Commissioning of a Large Calibration Chamber for Cone Penetration Test in Silty Sands and tailings

Wei Liu

University of Toronto, Toronto, Canada, weiut.liu@mail.utoronto.ca

Audrius Azubalis, Mason Ghafghazi,

University of Toronto, Toronto, Canada, audrius.azubalis@mail.utoronto.ca, mason.ghafghazi@utoronto.ca

ABSTRACT: Interpretation of the Cone Penetration Test (CPT) in sands is generally based on empirical correlations from calibration chamber tests. Limited calibration chamber data are available for sand-silt mixtures and tailings encountered in engineering practice. A CPT calibration chamber testing system is commissioned at the University of Toronto. The chamber can accommodate a specimen that is 1.4 m in diameter and 1 m tall. This paper will introduce the primary testing setup, procedures, challenges, future work, and potential contributions. To have a variable penetration rate to investigate the effect of partial drainage conditions, a servo-controlled hydraulic push system is developed. Additionally, a Liqui-Cel de-airing system provides large volumes of de-aired water for saturating soil specimens. A custom membrane is also designed so the vertical and horizontal stresses can be controlled independently. Various specimen preparation techniques will be attempted to mitigate the segregation of silt and sand fractions while producing uniform specimens and at a range of densities.

Keywords: calibration chamber tests; partial drainage; variable penetration rate; silty sands; tailings.

1. Introduction

CPT has been widely used for several decades to estimate soil properties and evaluate soil liquefaction potential [1-3]. The standard rate of CPT penetration is 2 cm/sec [4], which results in a fully drained penetration for sand, undrained penetration for clay, and partially drained penetration for intermediate soils, such as silty sands and silt-rich tailings. Existing correlations based on CPT measurements (tip resistance, sleeve friction, and pore water pressure) to determine soil properties and liquefaction potential are only valid for fully drained or fully undrained condition, which may lead to an inaccurate estimation of the properties of intermediate soils. Many studies have investigated the effect of drainage conditions on CPT results by conducting penetration tests at variable penetration rates for clays, intermediate soils, and Kaolin-sand mixtures [5-12]. They have shown how CPT measurements change with variable penetration rates. There is a clear trend between the CPT measurements and normalized penetration velocity (V), which is a function of the cone penetration rate (v), the cone diameter (d), and the horizontal coefficient of consolidation (c_h). Their results have provided a practical framework for the selection of penetration rates required to obtain drained, partially drained, and undrained measurements for a given soil. Most of their works are focused on evaluating the effect of variable penetration rate on in-situ strength and consolidation characteristics. However, the effect of variable penetration rate on the interpretation of state parameter has not been addressed well, especially for silty sands and tailings.

The state parameter is defined as the difference between the current void ratio and the void ratio at the critical state for the same mean effective stress [13]. Soil is expected to be contractive during shearing if the state parameter is greater than zero and dilative if the state parameter is less than zero. Soils with the same state parameter is expected to have the same static and dynamic liquefaction potential [14]. Many efforts have been put into developing the correlation between state parameter and CPT tip resistance through calibration chamber tests by Been and his co-workers in a series of papers [15-17]. These correlations have been used to determine the in-situ state parameter from CPT measurements in the field and provided reliable results for different sands [16]. However, a problem arises when applying the correlations to silty sands and tailings because all the calibration chamber tests have been performed on clean sands by allowing fully drainage condition. The presence of the fines in silty sands and tailings affects the CPT measurements due to partial drainage condition. Accordingly, the dependence of CPT measurements on drainage conditions introduces uncertainty in the interpretation of the state parameter. The uncertainty results in decreasing or increasing conservatism when assessing the liquefaction susceptibility of soils from CPT field data.

This paper summarizes the commissioning of a calibration chamber testing setup at the University of Toronto, aiming to investigate the effects of fines content and drainage conditions on CPT measurements through calibration chamber tests at variable penetration rate on silty sands and tailings. The results will help engineers to better interpret the in-situ state parameter and other soil properties with a better understanding on how fines content and drainage conditions affect CPT measurements. Procedures for conducting calibration chamber tests, challenges, future work, and potential contributions are pointed out.

2. Apparatus

2.1. Calibration chamber

The calibration chamber testing system used by Been [17] is being recommissioned at the University of Toronto, as can be seen in Fig. 1, with important components labelled. Fig. 2 shows the schematic diagram of the calibration chamber testing setup.

The chamber can accommodate a soil specimen up to 1.0 m deep with a diameter of 1.4 m. This diameter provides a ratio of the chamber to standard cone diameter of 38. Previous results obtained from this chamber have proved that modest correction on CPT measurements must consider the chamber size and boundary effects. More details about selecting the value of the 'correction factor' to account for the effects can be found in [15,16]. The rigid base of this chamber is considered to be better than the flexible membrane-sand interface used in other chambers to represent the field condition. The top and lateral boundary of the chamber are flexible, so constant vertical and horizontal stresses can be applied, independently.

Principal stresses of up to 700 kPa can be applied independently through an upper (σ_v) and circumferential (σ_h) cavity, as illustrated in Fig. 2. Back pressure can be directly applied to the soil specimen for full saturation after circulating carbon dioxide gas and flushing de-aired water through if necessary. Three air-water reservoirs (vertical stress, horizontal stress, and back pressure) are used to impose various stress conditions on the specimen. The air-water reservoir is fully filled with de-aired water and contains an air-jack inside fed by a pressurized air supply to exert pressure on the specimen. Constant stress conditions are achieved by pressure regulators. Horizontal stress is applied to the specimen through a latex rubber membrane, while the vertical stress is applied through a top cap. The top cap sits above the soil surface and moves vertically if the specimen height changes during consolidation and cone penetration.

The calibration chamber is mounted on three load cells with a capacity of 2 tons each. Three independent digital readouts are connected to each load cell to monitor total chamber weight during specimen preparation, saturation, consolidation, and cone penetration. This helps determine the void ratio of a specimen at each stage. A self-reacting frame is attached to the base of the chamber, so the reaction force induced by cone penetration testing would not affect the load cell readings or put additional demand on the surrounding structures and foundation.

An electronic cone with three channels is used to measure tip resistance, pore pressure, sleeve friction in the process of penetrating. The cone is in a standard circular cone shape, and it has a standard 10 cm^2 projected tip area with a cone apex angle of 60° and a 150 cm^2 friction sleeve area. The pore water pressure is measured behind the cone in what is referred to as the u_2 position [4]. Due to the inner geometry of the cone, water pressure that acts behind the cone tip will reduce measured cone resistance, by the magnitude of water pressure acting on unequal areas of the tip geometry. This effect is often referred to as the unequal end area effect [18-19]. Corrections are required to the measured tip resistance due to the unequal end-area effect. The net area ratio of 0.83 determined from laboratory calibration by the manufacture is selected to correct the unequal end area effect.

The cone penetrometer is advanced into the specimen at a variable penetration rate (2 cm/sec, 0.2 cm/sec, and 0.02 cm/sec) by a servo-controlled hydraulic jack with a maximum force of 50 kN.

An optical encoder is used to monitor cone penetration depth during sounding. Three sets of data, including tip resistance, sleeve friction, and pore pressure are recorded every second. The depth readings and the cone channel output are shown in a computer interface software and saved for subsequent data processing.

Further details of other essential components in the calibration chamber testing system, such as membrane and seals, air-water reservoirs, de-airing system, hydraulic push system, and data collecting unit, will be provided in the following sections, individually.

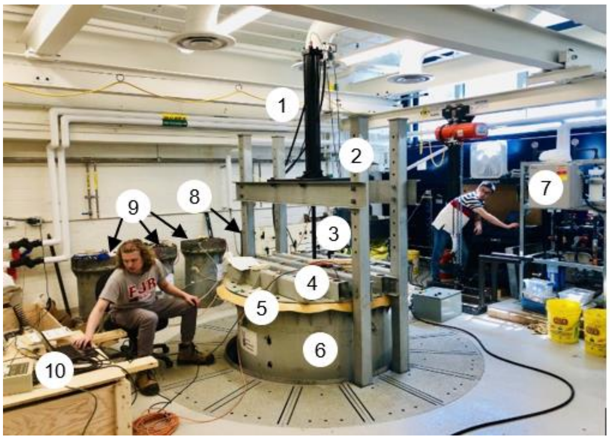

Figure 1. Calibration chamber testing system at the U of T
1-Hydraulic push system; 2-Reaction frame; 3-Cone rod; 4-Calibration chamber lid;5-Membrane; 6-Calibration chamber wall; 7-de-airing system; 8-Pressure panel; 9-Air-water reservoir;10-Data collecting unit

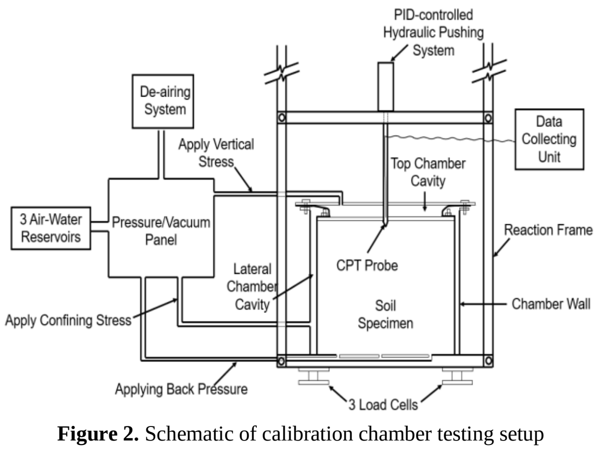

Figure 2. Schematic of calibration chamber testing setup

2.2. Membrane and seals

Fig. 3 shows the membrane is sitting inside the chamber, sealed at the base, and ready to prepare a soil specimen. The membrane is 1.35 m in diameter, 1.75 m long, and 0.003 m thick. The bottom, side, and top parts of the membrane are made of natural latex rubber and glued together to form an open cylinder with bottom and top flanges. The membrane is sealed on top and bottom by clamping steel gaskets; A series of bolts around the circumference of the membrane, gasket, top cap, and later the chamber lid clamp the system together.

To be sealed at the bottom and top, the membrane is folded towards the specimen at the bottom and folded out away from the specimen on top.

Figure 3. Photograph of membrane

A wet soil specimen is contained and sealed by the membrane to apply pressure on it from the outside. The left side of Fig. 4 illustrates that the membrane (in red) encloses a soil specimen on the base of the chamber and seals the chamber on the lid. The right side of Fig. 4 provides further details of the seals at the base (A and B), the top cap (C and D), and the chamber lid (E and F). The bottom seals (A and B) are achieved by tightening nuts on screws to pushing down a steel gasket to compress the membrane. The seals (C and D) are achieved similarly at the top cap. The chamber seals (E and F) are achieved by tightening the nuts on the screws to compress the membrane at a flat surface contact between the chamber lid and outer edge of chamber wall.

Another two important seals are between the cone rod and the chamber lid and the cone rod and the top cap. These two seals (G and H) are accomplished in a similar way by having a couple of O-rings secured in bushings to prevent leaking from pushing the cone rod. These bushings have flexible connections to the top cap and the lid to allow for potential minor misalignments without bending or jamming the cone rod.

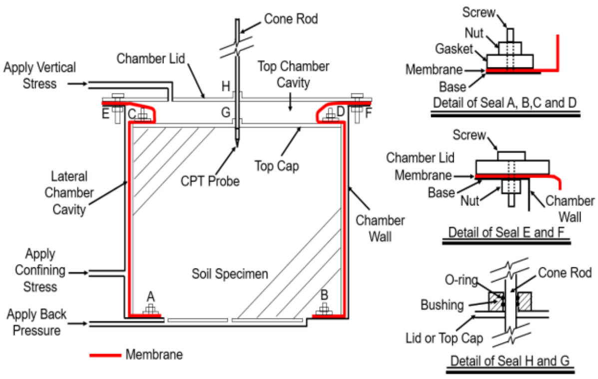

Figure 4. Details of membrane and seals

2.3. Air-water reservoir

A typical approach to pressurize a soil specimen is to apply water pressure that is transferred from regulated air pressure in an air/water reservoir. In this approach, safety is always a concern because air is highly compressible, and having pressurized air in the reservoir could potentially create a blast hazard. Accordingly, an air-jack pressure system is designed to address the safety concern.

As can be seen in Fig. 5, the air-water reservoir is sealed and filled with de-aired water, and a pneumatic jack is enclosed inside the reservoir. When there is no pressure in the air-water reservoir, the pneumatic jack is at its original position without any inflation. When air pressure is applied, and air is allowed to flow into the pneumatic jack, the pneumatic jack starts to inflate. The pressure fed by the pressurized air supply is transferred to water pressure that can be monitored through a pore pressure transducer outside of the reservoir. Therefore, desired pressure can be obtained to impose a variety of stress conditions on the soil specimen. Three similar air-water reservoirs have been built to apply confining stress, vertical stress, and back pressure to the soil specimen. It needs to be mentioned that the inflatable space of the pneumatic jack should be large enough to compensate for the volume change induced by the compliance of the system and consolidation of the soil specimen.

The pneumatic jack is made of natural rubber and can withstand a maximum pressure of 1000 kPa, which is 1.5 times higher than the maximum pressure that can be supplied. A safety pressure relief valve is also designed to prevent over-inflation.

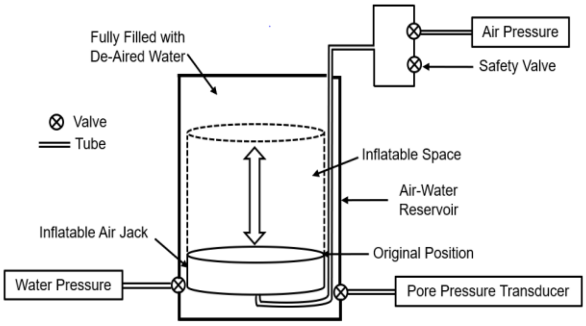

Figure 5. Schematic of air/water reservoir to apply pressure

2.4. Liquid-Cel de-airing system

Fig. 6 shows the Liquid-Cel de-airing system that is used to supply de-aired water to the chamber. The system makes it possible to transfer gas to or from an aqueous stream without dispersion and is used to continually provide a large volume of de-aired water in a short period time for specimen saturation. Fig. 6 also illustrates the simplified working principle for the system. More specifically, tap water flows into a membrane, which contains thousands of microporous polypropylene holes to remove the gases from the water by applied vacuum, and comes out as de-aired. Eventually, de-aired water can continuously flow out from the membrane at different flow rates from 0.05 L/sec to 0.3 L/sec.

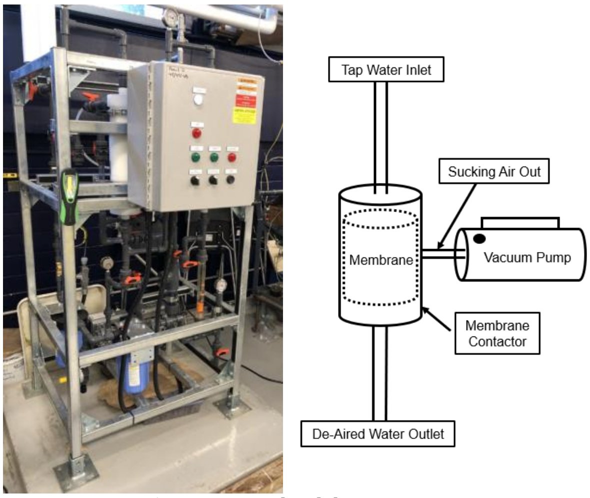

Figure 6. Liquid-Cel de-airing system

2.5. Hydraulic push system

Fig. 7 shows the schematic diagram of the servo-controlled hydraulic push system. An oil tank with a servo proportional valve works with a pump to provide energy for CPT penetration for the hydraulic cylinder. The movement in the axis of the hydraulic cylinder is controlled by a motion controller with an associated commercial interface software (RMC). The system is designed in a feedback control loop and enables a penetration at a maximum force of 50 kN and is fully programmable for 1 m penetration intervals with multiple penetration rates from 0.02 cm/sec to 2 cm/sec. Decreasing the penetration rates slower than 0.02 cm/sec could be achieved by equipment modifications but conducting the tests at this rate is time-consuming.

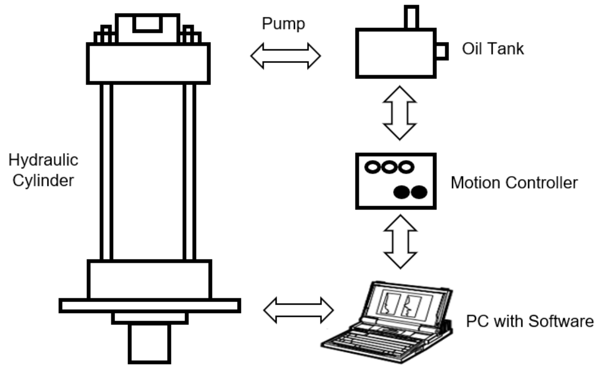

Figure 7. Servo-controlled hydraulic push system

2.6. Data collecting unit

Fig. 8 describes the CPT data collecting unit. As the CPT probe starts penetrating the soil, data are transmitted as a digital signal via a cable to the computer interface box, which also receives depth, from a depth encoder. The data is then sent to a laptop. The data are presented simultaneously on the screen.

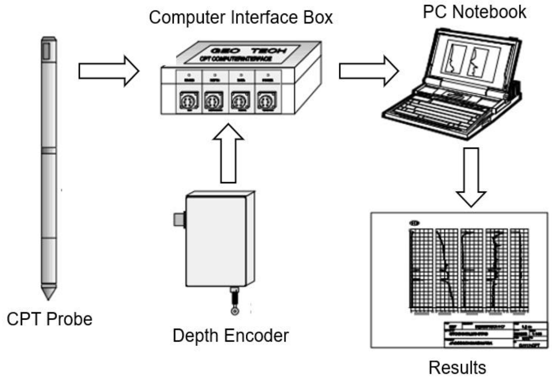

Figure 8. Description of the data collecting unit with cable

3. Operation and procedures for calibration chamber test

The procedure for conducting a calibration chamber test involves the following major tasks:

1. Specimen preparation
2. Saturation and consolidation
3. Penetration
4. Uniformity check and emptying the chamber

3.1. Specimen preparation

A soil specimen in the calibration chamber can be prepared by air pluviation, water pluviation, or moist tamping. The procedure for preparing a specimen in this chamber is similar to that used for a triaxial specimen with some modifications because of the enormous specimen size.

The initial soil fabric created by different specimen preparation methods is different, and thus different responses to CPT loading are expected. However, limited studies are available on investigating the effects of initial soil fabric on CPT measurements. Most of the correlations used to estimate soil properties in situ conditions are developed from calibration chamber tests without considering the effects of initial soil fabric. The authors are currently conducting experimental research on investigating the effect of initial soil fabric induced by different specimen preparation methods on CPT measurements.

In addition to described methods, the authors are designing and building equipment for reconstituting a soil specimen by slurry deposition method originally developed by Kuerbis and Vaid [20] for triaxial tests. The slurry deposition method will be used in future for specimen preparation in the chamber testing to overcome particle segregation and investigate the effect of fines content and drainage condition on CPT measurements.

After a specimen is prepared, the specimen weight and dimension are measured to calculate the overall void ratio and density.

3.2. Saturation and consolidation

Following the specimen preparation, the top cap, the steel gaskets, the chamber lid, and the seals are assembled, and corresponding bolts are tightened. As the chamber lid is lowered to close the chamber, the water level in the lateral cavity of the chamber is slowly raised to fill the lateral chamber completely. Any trapped air bubbles are flushed out before entirely closing the lid. Next, the cone rod with CPT probe is placed in a position to help seal the vertical cavity of the chamber. Before that, the filter of the CPT probe must be fully saturated for obtaining reliable pore pressure readings. After that, the water level in the vertical cavity of the chamber is slowly raised to fill the vertical chamber completely. Finally, the reaction frame is assembled, and hydraulic jack for pushing the CPT rod is placed in position. At this point, the soil specimen is ready for saturation, consolidation, and penetration.

For fully saturating the specimen, carbon dioxide gas is circulated, and de-aired water is flushed through the specimen from the bottom to the top. A good B-value is achieved by applying the back pressure to the specimen. It is essential to check and address if there are any leaks in the system.

The specimen is then ready to be consolidated to desired stress level under isotropic or anisotropic stress conditions. Stress, chamber weight, and volume change of the specimen are continuously measured and recorded.

3.3. Penetration

After the required effective stress is reached, the cone penetration test is carried out. The CPT cone rod is pushed into the soil by the hydraulic cylinder mounted on the reaction frame. The hydraulic push system's rate of penetration is controlled with a feedback control and maintained at a desired rate (i.e., 2 cm/sec, 0.2 cm/sec, and 0,02 cm/sec). After penetration is completed, the penetrometer is withdrawn using the hydraulic push system.

Alternatively, variable penetration rate CPTs (or "twitch tests") wherein the velocity is systematically reduced following short penetration intervals can also be conducted in the commissioned testing system. These tests allow assessing the effect of partial drainage on CPT measurements [21]. Typically, the penetration rate is reduced by a order of magnitude (e.g., v = 2 cm/sec, 0.2 cm/sec, and 0.02 cm/sec), and 3 to 4 cone diameters of penetration is required before steady condition is achieved based on previous numerical and experimental results [11-12]. Accordingly, a four cone diameter is adopted as a penetration interval for conducting variable penetration rate CPTs, so the sufficient data is available to select representative cone measurement value at the end of each penetration rate.

3.4. Uniformity check and emptying the chamber

After the penetration, the soil specimen is depressurized, and the water in lateral and vertical cavities is allowed to drain over for several hours. The reaction frame, chamber lid, and top cap are removed in sequence. Then, the specimen is removed by using shovels and a vacuum. Four thin-wall Shelby tubes samples (150 mm long, 75 mm diameter) are extracted from the specimen after every 50 mm removal to obtain a detailed specimen void ratio profile with depth, compared to average void ratio obtained based on the known total specimen dimensions and weight. One of the undisturbed samples is collected around the penetration path to quantify particle breakage, and the rest of the samples are taken at other representative locations. The wet sand sample removed from the chamber is oven dried for 24 hours, and the weight of the dry sample is measured.

Two people are required for the execution of the calibration chamber test, and one test per week can be performed. The progress of a test for clean sand, either dry or wet, is shown in a flow chart in Fig. 9. It needs to be mentioned that the soil specimen with higher fines content would require a much longer time to be prepared in the chamber due to the challenge of particle segregation and achieving full saturation due to the low permeability of the specimen. One test per two or three weeks is expected for silty sands with high fines content and silt-rich tailings. Maintenance is usually limited to the repair or substitution of the membrane, which would take about two weeks.

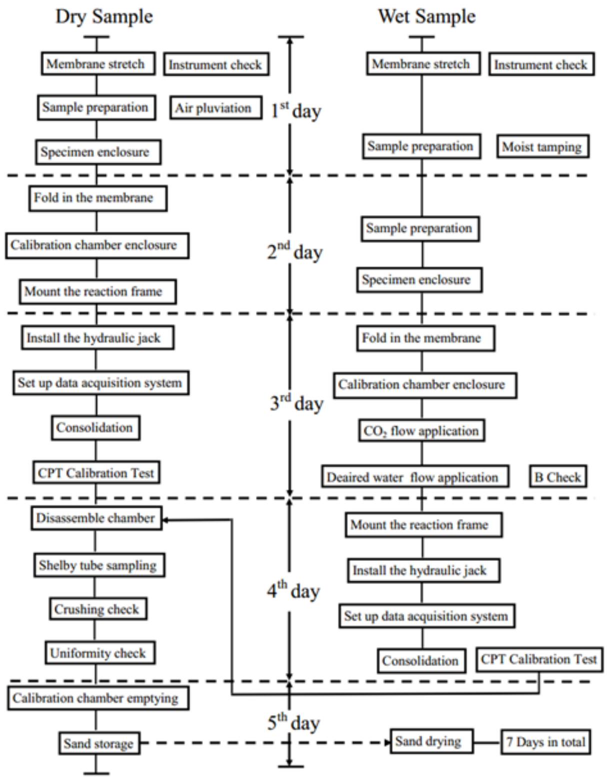

Figure 9. Flow chart of the main stages of calibration chamber test

4. Problems, preliminary tests, and future work

Even though virtually all the methods and testing procedures have been developed and some preliminary data for clean sand have been obtained, the authors are still facing some potential challenges. More specifically, it is still very challenging to achieve a full seal of soil specimen and chamber during every test at high pressure levels. It requires paying great attention to all the technical details throughout the test. Second, it is challenging to prepare a uniform soil specimen for silty sands with high fines content due to segregation of fines and difficulties with the equipment by various specimen reconstitution methods (i.e., water pluviation, moist tamping, and slurry deposition).

Future work will be carried out to improve the current seal by replacing or adding necessary components to the chamber to achieve a complete seal at high-pressure levels. It is then planned to begin testing on clean sand specimens prepared by various reconstitution methods to validate the results. Once the validation is completed, a series of calibration chamber tests will be systematically conducted at variable penetration rates on silty sands and tailings with various fines content. As mentioned above, the purposes of the tests are to investigate the effects of fines content, initial soil fabric induced by different reconstitution methods, and drainage conditions during penetration on CPT measurements. The results will help geotechnical engineers better interpret in-situ CPT measurements and determine the in-situ state parameter and other soil properties and evaluate the liquefaction susceptibility of silty sands and tailings.

5. Conclusion

A large calibration chamber has been commissioned at the University of Toronto. The calibration specimen can be prepared by various reconstitution methods to simulate the initial soil fabric in the field. The testing system allows conducting calibration chamber tests on saturated specimens with the help of circulating carbon dioxide gas, flushing de-aired water through the sample, and applying back pressure. The testing system also allows conducting CPT penetration tests at variable penetration rates to investigate the effect of drainage conditions on CPT measurements.

The testing instrumentation and procedures were described, and challenges, future work, and potential contributions were pointed out.

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