Calibration chamber testing on tailings for interpretation of partially drained CPT

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ABSTRACT

The Cone Penetration Test (CPT) is the primary site investigation tool in silt-rich tailings. The permeability and compressibility range of tailings often puts the standard CPT penetration rate in the partial drainage range where the tip resistance, pore water pressure, and sleeve friction become functions of not only the state, but also drainage conditions. This makes interpretation of the state parameter, which represents liquefaction susceptibility and residual strength of tailings particularly challenging. It is not clear whether existing CPT interpretation frameworks are capable of accounting for effects of partial drainage. Developing field correlations for interpreting partially drained CPT data in tailings is hampered by spatial variability and sampling disturbance. CPT tests were performed in a calibration chamber and in the field on a gold tailings material. Dissipation tests were performed, and the pore water pressures on the cone at the u_2 position were monitored. The degree of partial drainage was estimated based on the coefficient of consolidation inferred from these dissipation tests. Similarities and differences of the calibration chamber and field CPTs were discussed.

Keywords: calibration chamber test; field measurements; partial drainage; tailings.

1. Introduction

The Cone Penetration Test (CPT) is a widely utilized site investigation technique. Generally, CPT penetration with a standard rate of 2 cm/s measures tip resistance q_c, sleeve friction f_s, and pore water pressure at the cone shoulder position u_2. An effective laboratory method to replicate CPT in-situ conditions is the calibration chamber test. This method ensures known stress history, boundary conditions, and uniform specimens with known densities. Numerous chambers have been designed and utilized for simulating the cone penetration test in clays and sands (e.g., Holden 1971; Bellotti et al. 1982; Been et al. 1987; Sweeney and Clough 1990; Kurup et al. 1994; Hsu and Huang 1999; Liu 2023). Many existing interpretation methods for CPT measurements were developed based on drained penetration in calibration chamber tests on sands (e.g., Been et al. 1986; Plewes et al. 1992; Shuttle and Jefferies 1998; Mozaffari and Ghafghazi 2023).

It is not clear whether interpretation methods developed in clean sands are applicable to intermediate soils, such as tailings, due to variations in drainage conditions during penetration. Generally, the standard penetration rate induces fully drained penetration in sands, and undrained penetration in clays, where pore pressures are generated than they dissipate.

The influence of penetration rate on drainage conditions has been studies analytically (e.g., Oliveira et al. 2011; DeJong and Randolph 2012; Ayala et al. 2023), numerically (e.g., Teh and Houlsby 1991; Silva et al. 2006; Yi et al. 2012), in centrifuge tests (e.g., Silva and Bolton 2005; Jaeger et al. 2010; Oliveira et al. 2011; Price et al. 2019) or based on field data (e.g., Kim et al. 2008; Schnaid et al. 2010; Dienstmann et al. 2018). Limited research has been conducted using calibration chamber tests (Tan 2005; Kim et al. 2008, 2010; Huang 2015; Sivaratnarajah 2016) and there are only a few calibration chamber tests done on tailings (Ayala et al. 2020; Russell et al. 2022). This paper focuses on a fine grained gold tailings tested in a calibration chamber and in the field. The calibration chamber is first introduced, followed by a comparison of chamber results with field measurements. Two dissipation tests performed in the chamber and in the field are then compared and analyzed, and the degree of partial drainage as a function of penetration rate is discussed.

2. Calibration chamber test

2.1. Equipment

The calibration chamber currently in use at the University of Toronto originates from Golder Associates' (now WSP) Calgary laboratory (Been et al. 1987). It was recommissioned in 2018 (Liu et al. 2022) with additional components including a pressure control panel, a water de-airing system, and a hydraulic jack, as shown in Fig. 1. The chamber is 1.14 m deep and has an inner diameter of 1.4 m. The chamber wall is approximately 1 cm thick, providing semi-rigid lateral boundary conditions. The vertical confining pressure is applied on top of the sample through a latex membrane. The vertical confining pressure and back pressure are controlled by air-water reservoirs. Initially, the cone is pushed to an initial position within the sample through bushings in the chamber cap and membrane to seal the chamber and specimen. Consolidation stresses are applied via a pressure control panel. Cone penetration is done by a hydraulic jack, which operates at a user-defined rate between 0.002 cm and 3 cm/s. It can apply a total force as high as 50 kN. Tip resistance q_c, sleeve friction f_s, and pore water pressure at the cone shoulder position u_2 and tip position are recorded in the data acquisition system. A standard 10 cm^2 analogue cone (diameter of 35.7 mm) manufactured by ConeTec was used.

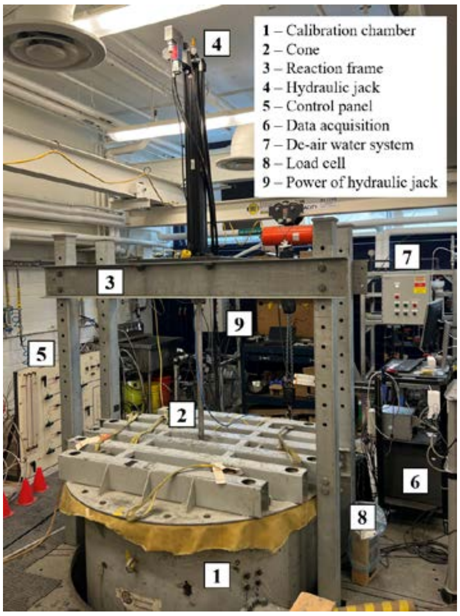


Figure 1. The University of Toronto calibration chamber components.

2.2. Tailings properties

The tailings tested originate from a gold mine tailings storage facility in Canada. The grain size distributions of the specimen tested in the chamber as well as field samples are depicted in Fig. 2. The fines content of the chamber specimen ranged from 73 % to 82 %, surpassing that of the field slurry tailings (62% to 68%). The specific gravity of the tailings particles G_s is 3.2.

Prior to sample preparation, a pair of clear plastic sheets with graphite grease sprayed in between were hung against the chamber wall for friction reduction. A porous layer was created at the base of the chamber using a 5 cm thick layer of clean medium sand, overlain by a geotextile, overlain by a perforated steel disk. The sample preparation was done by slurry deposition. Initially, the tailings were mixed thoroughly in a sealed concrete mixer, with de-aired water added and vacuum applied to improve saturation, ensuring uniform gradation and water content in each mixture with minimal entrapped air. The water content of the slurry mix was about 36%. The slurry was then pumped into the chamber through a tube with a consistent movement pattern to achieve uniformity. The slurry was always deposited under water (see Fig. 3) in layers and the amount of water overlaying the specimen was kept to a minimum by draining excess water from the bottom of the chamber as needed. As the tailings reached the top, a permeable layer mirroring the one at the bottom was created before the latex membrane was laid over and the chamber was closed off.

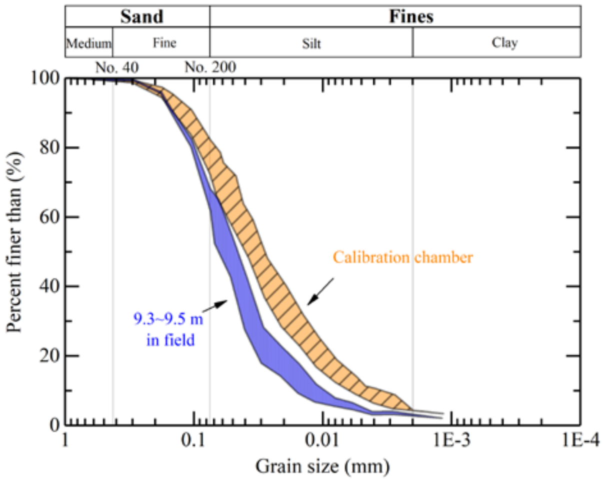


Figure 2. Grain size distribution of the gold tailings.

2.3. Test procedures

The specimen was then flushed with water for two weeks, during which about 160 litres of water passed through. By monitoring three load cells positioned under the chamber and measuring the water content of the specimen, the total weight, density, and void ratio of the sample can be calculated. In the test here, the vertical pressure σ_v was 350 kPa, and the back pressure σ_b was 200 kPa, thereby establishing a vertical effective stress σ'_v of 150 kPa on top of the specimen, with a 12 kPa increase at the bottom of the specimen due to the weight of the soil.


Figure 3. Slurry deposition of tailings sample in chamber.

The penetration test was performed in two stages. First the cone was pushed at the standard rate of 2 cm/s to the middle of the sample, where a pore pressure dissipation test was completed. Subsequently, the cone was pushed at the slow rate of 0.02 cm/s. After the test the specimen was removed and carefully sampled in 10 layers, before the chamber was cleaned up and prepared for the next test. Overall, this test usually takes up to 10 weeks.

3. Results

3.1. Calibration chamber test

The CPT measurements from the chamber, depicted in Fig. 4, illustrate depth on the vertical axis and tip resistance q_t, sleeve friction f_s, and excess pore water pressure Δu_2 on the horizontal axis. The measured cone tip resistance q_c was corrected for unequal area effect to obtain q_t. The depth normalized by the cone diameter (z/d) is plotted on the right vertical axis. The top chamber horizon is designated as zero, and the cone is stopped at a mid-depth of z=58 cm, indicated by the dashed line. During the first part of penetration z=43-56 cm, the tip resistance ranges from 4.5 to 5.2 MPa, accompanied by sleeve friction of similar pattern ranging between 33 and 41 kPa. Excess pore pressure Δu_2 exhibits a noticeable negative value towards the latter part of this stage of penetration, with a maximum reaching -150 kPa. Additionally, the peaks and troughs of excess pore pressure inversely correspond to those of tip resistance, confirming the potential role of dilation. In the second part of penetration, conducted at a rate 100 times slower. Both tip resistance and sleeve friction stabilize past 70 cm depth with a slight decrease past 80 cm and remain stable thereafter. Excess pore pressure remained at zero confirming drained penetration.

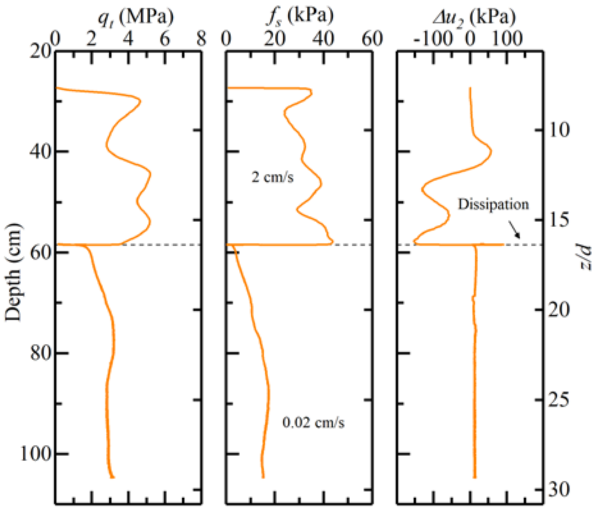


Figure 4. Results of calibration chamber test.

3.2. Field CPT measurements

The results from a CPT test (with a 15 cm^2 cone) performed as part of a site investigation program carried out by ConeTec are shown in Fig. 5 along with the calibration chamber results. The water table in the field is 6.1 m deep. Assuming a saturated unit weight of 22 kN/m^3 and a wet unit weight of 18.8 kN/m^3 in the field (based on unit weights obtained in the chamber), the 150 kPa vertical effective stress of the chamber is assessed to correspond to 9.2 m depth, where the chamber data are placed. Both tip resistance and sleeve friction from the chamber align closely with the field measurements at equivalent depth. However, Δu_2 (the pore pressure at u_2 minus the hydrostatic pore pressure) is staying close to zero in the field.

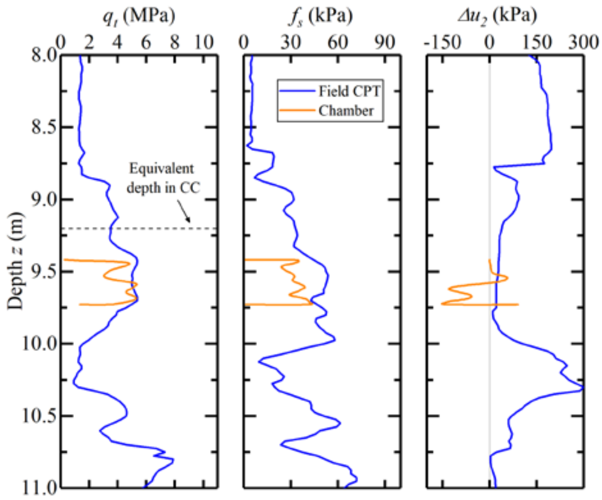


Figure 5. Comparison of CPT measurements between field and calibration chamber.

3.3. Comparison of dissipation tests

In Fig. 6, pore pressure dissipation tests in both chamber and field are shown. A non-standard dissipation is observed during u_2 dissipation in the chamber, characterized by an initial increment in pore pressure followed by a monotonic decrease. This trend is commonplace in dilative soils. To address this non-standard dissipation after cone stops, Chai et al. (2012) proposed an empirical equation to correct the value of t_{50}, grounded on the assumption of initial excess pore pressure distribution in the radial direction in numerical modelling. Following the correction, the t_{50c} in the chamber is 4.7 s, which closely aligns with the 6.9 s obtained in the field when the larger diameter of the field CPT is considered.

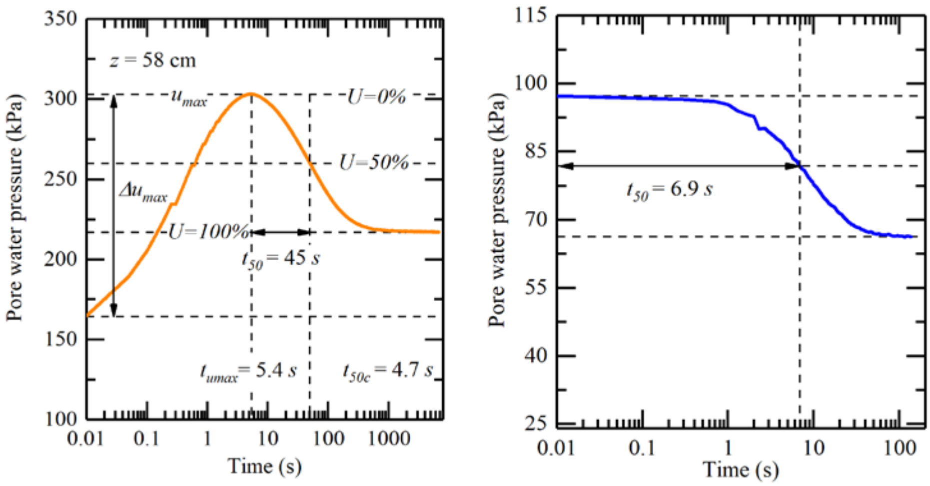
Table 1 presents the interpretation of the horizontal coefficient of consolidation c_h from dissipation tests in both calibration chamber and field using the DeJong and Randolph (2012) method with three levels of partial drainage assumed. The time factor T'_{50} is the resulting apparent time factor when half of the excess pore pressure has dissipated and is related to c_h through Equation 1.

$$c_h = \frac{T'_{50} d^2}{t_{50}} \tag{1}$$

where d is the cone diameter and t_{50} is time it takes for half of the pore water pressure to dissipate.

For the dissipation test performed in the chamber, the pore pressure initially rose as expected for tests performed in dilative materials. The time passed was recorded relative to the time the pore pressure peaked. (Chai et al. 2012).

The field and calibration chamber tests produced nearly identical results for each assumed degree of partial drainage. Assuming a larger degree of partial drainage leads to a larger coefficient of consolidation, as soils consolidate more rapidly, and the normalized rate shifts towards a drained state.



(a) (b)

Figure 6. Dissipation of pore pressure in a) calibration chamber test; b) field.

4. Discussion

The calibration chamber results presented in Fig. 4 suggest reasonable uniformity and is encouraging given the difficulties of performing large scale calibration chamber tests in tailings. A comparison of calibration chamber results in Fig. 4 suggests that drained penetration produced lower tip resistances than undrained penetration. This is a signature of penetration in dilative materials (Silva and Bolton 2005; Ayala et al., 2023) and is confirmed by the negative pore water pressures observed. This dilative trend is confirmed by the initial increase in the pore water pressure during the dissipation test (Fig. 6a). The similarity of tip resistance and sleeve friction between the chamber and the field is also encouraging. The difference between the pore pressures may be due to different densities or can be a result of higher drainage in the field, given the lower fines content observed in the field (Fig. 2).

Fig. 7 illustrates the impact of penetration rate on normalized tip resistance q_t/q_{dr}, incorporating calibration chamber results, field measurements, and centrifuge tests of dilative silica flour by Silva and Bolton (2005). The vertical axis is the ratio of the corrected tip resistance q_t divided by the tip resistance q_{dr} during drained penetration. So, the lower half of the calibration chamber test produced a q_t/q_{dr}=1 given the slow rate of penetration leading to drained penetration. The standard rate tests in the upper half of the test and the field produced values of 1.58 and 1.60 MPa respectively. Vertical error bars are included to cover the range of tip resistance values observed. This higher value is consistent with a dilative material as observed earlier. The horizontal axis is the normalized penetration rate $V=vd/c_v$, where v is cone penetration rate, d is the penetrometer diameter and c_v is coefficient of consolidation in vertical direction. c_h =2c_v is assumed (Dienstmann et al. 2018) to account for potential differences between the vertical and horizontal properties.

The silica flour data (Silva and Bolton 2005) suggest that partially drained penetration occurs between normalized velocities of 0.1 to 10, not too far from the range proposed by Finne and Randolph (1994) and Randolph (2004). Based on this range, it appears the bottom half of the calibration chamber test, which was performed at 0.02 cm/s was almost certainly drained, while the standard rate tests (2 cm/s) performed in the upper half of the chamber and the field were nearly undrained. The horizontal error bars show the influence of the small degrees of potential deviation from undrained conditions (5, 10, or 20%) for these tests.

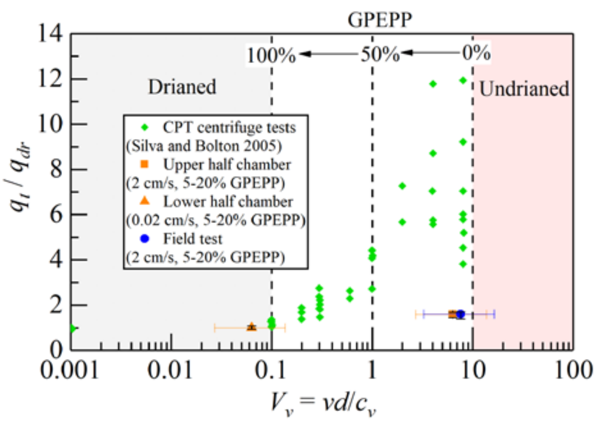


Figure 7. Influence of penetration rate on tip resistance in dilative soils.

Table 1. Summary of coefficient of consolidation c_h values computed

Test	Cone diameter (cm)	Rate (cm/s)	t_{50} (s)	Assumed degree of partial drainage during penetration (DeJong and Randolph 2012)								
				5%			10%			20%		
				T'_{50}	c_h (cm^2/s)	V_h	T'_{50}	c_h (cm^2/s)	V_h	T'_{50}	c_h (cm^2/s)	V_h
Chamber	3.57	2	4.7	0.385	1.04	6.84	0.83	2.25	3.17	1.94	5.26	1.36
Field CPT	4.37	2	6.9		1.07	8.20		2.30	3.80		5.37	1.63

5. Conclusions

A CPT calibration chamber test conducted on a gold tailings was presented and compared to field measurements in the same material at a similar overburden pressure. Tip resistances, sleeve frictions, and dissipation properties were very similar between the chamber and field tests, while the negative pore pressures observed in the chamber were not present in the field. This was attributed to different dilation levels, or different degrees of partial drainage. The CPT tip resistance had higher values at the standard rate of 2 cm/s compared to the slow rate of 0.02 cm/s. This suggested dilative behaviour, confirmed by the pore pressure dissipation trend observed during a dissipation test performed. Comparison to centrifuge data confirmed that the tailings are likely dilative in the chamber and undergo partial drainage during standard Cone Penetration Testing.

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