CPT in unsaturated soils using a new calibration chamber

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ABSTRACT: The development of a calibration chamber for conducting cone penetration tests (CPT) in unsaturated soils is presented. The chamber allows lateral and vertical pressures to be applied independently to an unsaturated soil specimen. Horizontal pressure is applied by cell water pressure pushing on a durable rubber membrane enclosing the specimen, vertical pressure is maintained by a hydraulic loading ram placed under a chamber piston at the specimen base. Suction is controlled in a specimen using the axis translation technique. Air pressure is applied at the top of the chamber where it spreads uniformly across the top of the specimen. Pore water pressure is applied through eight high air entry value porous disks embedded in the base plate. A novel aspect of the design is the specimen formation system which enables specimens of repeatable properties to be formed. It comprises four movable cylinder quarters attached to the chamber shell which may be locked together to make a rigid former. Sand specimens may be placed within the former by dry pluviation, then saturated, and then unsaturated to induce suction. CPT results are presented and the significant contribution of suction to penetration resistance is highlighted.

1 INTRODUCTION

The engineering behaviour of unsaturated soils is complex and influenced by many factors including externally applied stresses, soil type and suction. Most notably, suction increases the soil's strength and stiffness. Upon wetting an unsaturated soil may weaken significantly and exhibit volumetric collapse. Unsaturated soils are widely spread and need to be dealt with in many engineering problems including foundations, fills and embankment dams, pavements and airfields as well as natural and made slopes.

At present the characterization of unsaturated soils requires expensive and time consuming site investigations involving soil borings and undisturbed sampling for laboratory testing to obtain even the most basic information on the suction dependant strength and stiffness. Performing the cone penetration test (CPT) in unsaturated soils, a commonly used in situ test, may enable less costly and more rapid characterization.

Many correlations have been proposed for the determination of engineering properties of saturated soils from CPT results (e.g., Schmertmann 1978, Robertson & Campanella 1983, Keaveny & Mitchell 1986, Jamiolkowski et al. 2001). However, no correlations currently exist for interpretation of CPT data in unsaturated soils. Engineers are left to interpret CPTs performed in unsaturated soils using correlations developed for saturated soils which may lead to unknown misrepresentations in estimated soil properties.

Calibration chambers have been used extensively in the past to develop correlations under laboratory controlled conditions for saturated or dry soils (e.g., Holden 1971, Bellotti et al. 1982, Huang et al. 1988). More recently a calibration chamber for performing CPTs in unsaturated soils was designed and built at the University of Oklahoma (Miller et al. 2002). In that chamber specimens were prepared by static compaction inside a specimen former, although difficulties were encountered due to a low former rigidity (Tan 2005).

This paper presents a new calibration chamber being used at The University of New South Wales (UNSW) in a study of the CPT in unsaturated soils. It also outlines a novel specimen formation system enabling specimens of repeatable properties to be created. CPT results in saturated and unsaturated uniform quartz sand specimens are presented and the effect of suction on penetration resistance is highlighted.

2 THE NEW CALIBRATION CHAMBER

2.1 *Chamber configuration*

The new calibration chamber accommodates a cylindrical soil specimen that is 460 mm in diameter and 800 mm in height. The chamber is designed to allow combinations of axially symmetric lateral and vertical pressures to be applied independently to the external walls of the specimen. Lateral stresses are applied by water pressure acting on a rubber membrane enclosing the soil specimen. Vertical stress is applied by a hydraulic loading ram pushing on the chamber piston connected to the base of the specimen. A cross section of the chamber is shown in Figure 1.

Suction within the specimen is also controlled independently using the axis translation technique (Hilf 1956). In an unsaturated test air pressure is applied at the top of the chamber via fittings on the top cap and holes cut through the top plate. It spreads uniformly across the top of the specimen. Pore water pressure is applied through eight high air entry value porous disks embedded in the specimen bottom plate. A pore air pressure (u_a) that is larger than pore water pressure (u_w) induces suction ($s = u_a - u_w$) in the soil specimen. High air entry value porous disks embedded in the bottom plate are shown in Figure 2.

A novel specimen formation system has been developed and included in the design which enables creation of specimens of repeatable properties from variety of soil types. It consists of four cylinder quarters built in to the chamber. Two handles are attached to each cylinder quarter near their top and bottom which enable them to be moved manually towards and away from the center of the chamber. During specimen preparation, the former quarters are pushed together and locked into position to form a rigid cylindrical mould. A rubber membrane is positioned inside the mould to contain the specimen. Vertical compaction/compression of soil can be performed within the mould without experiencing problems of bulging or distortion. After specimen preparation the chamber is assembled and a confining cell pressure is applied. The quarters of the former may then be pulled away from the specimen. A cross section of moveable former is shown in Figure 1.

A hole of 50 mm diameter is cut through the centre of top plate and top cap allowing the penetrometer to be pushed into the specimen. There are four threaded holes cut through the top plate and top cap: two are connected to the pore air pressure control system and two may be connected to either a pore water pressure control system or used as an air vent during specimen flushing.

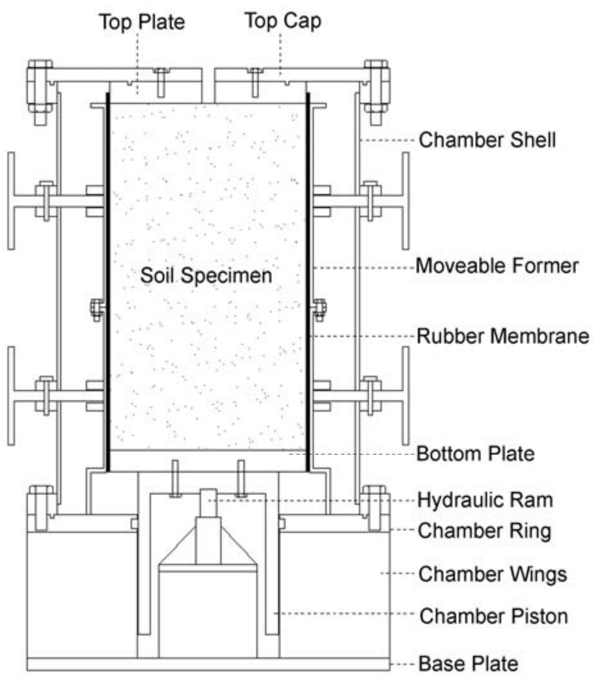

Figure1. Calibration chamber cross section

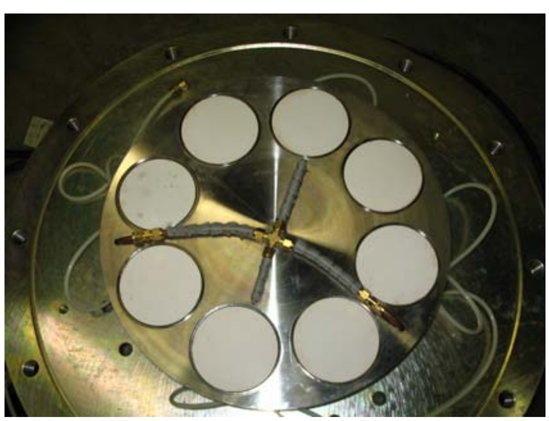

Figure 2. High air entry value porous disks embedded in the bottom plate and copper tubing for satu ration of specimen

2.2 *Control and measurement units*

The calibration chamber requires a number of control and measurement units including a cell pressure supply system, a loading ram for controlling the vertical stresses on a specimen, and separate pore air and pore water pressure systems for controlling suction. The general arrangement of the units is shown in Figure 3.

The chamber is filled with water which is then pressurized to supply a lateral stress to a specimen. The cell pressure is supplied using an air water interface cylinder, in which the air pressure is manually adjusted and measured using an air pressure regulator and analogue pressure gauges. Cell water volume change is determined by recording the water level in the air water interface cylinder with an accuracy of about ±10 mL, and a glass burette volume change unit with an accuracy of about ±0.5 mL.

The chamber has two separate lines to supply pore water to the base of a specimen. One line is connected to perforated copper tubes at the bottom plate (as can also be seen in Figure 2) and is used to flood the specimen with water. The other set is connected to the porous disks embedded in the base plate and controls pore water pressure within an unsaturated specimen. Pore water volume changes are measured using separate volume change units comprising glass burettes and water oil interfaces. Pore air pressure supplied to the top of the specimen is controlled and measured using a pressure regulator and pressure gauge.

A 10 tonne hydraulic ram pushing upwards against the piston and the bottom plate supplies the vertical stress to the specimen. An electric micro pump is used to operate the ram. A linear varying displacement transducer (LVDT) mounted below the piston captures the vertical displacement of the ram, which is equal to the vertical deformation of the specimen. All vertical displacements are recorded using a computerized logging system.

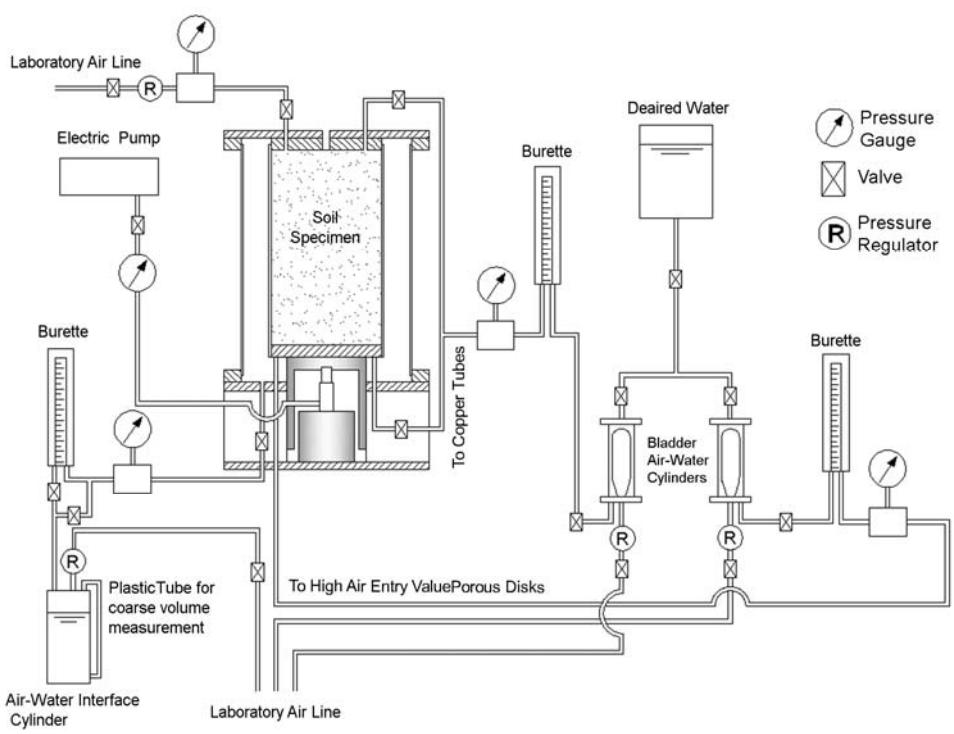

Figure 3. The Calibration Chamber Control System

3 TESTING PROCEDURE

The procedure for performing a CPT in a dry, saturated or unsaturated sand specimen is outlined here.

3.1 *Formation of sand specimens*

Dry sand specimens are prepared by the pluvial deposition technique. Sand is placed in a large hopper positioned above the calibration chamber. The sand is then allowed to flow through the base of the hopper through an opening. The flow rate is controlled by adjusting the size of the opening using a movable flap. The sand then passes through a diffuser consisting of two sieves aligned and fastened to a pulley system before it finally drops into the chamber. A uniform flow rate of sand through the diffuser and a uniform drop height (distance between diffuser bottom and placed sand surface) enables preparation of a homogenous specimen. The system is designed so that the diffuser is moved upward during the pluviation process using the pulley system to maintain a constant drop height. Specimen dry density depends on the drop height and flow rate (Rad & Tumay 1987).

The next stage of the specimen formation procedure is leveling off the surface of the specimen. A gravel layer 50 mm thick may be placed at the top of the specimen to enable even spread of air/water pressures across the specimen top. The top plate is then moved to position and the rubber membrane is clamped to the top plate. The chamber top cap is then fastened. Once the chamber top cap is bolted to the top flange a small cell confining pressure is applied to the specimen and the moveable formers are pulled away from the specimen towards the chamber shell. This provides a stress controlled lateral boundary condition. The cell pressure and axial pressure are increased to desired values and the specimen is allowed to consolidate. Specimen densities are determined by calculating the weight of sand which has exited the hopper to create the specimen. By conducting several trials it was confirmed that this system was able to create specimens with repeatable densities equal to target values dependant on the drop height and controlled flow rate.

A dry specimen may then be saturated by passing de-aired distilled water through perforated copper tubes at the bottom plate while applying a slight vacuum to the specimen top. The water is supplied by a de-aerator unit.

Unsaturated specimens can be formed by saturating an initially dry pluviated specimen as described above, and then letting the moisture content reduce to achieve a target suction. Initially, water is allowed to drain under its self weight by opening the valves connected to the copper tubing at the base. The copper tubing is then resaturated using deaired water, being careful to flush just enough water to fill the tubes and the surrounding soil pores in the lowest 50 mm of the specimen. The copper tubing is then sealed, and pore air pressure and pore water pressure applied via the top and high air entry ceramic discs at the base, respectively. The pore water volume change is monitored during this process until equilibrium is reached within the sample.

3.2 *Cone penetration*

Cone penetration tests are conducted using a miniature electrical cone, model ELC2, manufactured by A.P van den Berg. The cone is 16 mm in diameter and the cone tip area and friction sleeve area are 2 cm^2 and 30 cm^2, respectively. The cone is pushed by a HYSON 100 kN single cylinder static cone penetrometer powered by a petrol driven power pack. A loading frame specially built to mount the HYSON penetrometer is positioned above the chamber and bolted to the top cap and top flange. Figure 4 shows the frame and penetrometer mounted on the top of the chamber. A hollow bush cylinder creates a seal around the cone and the centre hole of the chamber top cap. The cone is pushed into the soil specimen with an insertion rate of 2 cm/s – although the hydraulic ram allows this to be set at any constant rate in the range 0.2 to 2 cm/s.

Figure 4. Penetrometer mounted on the top of the chamber

4 TEST RESULTS

Results of CPTs conducted in saturated and unsaturated Sydney sand are shown in Figure 5. Sydney sand, a predominantly quartz sand, is classified as SP with a D_{50} of 0.3 mm. The relative densities of the formed specimens were about 61%. The saturated specimen (S1) was subjected to an isotropic effective stress of 100 kPa (lateral, vertical and pore water pressures of 350 kPa, 350 kPa and 250 kPa, respectively). The first unsaturated specimen (U1) was subjected to an isotropic net confining stress of 100 kPa and controlled suction of 50 kPa (lateral, vertical, pore water and pore air pressures of 200 kPa, 200 kPa, 50 kPa and 100 kPa respectively). The second unsaturated specimen (U2) was subjected to an isotropic net confining stress of 100 kPa and controlled suction of 200 kPa (lateral, vertical, pore water and pore air pressures of 350 kPa, 350 kPa, 50 kPa and 250 kPa respectively).

The most useful portion of the test records is between depths of 0.3 m and 0.55 m where the q_c values are approximately constant and free of influence from the top and bottom boundaries. The values of the cone tip resistance recorded between about 0.1 m and 0.25 m are slightly higher, caused by interaction between the top of the specimens and the top plate. From about 0.55 m the cone tip resistance values show a modest increase due to interaction with the rigid base boundary so tests are terminated around depths of 0.2 m from the bottom of the specimens. Between 0.3 m and 0.55 m depths the cone tip resistance averages about 10.7 MPa, 11.7 MPa and 13.6 MPa for S1 (saturated), U1 (unsaturated, s = 50 kPa) and U2 (unsaturated, s = 200 kPa) specimens, respectively. The suction noticeably increases the penetration resistance and clearly shows the importance of considering suction in interpreting CPT results. New correlations considering suction need to be developed, using results performed under controlled laboratory conditions.

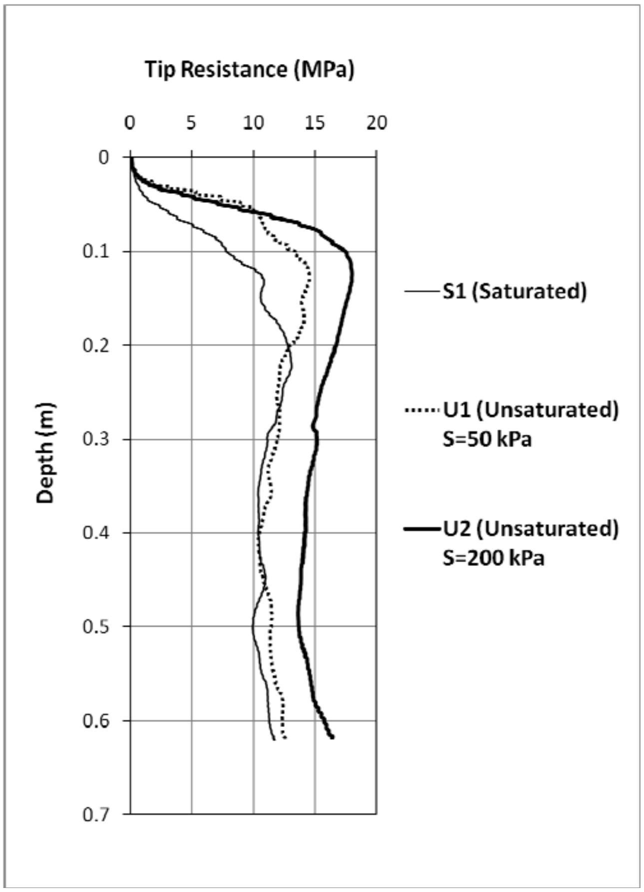

Figure 5. CPT results in saturated and unsaturated sand specimens prepared by the pluviation deposition method (D_r = 61%)

5 CONCLUSIONS

A new calibration chamber for conducting cone penetration tests in unsaturated soils under laboratory controlled conditions has been presented. It includes a novel specimen formation system which has been used here to prepare dry, saturated or unsaturated sand specimens. Results of cone penetration tests carried out in saturated and unsaturated sands show that suction noticeably increases average penetration resistance. Correlations developed for saturated (or dry) conditions cannot be used for interpretation of cone penetration test results conducted in unsaturated soils. New correlations considering suction need to be developed.

6 ACKNOWLEDGMENTS

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