching effects caused by the friction that is developed between the specimen and the container wall and influence of the rigid bottom plate on test results. The main scale effects are related to the ratio between the average grain size diameter (D_{50}) and the cone diameter (D_c).

In order to investigate the performance of cone penetration testing in centrifuge models, a series of penetration tests were performed in sand specimens submitted to different test conditions. The main purpose of these tests was to investigate boundary effects and scale effects, and how they interfere on CPT test results. The tests were performed with samples prepared with Nevada #100 Sand. For reference, its physical properties are listed in Table 2.

Each sample was prepared by the pluviation technique to a specified relative density. After checking its volume and weight, the sample was placed in the rotary stand for being tested in the centrifuge. Figure 6 depicts a top view of the container showing the positions where the penetrations tests were performed. By means of the rotary mechanism, any position along the outer circle (Position A) and along the inner circle (Position B) could be reached in flight.

Table 2. Nevada #100 Sand Properties

Specific gravity, G_s		2.67	
Max. dry density, $\rho_{d,max}$		17.33 kN/m^3	
Min. dry density, $\rho_{d,min}$		13.87 kN/m^3	
Max. void ratio, e_{max}		0.89	
Min. void ratio, e_{min}		0.51	
Avg. grain size		0.15 mm	
Relative density, D_r	58 %	72 %	85 %
Dry unit weight, γ_d	15.68 kN/m^3	16.19 kN/m^3	16.70 kN/m^3
Peak friction angle, ϕ_{peak}	37°	41°	45°

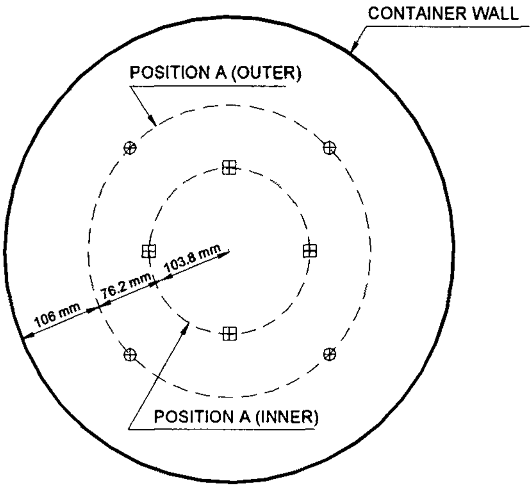

Fig. 7. Penetration Test Site Position

For cohesionless soils, one of the most important aspects that may interfere with CPT results is related to *scale effects*. The importance of these effects is mainly related to the ratio between the cone diameter (D_c) and the average grain size diameter (D_{50}) of the specimen sand. Performing penetration tests in calibration chambers, de Lima and Tumay (1992) suggested correction factors to adjust the measured penetration resistance (q_c) achieved with cones having a diameter different from 35.7 mm.

Another source of concern are the so-called *boundary effects*, which are the effects of the imposed boundary conditions on test results. When performing penetration tests in conventional calibration chambers, the rigid testing container wall and rigid plates used to apply the vertical overburden pressure may cause perturbations, which have to be accounted for in the results interpretation. As observed by Parkin (1988), potential boundary effects are governed by the calibration chamber diameter (D_{cc}), the specimen density, the penetrating cone diameter and the distance between the penetration test site and the container wall (L_w).

In the present work, penetration tests were performed to investigate some specific experimental conditions affecting the cone penetration testing. These tests were grouped in two series, which are briefly described as follows.

The first test series was intended to investigate *scale effects*. Penetration tests were performed in the same specimen with cones having different diameters. Each specimen having a specified density was tested under different g-levels. Special attention was given to investigate the variation of the cone penetration resistance with the cone diameter. Figure 8 shows typical results obtained in this test series. It can be seen that the penetration resistance profiles, obtained with penetrometers with different cone diameters, are very close to each other.

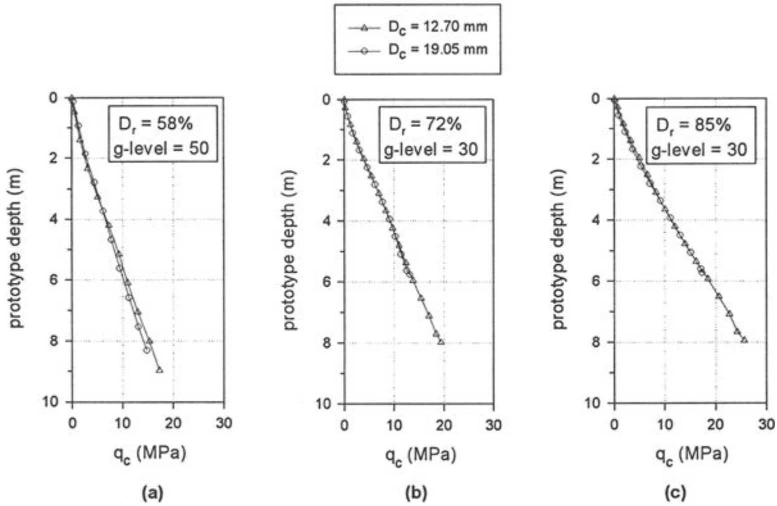

Fig. 8. Penetration Tests Results Showing Negligible *Scale Effects*

The second test series was intended to investigate *boundary effects*. Initially, it was investigated the influence of the test site position from the container wall on test results. Penetration tests were performed in the same specimen, with the same penetrometer, at sites with different distances from the container wall. Figures 9a and 9b show comparisons when the tests were performed at sites located along the inner and outer paths, as shown in Figure 7. The next step in this test series was to search eventual arching effects caused by the friction between the sample and the container wall. In order to minimize the development of shear stresses in the contact between the sand specimen and the container wall, the specimen was involved by a latex membrane soaked with oil. Also, it was studied the influence of the rigid container bottom plate on the penetration test results. This influence was searched by installing a semi-circular 20 mm thick foam rubber plate on the container bottom. Since arching effects are more prone to be noticed at higher densities, the specimen was molded at a relative density equal to 85%. Figure 9c show a comparison between penetration resistance profiles, corresponding to specimens with membrane and without membrane, respectively.

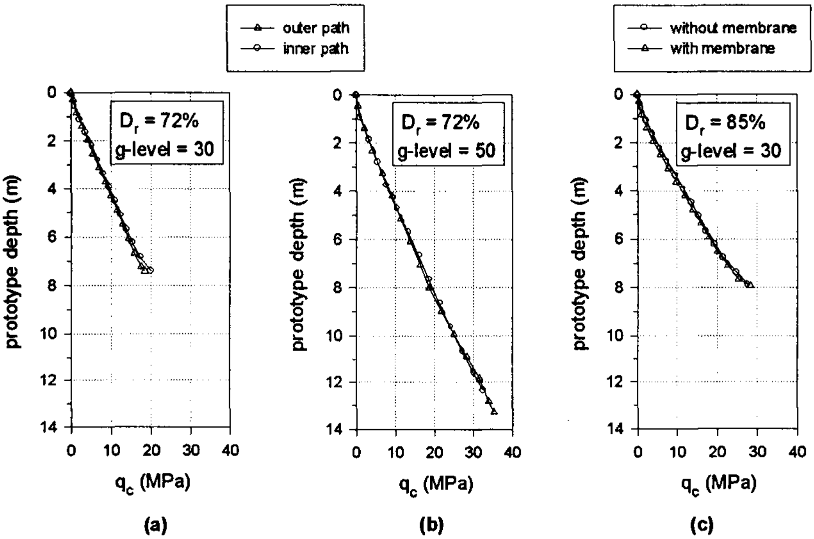

Fig. 9. Penetration Tests Results Showing Negligible *Boundary Effects*

CONCLUSIONS

This research has shown that CPTU and CPT testing in centrifuge environments is feasible, producing consistent and reliable data. With the aid of a centrifuge, it is possible to test models under conditions that approximate those in the field in terms of in-situ stress profile, including the vertical effective stress gradient. Cone penetration testing results in the centrifuge environment are practically not affected by boundary conditions. Piezocone tests performed on centrifuge soil models may produce a large data base leading to the study of correlations such as clay undrained shear strength versus penetration resistance or sand peak friction angle versus cone penetration resistance. Penetration tests in sand centrifuge models have shown no evidence of *scale effects* for the ratio D_c/D_{50} ranging from 84 to 127. Also, these tests have shown no noticeable evidence of *boundary effects* for the ratio D_{cc}/D_c ranging from 30 to 45 and the ratio L_w/D_c ranging from 5.6 to 14.3.

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INCLUSION OF THE PERFORMANCE MODEL TO DIRECT AND CONTROL SITE CHARACTERIZATION

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ABSTRACT

A powerful method to quantitatively control and direct exploration that combines the uncertainty (or variance) of three dimensional (3D) site characteristics with sensitivity of the performance model through a Taylor series expansion is demonstrated. Fundamentally, the approach is made possible by directly differentiating the performance model to obtain its 3D sensitivity to changes in subsurface properties. A one-time only direct differentiation of a generic code for performance analysis allows sensitivity to be determined with a single model run for any subsurface geometry. Thus direct differentiation avoids 1000's of model runs necessary with parameter perturbation or Monte Carlo simulation.

The integrated exploration approach will be demonstrated with three examples, each with very different performance objectives (settlement, groundwater flow, and contaminant transport). The examples will demonstrate the process of producing calculated performance variance from 3D model sensitivity and uncertainty associated with site layer geometry and properties. Exploration is directed to locations of maximum variance in project performance. Sampling at these points produces the maximum reduction in performance uncertainty. As directed exploration proceeds, sufficiency of characterization effort is quantitatively determined through a reliability index. This index combines calculated performance, variance in calculated performance, and required performance.

INTRODUCTION

Site characterization is often incorrectly thought to have as its objective the definition of subsurface layer geometry and material properties. Such an objective is too

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