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Interpretation of centrifuge piezocone tests in dilatant, low plasticity silts

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Abstract

When drainage conditions during standard piezocone penetration is fully understood, the piezocone parameters are correlated to the physical and mechanical properties of soils such as shear strength and consolidation. Otherwise, the piezocone parameters are, in principle, able to identify only the layering and characteristic grain size of soils. In this paper, model piezocone tests (PCPTs) have been carried out in a centrifuge model at different velocities to investigate the rate effect to penetration drainage conditions. The model consisted of a dilatant milled quartz material resembling particles from mine tailing wastes within silt fraction. The data are used to describe the behaviour of the dilatant soil sample with increasing penetration rate and the difficulties in the soil characterization. On the other hand, drained penetration resistance appears to be correctly predicted by cavity expansion analysis obeying the Mohr-Coulomb criterion.

Keywords: *piezocone, centrifuge, penetration rate, silica flour, mine tailing.*

1 Introduction

Drainage conditions during standard piezocone tests (PCPTs) are largely dependent on the rate of dissipation of soils and hence on the soil characteristic grain size. Measurements of pore pressure (u) are therefore extremely useful for assessing the characteristic grain size of soils in addition to the other piezocone records, i.e. cone resistance (q_c) and sleeve friction (f_s). However, interpretation of the piezocone records to furnish geotechnical design parameters depends on whether the penetration is fully drained or undrained. It is generally accepted that undrained penetration occurs in soft to firm clay soils when a standard piezocone is inserted at 20-mm/s speed. On the other hand, standard PCPTs in intermediate soils such as silts and clayey sands vary from undrained to partially or fully drained penetration. The degree of drainage is associated with the content of fine-grained particles, with soil interlocking and hence with soil permeability and compressibility properties. The assessment of the degree of drainage during penetration is therefore the first step to analyze the piezocone parameters in such soils.

In a contractant soil, the common trend is that increasing the penetration rate at relative high values, the dynamic pore pressure u_2 and corrected cone resistance q_t also increase. The combination of both q_t and u_2 derive values of pore pressure ratio (B_q) which are largely unaffected within the undrained penetration zone in clayey soils (Randolph, 2004). The derived piezocone parameter B_q is therefore used to compute the undrained penetration behaviour of contractive clayey soils. Analyses of PCPTs from High *et al.* (1994) appear to suggest that penetration is fully undrained when the B_q values are greater than 0.5 (Schnaid *et al.*, 2004). However, changes in drainage conditions during PCPTs are difficult to determine in intermediate soils. Silty soils generate B_q values smaller than 0.5 as shown, for example, in Robertson's (1990) soil classification chart. Schnaid *et al.* (2004) found that testing conditions predominantly undrained are still characteristic of normally consolidated silty soils when B_q values lie between 0.3 and 0.5. In dilatant intermediate soils, zero or negative excess pore pressure measured on the filter element at the cone shoulder can imply either partially drained or undrained penetration, so that B_q may not be the ideal parameter to assess the drainage condition during penetration.

2 Partially drained penetration

The degree of drainage during a penetration process can best be inferred by conducting PCPTs at different penetration rates (Silva and Bolton, 2004; Randolph, 2004). For the full range of possible penetration rates, undrained to partially or fully undrained penetration can take place depending on the soil flow properties and loading conditions. Schnaid *et al.* (2004) suggested that a combination of independent measurements would therefore assist on the identification of the drainage condition during penetration. Recently, the addition of a non-dimensional velocity $V = vD/c_v$ (House *et al.*, 2001) proved useful, where v is the penetration rate, D is the cone diameter, and c_v is the coefficient of consolidation. It was observed that undrained penetration prevails when the V value lies between 20 and 50 in contractive silty soils, while in clayey soils V should be greater than 200.

It is clear from the definition of V (= vD/c_v) that if a penetration test is carried out in a standard manner in a silty soil, for example, then the upper boundary value of c_v in which a test should be performed under undrained conditions is about 14.3 mm^2/s. Any test, therefore, carried out in a soil with greater c_v value should hence be performed at higher velocity in order to maintain the undrained nature of the penetration. Furthermore, if a model piezocone of 10 mm diameter is inserted in identical soil with the same consolidation properties, for example, then it should travel 3.57 times faster compared with the standard probe under undrained conditions.

Partially drained to fully drained penetration are obtained when values of V decrease from the limiting undrained V. In order to perform partially drained PCPT in fine-grained soils, careful combination of low penetration rates, probe diameter and c_v of soil should be assigned. In this paper, commercially available silica flour was therefore used for centrifuge PCPTs because of its flow and compressibility properties, i.e. high c_v values. Also, centrifuge tests were chosen due to the good control of test conditions such as sample properties and penetration speed, while in-flight centrifuge samples attain the same stress conditions with depth as in field situation. A special 12-mm diameter model piezocone was also designed to provide information during the model PCPTs at different penetration rate.

3 The soil sample

Silica flour is a product of vitreous, amorphous quartz which was mined and then milled. The result produces silica grains which are highly angular and therefore resemble particles from

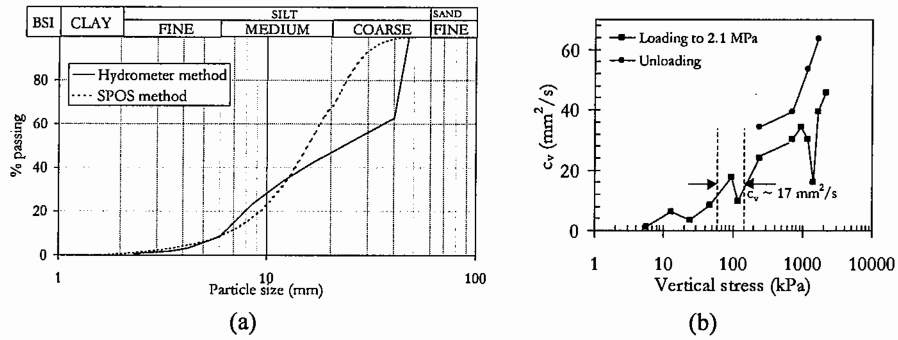


Figure 1. (a) Particle size distribution; (b) Results from standard oedometer consolidation.

mine tailing waste. The main mineral encountered in mine tailing deposits is also silicon dioxide, i.e. quartz, which is the main constituent of most of known rocks. Regardless of their geological origin, Mlynarek *et al.* (1995) observed that the particles of mine tailing wastes are generally similar.

Particular difficulty arises in obtaining undisturbed samples of low plasticity direct from mine tailing waste (Mlynarek *et al.*, 1995). Therefore, direct interpretation of PCPT results to evaluate mine tailing deposits are also difficult. In this paper, centrifuge PCPTs into low plasticity silica flour were hence performed parallel to standard size triaxial tests with reconstituted samples to the same conditions as the centrifuge sample. The centrifuge soil samples were prepared by sedimentation process. The PCPTs in the centrifuge models were then used to validate comparisons with the required prototype conditions.

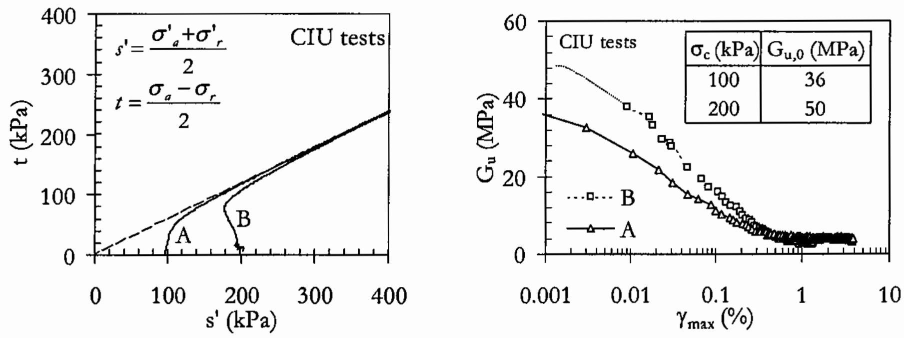
Figure 1(a) shows the PSD curves obtained by the standard hydrometer test and the single particle optical sizing (SPOS) technique. The two techniques compare favorably in result of equivalent diameter range. The silica flour consisted then of particles in the range of silt fraction, in which the representative particle size d_{10} is between 6.2 and 6.6 μm. Figure 1(b) shows the coefficient of consolidation from standard oedometer tests. A c_v value of about 17 mm^2/s was obtained at about 100 kPa vertical stress. Also, results from triaxial permeability tests showed that an average value of 6.0×10^{-8} m/s can be assumed as the permeability of the silica flour within 0.62-0.70 voids ratio range.

The liquid limit was determined by means of the fall-cone test. Consistent measurements from the test enabled to plot the graph of penetration depths of a 80-g mass falling cone into silica flour with known moisture content. The liquid limit obtained was 29%. On the other hand, the silica flour could not be rolled out to 3-mm diameter threads for the determination of the plastic limit. As the silica flour appeared to turn from a semi-solid to a 'paste,' i.e. liquid state, at a moisture content of about 27%, the plasticity index would therefore be smaller than 2%.

The trend for dilatancy of the silica flour was captured by undrained and drained compression triaxial (CIU and CID) tests under similar stress conditions as in the centrifuge. Reconstituted triaxial specimens of silica flour were made from lumps of the soil sample in the centrifuge tub just tested, and were prepared to give similar density after consolidation as the centrifuge soil sample. The soil lumps were collected at mid-depth of the centrifuge sample and tamped directly into 52-mm diameter cylindrical PVC moulds lubricated with silicone grease The moulds had 102 mm height from where the specimens were extruded. Figure 2 shows the results from two CIU tests with initial isotropic consolidation pressures of 100 kPa and 200 kPa and voids ratio of about 0.68.

The silica flour exhibits non-linear and ductile behavior throughout loading, and no peak failure point was observed. The deviator stresses (= $2t$) seems to increase indefinitely with local axial displacement. From about 2% local axial strain, the effective stress paths approached a straight line intersecting the origin in the *s-t* space, representing then the appropriate failure line for the set of undrained tests. Similar undrained shear behaviour was also found by Hoeg *et al.* (2000) in undisturbed and reconstituted, moist tamped dense triaxial specimens of silty tailing material. Figure 2(b) shows the rate of degradation of tangent shear modulus G_u with increasing maximum distortional strain γ_{max} during the CIU tests. Also, the figure shows the variation of small strain shear modulus G_{u0} with the mean effective stress p'.

It is not possible to estimate a single value of undrained shear strength (s_u) as there is a gain in strength during undrained shearing at the confining stresses (σ_c) applied in the triaxial tests. Greater pressures are then necessary to suppress the dilative behaviour of the silica flour. Villet and Darragh (1985) observed, for example, that there was no strength gain in a highly overconsolidated offshore silt from stresses corresponding to about 46 m depth. For the range of confining stresses in the CIU tests, an effective friction angle of 36.6^0 was estimated.



(a) Effective stress paths

(b) Undrained shear modulus

Figure 2. Results of undrained compression tests (CIU) with silica flour

4 Centrifuge equipment

A standard centrifuge tub was used for preparation of the soil model. The tub consists basically of a rigid thick-walled steel cylinder of 850 mm internal diameter and 40 mm height. A mechanism for driving the model piezocone was sat on the top of the tub wall. The driving mechanism allows a maximum vertical displacement of 300 mm, an axial load capacity up to ±10 kN, and a maximum linear speed of ±10 mm/s at an in-flight centrifuge acceleration of up to 100g. The model piezocone used in the investigations had 12 mm outer diameter and a 1677.6 mm^2 friction sleeve area. The filter element for the dynamic pore pressure (u_2) measurements was located immediately behind the cone tip. Design details of the driving mechanism and the model piezocone are given by Silva and Bolton (2004).

5 Test procedure

In order to obtain a soil sample with characteristics of mine tailing deposits, the sedimentation technique of silica flour from slurry was adopted. Firstly, a 10-mm height fine sand layer was poured in the centrifuge tub. Two layers of geotextile was then used to separate the fine sand from the silica flour slurry. The tub inner wall was also covered in geotextile to provide infinite boundary seepage front. Slurry of silica flour with water at a water content of about 120% was prepared by mixing them in a concrete mixing machine. The slurry was then placed in the tub which had attached a 300-mm height extension. About 630 kg of mixed material was placed in the extended tub. As expected, the surface of the soil sample consisted of the finest particles of silica flour due to the sedimentation process. Once the sedimentation ceased (approx. 3 days), the excess of clean water and soil was extracted so that the final height of the sample was 300 mm.

Eight penetration tests were performed in the sedimented soil sample. In order to avoid the influence of the tub boundaries on the penetration resistance, the piezocone tests were located similarly to Silva and Bolton's (2004) centrifuge PCPTs. The best suited locations in the 850-mm diameter tub are shown in Fig. 3. The centrifuge tests were performed at a centripetal acceleration of 50g. The piezocone tests were performed at different velocities, as detailed in Table 1. The cone was inserted 200 mm deep into the soil model, which corresponds to an effective overburden pressure at about 10 m in the field. After each centrifuge stoppage for rotation of the driving mechanism, consolidation settlements were measured. The sample height measured as well as the estimated voids ratio before each piezocone test are also given in Table 1. The moisture content profile of the soil sample was determined after the series of piezocone tests had been carried out. The average moisture content was 31% and therefore the final average voids ratio of the sedimented silica flour was 0.82.

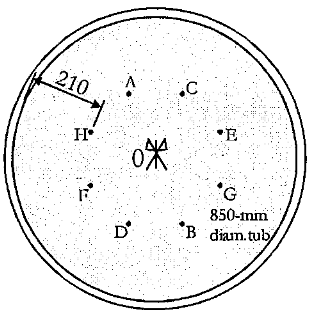


Figure 3. PCPT locations

Table 1. Centrifuge sample

Test location	Speed (mm/s)	Sample height (mm)	Voids ratio e
A	0.1	300	0.84
B	0.2	298.5	0.83
C	0.3	297.8	0.82
D	0.6	297.7	0.82
E	1.0	297.5	0.82
F	2.0	297.5	0.82
G	4.0	297.5	0.82
H	8.0	297.5	0.82

6 Centrifuge PCPT results

The two load cells in the model piezocone provided measurements of the cone resistance q_c and sleeve friction f_s throughout each penetration test. Also, the pressure transducer measured the dynamic pore pressure at the cone shoulder. The results of the centrifuge piezocone tests at different penetration rates in the sedimented soil sample are shown in Figure 4. For clarity, the figure shows only the penetration-graph results of the tests at 0.1, 0.3, 0.6, 2.0 and 8.0 mm/s rates. Figure 4 shows that the corrected cone resistance q_t at any rate increases with depth. The rate of increase on q_t seems to decrease steadily with depth. For the penetration rates at 2.0 and 8.0 mm/s, the q_t curves assume an almost constant value from 120 mm depth. Constant q_t values of about 10 MPa and 14 MPa are obtained respectively to the penetration rates of 2.0 and 8.0 mm/s. At lower rate tests, q_t values increase steadily up to 180 mm depth. At a depth of 190 mm, the q_t value of the penetration test at 0.6 mm/s rate is about 7 MPa. The increase of q_t values with increasing penetration rate is better observed in Fig. 5(a) where the values of q_t are plotted against penetration rate every 20 mm depth. In general, the average distance between two consecutive points at same penetration rate, i.e. same vertical, decreases as the penetration rate increases, showing that the gradient of q_t with depth becomes steady from 20-40 mm depth.

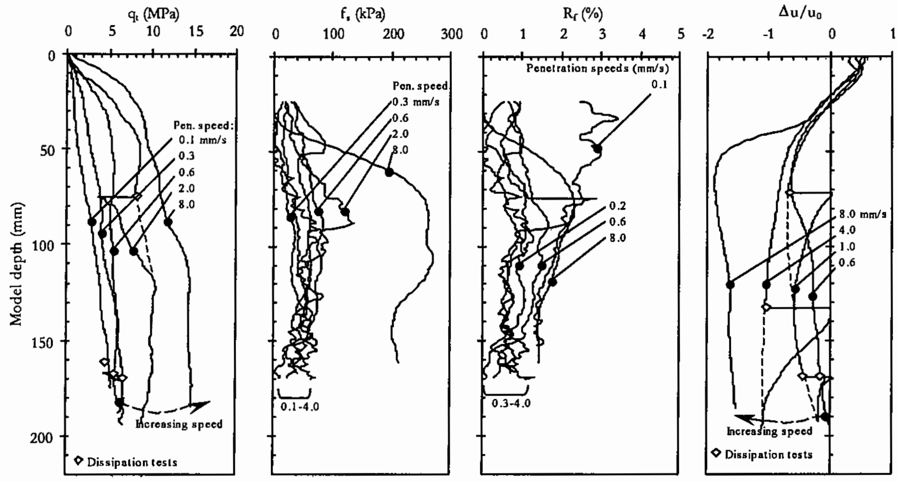
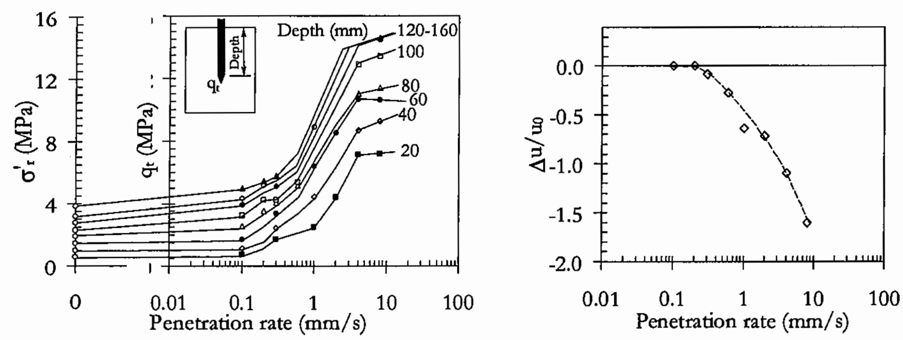


Figure 4. Penetration-graph results

Though noisier, the sleeve friction f_s curves at any rate show an almost steady value with depth except for the 8.0-mm/s penetration rate test. The range of f_s measurements is between 35 kPa and 80 kPa from 90 mm depth. However, it is difficult to determine whether there is an influence of the penetration rate on the f_s measurements in the 0.1 to 4.0 mm/s range. The penetration rate influence is more obvious when greater sleeve friction is measured at 8.0 mm/s penetration rate. The maximum sleeve friction measured in the sedimented soil sample is about 270 kPa. For the range of penetration rates tested, the friction ratio R_f is in the range of 0.5% and 1.8% from 100 mm depth.



(a) q_t *vs.* penetration rate

(b) $\Delta u/u_0$ *vs.* penetration rate

Figure 5. Summary of penetration-graph results

Figure 4 also shows the curves of excess pore pressure Δu measured at the cone shoulder normalized by the hydrostatic pressure u_0. The measured dynamic pore pressure u_2 shows an increase of negative excess pore pressure with increasing penetration rate. At 4.0 mm/s rate, for example, a constant value of $\Delta u/u_0$ of about −1 is measured from 120 mm depth. Also, almost constant $\Delta u/u_0$ values at other penetration rates are observed after a certain depth of penetration was achieved. However, derived values of B_q [$= (u_2 - u_0)/(q_t - \sigma_{v0})$] are very small and lie between −0.01 and zero. Figure 5(b) shows the average steady $\Delta u/u_0$ values for each penetration test against penetration rate. The $\Delta u/u_0$ measurements are zero at rates smaller than 0.2 mm/s. For the range of penetration rates tested, the negative steady $\Delta u/u_0$ values do not seem to stabilize with increasing speed.

6.2 Prediction of drained cone resistance

Changes in drainage conditions during penetration can be analyzed from the results of Fig. 5. Figure 5(a) shows that no substantial increase of q_t values is observed from 4.0 mm/s. However, the penetration rate at 8.0 mm/s, i.e. $V \sim 4.7$, still implies that undrained penetration was not yet achieved. On the other hand, the q_t curves appear to stabilize with decreasing penetration rate from 0.2 mm/s, i.e. $V \sim 0.12$, from where neither excess pore pressure was measured at the cone shoulder. Model PCPTs reported by Randolph and Hope (2004) in kaolin also suggests that drained penetration resistances were achieved for V smaller than about 0.1.

Cavity expansion analyses are widely used to simulate cone penetration, allowing reliable correlations to be derived. The simulation was performed with a computer program CAMFE (Carter *et al.*, 1979) and modeled as an elastic-perfectly plastic material yielding at the Mohr-Coulomb criterion with the set of geotechnical parameters for the silica flour from the laboratory tests. The drained cone resistances were predicted by simulating the penetration process as an expansion of a cylindrical cavity from a finite radius r_0 ($= D/2\sqrt{3}$). Figure 5(a) shows at 0 mm/s penetration rate the limiting effective radial stress σ'_r from the drained cavity expansion analysis at the ambient effective stresses associated with the corresponding centrifuge model depths. The values of σ'_r are approximately similar to the drained q_t values, showing therefore that the penetration resistance is mostly influenced by the ambient horizontal effective stresses (Houlsby and Hitchman, 1988).

6.3 Partially drained penetration, soil dilatancy and strength gain

Soil failure during a PCPT is associated with the combination of large physical displacement of soil and fluid as well as shearing of soil along the piezocone shaft. As the penetration rate increases, it is reasonable to assume that the zone of failure in fine-grained soils also increases because less time for drainage is allowed for dissipation during penetration. Also, the greater the disturbed surrounding soil during penetration, the greater is the induced excess pore pressure radial distribution, and vice-versa. Because such large strains mobilize the dilatant tendency of the silica flour as observed in the triaxial tests, increasing the penetration rate generates greater negative excess pore pressure. A dilatant soil thus gains strength, as the trend for dilatancy, i.e. high negative excess pore pressure, is associated with additional increase of effective shear strength and hence penetration resistance. Therefore, the q_t values in Fig. 5(a) increase from a drained penetration resistance as predicted by the finite element cavity expansion analysis with increasing penetration rate.

8 Conclusions

Results of centrifuge PCPTs within saturated silica flour were presented. The PCPTs were performed at 50g with a 12-mm diameter piezocone at different rates of penetration. Regardless of its origin, the shear strength characteristics of the silica flour resemble of reconstituted mine tailing specimens. Hence, the silica flour exhibited dilative and then ductile behaviour with no strain softening at the stress levels tested. The trend for dilatancy of the silica flour was also observed during the centrifuge PCPTs. Increasing the penetration rate, negative dynamic excess pore pressure Δu and corrected cone resistance q_t also increased. At relative low non-dimensional velocity, i.e. $V < 0.12$, drained q_t and zero Δu were measured. Drained q_t values were then compared with limiting σ'_r from finite element cavity expansion analysis from an initial radius, in which the soil model obeyed the Mohr-Coulomb criterion. The values of σ'_r were approximately similar to the drained q_t values.

Characteristic grain size of soils can be predicted when a standard PCPT is carried out at 20 mm/s speed. However, this series of centrifuge piezocone tests suggests that standard PCPTs performed in dilatant, low plasticity silts such as mine tailing wastes is partially drained to fully undrained even if the derived B_q values tend to zero. Hence, geotechnical parameters may be wrongly correlated from the piezocone parameters. The PCPT drainage condition should therefore be interpreted with the help of $\Delta u/u_0$ profile from a series of PCPTs at different penetration rates in the same soil. If increasing the penetration rate the positive $\Delta u/u_0$ values also increase or maintain constant, then the silty soil is contractant. Undrained parameters such as s_u may be yielded if B_q lies between 0.3 and 0.4. On the other hand, if the value of $\Delta u/u_0$ decreases with increasing penetration rate as well as the q_t values, then the silty soil is dilatant. Drained penetration conditions should be encountered by decreasing the penetration rate until a constant value of q_t is observed as well as $\Delta u/u_0 = 0$. The results may be interpreted by means of theoretical analysis, e.g. cavity expansion, to yield effective shear strength parameters such as the soil friction angle.

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