PASTE2020 | 23rd International Conference on Paste, Thickened and Filtered Tailings

Development of a New Large Calibration Chamber for Cone Penetration Testing of Thickened Tailings

Juan Ayala*, Andries Fourie and David Reid
The University of Western Australia, Australia

ABSTRACT

New tailings storage technologies come with new geotechnical characterisation challenges. Additional to the already difficult task of assessing the stability of tailings dams is the frequent requirement of measuring the time-dependent behaviour of tailings. Such time-dependent tailings responses can be monitored using piezometers, which provide continuous data of the pore water pressure within the dam. However, this frequent monitoring must be complemented by in situ investigations. For such in situ testing, the cone penetration test is recommended, mainly because of the useful data that it provides to practitioners, the worldwide availability of suitable equipment, and the rich database of correlations and interpretations available. For the development of these widely used correlations, different techniques have been used in the past including theoretical, numerical and experimental approaches. Since the first two techniques correspond to approximations, experimental data is preferred. These experimental data are usefully derived from calibration chamber testing, which has provided valuable contributions. Since paste and thickened tailings do not generally segregate after deposition, there is an increasing need for developing correlations for cone penetration testing in such materials, which invariably have substantial fines contents.

A variety of different calibration chambers have been used for many decades, mainly to create correlations between known soil density, effective stress and saturation conditions. This work presents the development of a new large calibration chamber at the University of Western Australia, the design of which is based on other currently available calibration chambers, but with added capabilities identified as necessary from laboratory characterisation experience of mine tailings within the critical state soil mechanics framework. These include enabling improved tracking of volume changes during saturation and consolidation, as this aspect requires special attention for many thickened tailings materials.

INTRODUCTION

In the last few years, the stability of tailings storage facilities (TSF) has been a worldwide concern, mainly caused by the recent catastrophic failures in Feijão in 2019 and Samarco in 2015 in Brazil, and Mount Polley in 2014 in Canada. Along with these failures, new technologies such as thickened and paste tailings have received renewed attention as a potential solution for reducing TSF failure susceptibility by reducing the amount of water used by the slurry deposition systems, resulting in much reduced storage of water on these facilities.

These new technologies also come with new characterisation challenges, mainly caused by the reduced particle segregation that occurs. This reduced segregation presents a new geotechnical profile and characteristic particle size distribution (PSD) for the same material when compared to the profile found with the conventional slurry deposition method. In addition, although thickened tailings are deposited with less water than slurry tailings, they are still invariably saturated when placed on the TSF. Therefore, there is still the potential for development of positive excess pore pressures, which may be a concern for stability.

To facilitate quantification of shear strength and pore pressure profiles within a TSF, the cone penetration test (CPT) is usually the instrument preferred by most practitioners for field testing. Since most CPT correlations correspond to either clean sands or clays, and the unsegregated PSD of thickened tailings tend to be mainly composed of mixtures of silts and sands, the development of new correlations is a growing necessity.

Historically the most reliable way of generating these correlations has been by using controlled laboratory testing in calibration chambers (CC). Different CC designs have been used in the past (Sweeney and Clough, 1990, Ghionna and Jamiolkowski, 1991, Salgado et al., 2001, Pournaghiazar et al., 2012, Damavandi-Monfared and Sadrekarimi, 2015) with one of the main differences being the type of boundary condition used, e.g. either rigid (displacement controlled) or flexible (stress controlled). The CC introduced in this paper corresponds to a stress controlled option on the radial boundary, and displacement controlled option on the top and bottom ends.

The CC system developed at the University of Western Australia (UWA) was designed to perform CPT under controlled conditions of stress and sample volume changes, in order to track the void ratio changes during the entire CPT test. Accurate quantification of void ratio changes, in addition to determination of the corresponding critical state line (CSL), permits correlation of the state parameter (ψ) with the CPT normalized tip resistance (Qp).

NEW LARGE CALIBRATION CHAMBER

The system utilises a constant pressure source that maintains a pressure between 500 and 700 kPa. As shown in Figure 1, on the top left side the laboratory air pressure line is connected to an arrangement that includes a moist container to remove possible condensed water in the air line. After this, the line is divided in two, for back and cell pressure lines.

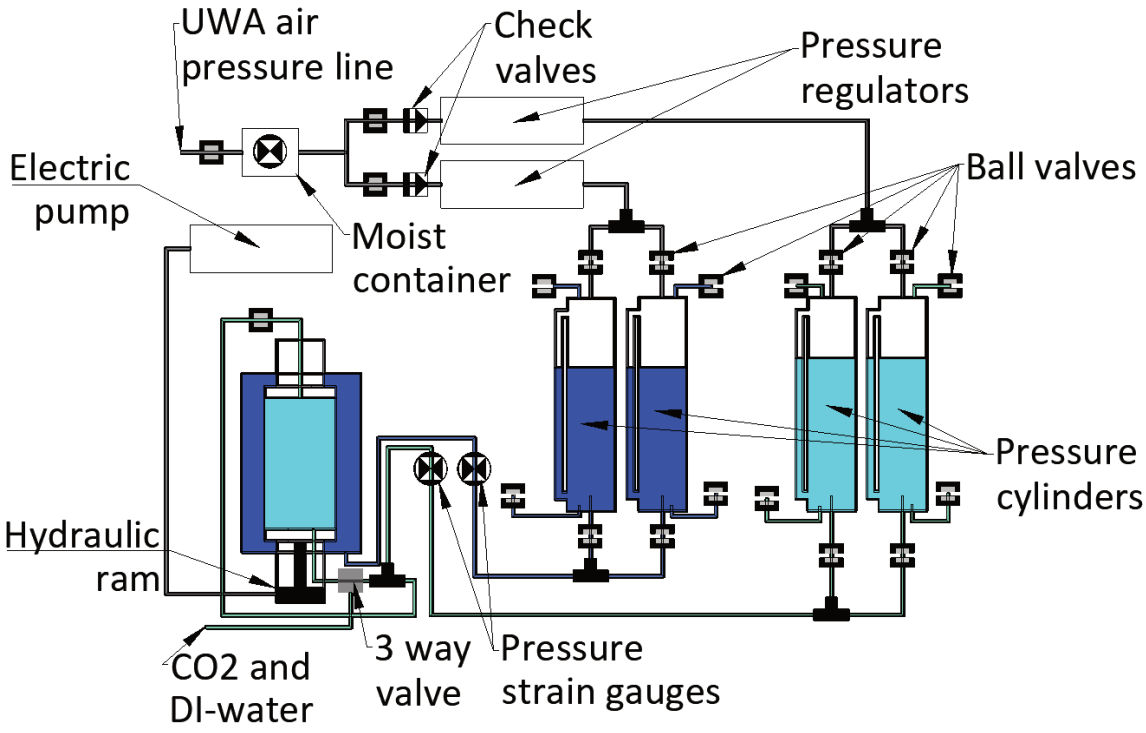

Figure 1 Large calibration chamber general scheme

Two check valves were added to the new lines in case the laboratory pressure line loses pressure. The positioning of these check valves is important for two reasons. Firstly, considering that sample saturation will likely take several days, and consolidation of large samples with high fines content will be necessary, the check valves will secure the testing pressure continuity in case of temporary pressure losses. Secondly, if the pressure drops, the check valves will protect the pressure regulators from being subjected to the pressure difference between the system and potentially atmospheric pressure in the University pressure line, which could severely damage the pressure regulators as these are not designed to work as check valves. The pressure regulators for the CC back and cell pressure lines can establish pressures of up to 2500 kPa. The system has ball valves in different locations that allow isolation of a region to allow depressurisation if needed.

Pressure transducers

After the pressure regulators establish the working pressure for the back and cell pressure lines, four pressure cylinders transmit the pressure from the air to the water. Each of these stainless-steel pressure cylinders are 1500 mm in height and 90 mm internal diameter, providing over nine litres of water volume in each cylinder. The system has two pressure transducers for each line as shown in Figure 1. The water volume is controlled through transparent hoses and a scale attached to the side

of each pressure cylinder. Each millimetre on the scale corresponds to about 6 cm^3 of water volume, which is less than 0.01 % of the sample size, giving good resolution of the sample volume changes.

Each cylinder has additional valves in the top for refilling, and the bottom for dewatering the tubes, depending on the needs of the stage and the expected volume change.

Connection to calibration chamber

Before connecting the water lines to the CC, two analog water pressure sensors are connected to the lines and located at half the height of the sample. After this, the cell pressure line is connected at the bottom of the CC. The back pressure line is divided into the bottom and top piston lines, the bottom line includes a triple ball valve in order to permit the access of CO_2 and DI-water from the bottom to the top of the sample during flushing and saturation.

Hydraulic ram and calibration chamber

The axial pressure on the sample is a combination of the cell water pressure and the bottom hydraulic ram. This hydraulic ram has an electric micro-pump that keeps the selected pressure constant. The hydraulic ram and the CC design are based on the equipment described by Pournaghiazar et al. (2011), with the principal difference being the addition of the top sample piston as can be seen in Figure 2. Other general characteristics of the CC are that the sample height is 950 mm with a diameter of 476 mm, and the cell has a height of 1030 mm with a diameter of 690 mm. The complete assembled system is over 3 m in height and is mainly composed of stainless steel grade 304.

Top sample piston

The CC described by Pournaghiazar et al. (2011) corresponds to a system oriented to study the CPT behaviour of unsaturated soils, while this new design is intended to replicate the behaviour of loose, saturated tailings samples, according to the behaviour observed during several triaxial tests. Accordingly, the addition of the top piston corresponds to the need to track the critically important sample volume decrease observed in the triaxial tests. Vertical movement of the piston can be controlled using a system of four threaded bars (see Figure 2). This system can also be used to prevent the piston from rising while the hydraulic ram pushes the sample upwards.

The top and bottom pistons have channels that facilitate an even flow of water in and out of the sample through two hose lines per piston that connects the internal sample flow with the exterior lines. The top piston differs from the bottom one, having the porous stone fixed with bolts to avoid non-concentric configurations during the system assembly, and an internal cylindrical plastic liner to avoid tilting of the CPT probe inside the top cap. In addition, the top porous stone has a 50 mm diameter hole for the CPT probe.

CPT probe

The CPT probe corresponds to an a.p. van den berg adapted system. The CPT has a reduced tip diameter and regular connection at the back end, and a diameter of 16 mm. The strain gauges arrangement acquires tip resistance (q_t), sleeve friction resistance (f_s) and pore water pressure (u_2), as does a typical CPTu probe.

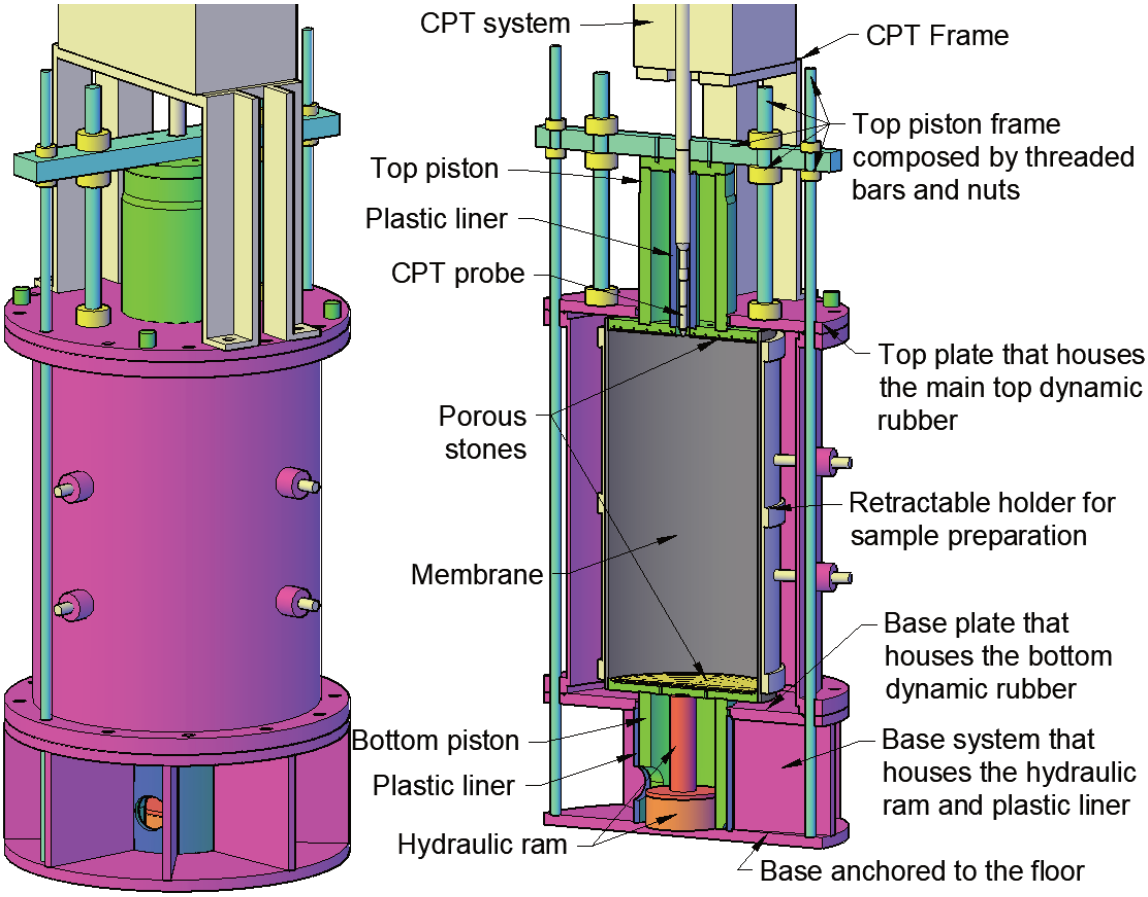

Figure 2 Large calibration chamber

TEST METHODOLOGY

The test methodology mainly accounts for sample preparation and sample volume change tracking during flushing, saturation, consolidation and testing. Samples are prepared using the moist tamping method presented by Ladd (1978). This method corresponds to gentle tamping of different layers with different masses and equal height, having an increasing mass distribution from the bottom to the top layer, with a total difference of 10 % of additional mass in the top than in the bottom layer. This mass difference accounts for the additional compaction of the lower layers while tamping the overlying additional layers. This technique has been used by different authors (Ishihara, 1993,

Verdugo and Ishihara, 1996, Jefferies and Been, 2000, Fourie and Tshabalala, 2005) for preparing triaxial test specimens and is recommended to achieve uniform loose samples (Fourie and Papageorgiou, 2001).

The sample volume record initiates with the known mass prepared and the initial sample dimensions. After this, the volume changes are recorded by the movements of both pistons and the volume of water that enters the cell while the sample decreases in volume during saturation. After saturation is achieved, alternate pressure increases between the cell and back pressure lines is used to record the water volume changes. While one line increases the pressure, the other is maintained constant. The resulting water volume change corresponds to the volumetric change of the sample. After consolidation to the final target stress is achieved, the top piston is fixed in place and the CPT test performed. Having tracked the saturated sample volume and the mass used during preparation, the void ratio can be obtained directly and compared to the corrected CPT data for the given stress condition. Data obtained from this test includes the state parameter versus the normalized tip resistance, the normalized tip resistance versus the normalized friction ratio, among others.

CORRECTIONS REQUIRED

Although laboratory tests strive to simulate field circumstances under controlled conditions, not all field conditions can be correctly simulated to the same extent, often requiring data corrections.

Size ratios

Different correction factors have been developed and used over the years to account for sample boundary proximity and CPT probe size implications on the acquired data. The most commonly used correction corresponds to the ratio of the sample and the CPT probe diameter, where a minimum ratio of 20 is recommended. There are different methodologies for correction of this effect (Bolton et al., 1999, Wesley, 2002, Pournaghiazar et al., 2012, Yang and Russell, 2015), but when testing loose, moist tamped samples that tend to contract when sheared (by the CPT probe penetration), localised volume reduction is not necessarily unduly affected by the radial boundary proximity, as these volume changes are likely to be contractive rather than dilative. The need for a correction factor may thus indeed become questionable.

In addition, a minimum value of 20 is recommended for the ratio between the CPT probe diameter and the mean particle size (d_{50}). Given that most mine tailings usually comprise of silt and sand, this is not an issue for the UWA CC.

Although CPT data is obtained from the time of insertion to the top of the specimen until the entire specimen has been probed, only the middle third is used to derive the required correlations, in order to avoid any influence of the top and bottom rigid ends. Gui and Bolton (1998) proposed a minimum of five cone diameters from the boundaries should not be used for loose sands and Gui et al. (1998) proposed ten cone diameters to avoid any disturbance on denser samples.

Vertical stress

Under field conditions the vertical stress at the level of the cone tip is simply the geostatic stress, whereas in many CC tests (including the new UWA CC) the vertical stress is applied through the base. Wesley (2002) proposed a correction for such CC configurations. His proposed correction is given in Equation 1 where σ_v corresponds to the vertical stress, σ_b is the vertical stress applied through the base of the CC, q_t is the tip resistance and R_D is the ratio of the sample diameter to the cone diameter.

$$\sigma_v = \sigma_b - \frac{q_t}{(R_D)^2} \quad (1)$$

After CC corrections are applied and field conditions achieved, regular normalisation equations can be used for characterisation purposes. These normalisations include the tip resistance normalized by mean effective stress (Q_p), the normalized friction ratio (F_s) and the normalized excess pore pressure (B_q) as described by Jefferies and Been (2015). Although no results are available to date, the CC commissioning is due for February 2020, and preliminary results will thus be presented at the conference, if available.

CONCLUSIONS

A new large-scale calibration chamber developed at the University of Western Australia is presented. This laboratory equipment is designed to test saturated thickened tailings with the resulting data being evaluated within the critical state soil mechanics framework. The cone used corresponds to a 2 cm^2 a.p. van den berg adapted CPTu. The calibration chamber incorporates some novel features such as the big pressure cylinders and the top piston, which allows tracking of the sample volume changes, thus enabling tracking of the sample collapse while being saturated. Although the main sample preparation method corresponds to moist tamping, other methods such as sand pluviation or slurry preparation can also be used using the retractable sample holder.

ACKNOWLEDGEMENTS

This work forms part of TAILLIQ (Tailings Liquefaction), which is an Australian Research Council (ARC) Linkage Project supported by financial and in-kind contributions from Anglo American, BHP, Freeport-McMoRan, Newmont, Rio Tinto, and Teck. The TAILLIQ project is being carried out at The University of New South Wales, The University of South Australia, The University of Western Australia (lead university), and The University of Wollongong. We acknowledge the support and contributions of project personnel at each of the supporting organisations.

NOMENCLATURE

σ_v	vertical stress in the calibration chamber
σ_b	vertical stress applied in the base
q_t	cone penetration tip resistance
R_D	ratio of the sample diameter to the cone diameter

REFERENCES

BOLTON, M. D., GUI, M. W., GARNIER, J., CORTE, J. F., BAGGE, G., LAUE, J. & RENZI, R. 1999. Centrifuge cone penetration tests in sand. *Géotechnique,* 49**,** 543-552.

DAMAVANDI-MONFARED, S. & SADREKARIMI, A. 2015. Development of a Miniature Cone Penetrometer for Calibration Chamber Testing. *Geotechnical Testing Journal,* 38**,** 878-892.

FOURIE, A. B. & PAPAGEORGIOU, G. 2001. Defining an appropriate steady state line for Merriespruit gold tailings. *Canadian Geotechnical Journal,* 38**,** 695-706.

FOURIE, A. B. & TSHABALALA, L. 2005. Initiation of static liquefaction and the role of K0 consolidation. *Canadian Geotechnical Journal,* 42**,** 892-906.

GHIONNA, V. N. & JAMIOLKOWSKI, J. H. A critical appraisal of calibration chamber testing of sands. *In:* HUANG, A.-B., BORDEN, R. H., PETERSON, R. W. & THMAY, M. T., eds. Proceedings of the First International Symposium on Calibration Chamber Testing, 1991 New York. Elsevier, 13-39.

GUI, M. & BOLTON, M. Geometry and scale effects in CPT and pile design. *In:* MAYNE, E. B. P. R. A. P., ed. Geotechnical site characterization., 1998 Balkema, Rotterdam. 1063-1068.

GUI, M., BOLTON, M., GARNIER, J., CORTE, J., BAGGE, G., LAUE, J. & RENZI, R. Guidelines for cone penetration tests in sand. Proceedings of the International Conference Centrifuge 98, 1998 Tokyo, Japan. 155-160.

ISHIHARA, K. 1993. Liquefaction and flow failure during earthquakes. *Géotechnique,* 43**,** 351-451.

JEFFERIES, M. & BEEN, K. 2000. Implications for critical state theory from isotropic compression of sand. *Géotechnique,* 50**,** 419-429.

JEFFERIES, M. G. & BEEN, K. 2015. *Soil Liquefaction: A Critical State Approach,* Boca Raton, FL, CRC Press.

LADD, R. 1978. Preparing Test Specimens Using Undercompaction. *Geotechnical Testing Journal,* 1**,** 16-23.

POURNAGHIAZAR, M., RUSSELL, A. & NASSE, K. 2011. Development of a new calibration chamber for conducting cone penetration tests in unsaturated soils. *Canadian Geotechnical Journal,* 48**,** 314-321.

POURNAGHIAZAR, M., RUSSELL, A. R. & KHALILI, N. 2012. Linking cone penetration resistances measured in calibration chambers and the field. *Géotechnique Letters,* 2**,** 29-35.

SALGADO, R., MITCHELL, J. K. & JAMIOLKOWSKI, M. 2001. *Calibration Chamber Size Effects on Penetration Resistance in Sand*.

SWEENEY, B. & CLOUGH, G. 1990. Design of a Large Calibration Chamber. *Geotechnical Testing Journal,* 13**,** 36-44.

VERDUGO, R. & ISHIHARA, K. 1996. The steady state of sandy soils. *Soils and Foundations,* 36**,** 81-91.

WESLEY, L. D. 2002. Interpretation of calibration chamber tests involving cone penetrometers in sands. *Géotechnique,* 52**,** 289-293.

YANG, H. & RUSSELL, A. R. 2015. Cone penetration tests in unsaturated silty sands. *Canadian Geotechnical Journal,* 53**,** 431-444.