Interpretation of Piezocone Penetration Tests in Centrifuge

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\textbf{ABSTRACT}

This paper presents results of Piezocone Penetration Tests (CPTu) in a sand during the flight of a geotechnical centrifuge at an acceleration of 50 g. Two rates of penetration were used and its effect on penetration resistance was interpreted. Calibration of the CPTu was performed to predict the internal friction angle of the sand using cavity expansion theory and compared with results obtained from laboratory triaxial tests. It is found that penetration rate has strong but different effects on tip resistance and sleeve friction. However, the internal friction angles predicted by cavity expansion theory are approximately identical using a friction ratio to include both the tip resistance and sleeve friction response. It indicates a minor effect of the predicting rate on the soil strength prediction. Further study is needed to clarify the mechanism.

\textbf{Keywords:} piezocone penetration test, sand, centrifuge

\section{INTRODUCTION}

Piezocone Penetration Test (CPTu) has been increasingly used for in-situ soil characterization and its application has been extended to a variety of field of geotechnical engineering in recent decades (Schmertmann, 1978; Mayne, 2007; Sawada and Towhata, 2011; Liu and Cai, 2012; Shen et al., 2016). The origins of Cone Penetration Test (CPT) dated back to the 1950s at the Dutch Laboratory for Soil Mechanics in Delft to investigate soft soils.

Many efforts have been made to develop correlations for the engineering properties of soils in terms of CPT interpretation (e.g. Huang, 2016; Giretti et al., 2018; Wang and Zhang, 2018). However, as the cone penetration response are highly influenced by the initial stress state, initial average density of soils, etc. More research is needed in this regard.

This paper carried out two groups of piezocone penetration test in a sand using a geotechnical centrifuge at an acceleration of 50 g. Results of the CPTu tests were interpreted by empirical equations based on cavity expansion theory (Vesic, 1977). The predicted internal friction angle of the sand was compared with that obtained from laboratory triaxial tests. The effects of penetration rate were examined.

\section{CENTRIFUGE MODEL AND MATERIAL}

Geotechnical centrifuge tests of piezocone penetration in a sand were performed on the 2.5-m-radius centrifuge at the Tsinghua University. All tests were performed at a centrifugal acceleration of 50 g. Fig. 1 shows a strong box with inner dimensions 600 mm \times 200 mm \times 520 mm high and a cone penetrometer probe fabricated by Thomas Broadbent & Sons Ltd. UK. Two electric motors were mounted on the strong box. One can push the penetrometer vertically into the sand at two controlled displacement rate, i.e. 15 mm/s and 20 mm/s at prototype for this study. The other motor will drive the penetrating system moving horizontally so that multiple penetration can be possible.

Fig. 1. Centrifuge model setup for piezocone penetration test.
The CPTu has an external diameter of 10 mm and incorporates a 60 degree cone at the penetrating end. It offers a maximum vertical resistance capacity of 5 kN (tip resistance). The penetration depth can be up to 300 mm. The tip resistance \(q_c\) is measured by load cells located behind the cone. Sleeve friction \(f_s\) is measured by load cells embedded in the sleeve and measure average skin friction as the probe is advanced through the soil. Sleeve friction is reported as a friction ratio \((F_r)\), the ratio of skin friction divided by the tip resistance. Pore water pressure can also be measured simultaneously by a miniature embedded pore pressure sensor (Fig. 2).

The centrifuge specimen of the sand were prepared at a dry density of 1650 kg/m\(^3\) in the strong box by layered compaction. After deposition, the sand was filled with water through an upward flow with a small hydraulic gradient to avoid soil disturbance. Tap water is used. It was then saturated at 1g level and consolidated for about 20 minutes in the centrifuge at 50 g. The two CPTu tests are referenced as test No. 1, and test No. 2, with penetrating rate of 15 mm/s and 20 mm/s. Each test yielded data points of tip resistance, sleeve friction, and pore water pressure. Results of the centrifuge tests are presented in prototype scale with standard scaling laws referred to Taylor (1995).

Results of Test

Fig. 3 and Fig. 4 show profiles of the tip resistance \(q_c\), sleeve friction \(f_s\) against soil depth, while the pore water pressure has been deducted. Fig. 5 shows the pore water pressures measured during penetrating, which are slightly higher than hydrostatic pore water pressures of the model. The peak excess pore water pressures in these two tests were \(-10\) kPa and \(-5\) kPa at the penetrating rates of 15 and 20 mm/s, which meant the penetrating process was more close to a partially to fully drained condition at these two penetrating rates.

As seen in Figs. 3 and 4, the tip resistance and sleeve friction increase with soil depth or vertical stress, however, the tip resistance decreases with the increased penetrating rate. The maximum tip resistance in test No. 1 is 20 MPa at 9 m deep, approximately two times of that in test No. 2. On the contrary, the sleeve friction increased with the penetrating rate. The maximum sleeve friction in test No. 1 is 115 kPa at 9 m deep, approximately one fifth of that, 580 kPa, in test No. 2. The penetrating rate had strong effect on both the tip resistance and the sleeve friction, but the effects are opposite. These effect will be integratedly evaluated in the calibration of the CPT results.

In these two tests, the average friction ratios are calculated to be 1% and 7%. Usually, high friction ratios are indicative of clayey materials (High \(c\), low \(\phi\)), while lower ratios are typical of coarse (sandy/gravel) materials. Typical values are 1% to 10%.


4 CALIBRATION OF CPTu TESTS

The purpose of CPT calibration is to determine the geotechnical engineering properties of soils and delineating soil stratigraphy. The tip resistance is theoretically related to soil strength. However, the difficulty in developing a rigorous model of cone penetration is associated with unknown initial soil conditions, complex soil behavior, and large stresses and strains imposed during the penetration process (Jamiolkowski et al., 1982). Therefore assumptions to simplify soil behavior, the penetration process, and boundary conditions are essential for any analytical method.

The cavity expansion theory can be utilized to predict the internal friction angle \( \phi \), taking account the behavior of sand. Based on the spherical expanding pressure, the bearing capacity factor \( N_q \) is defined as (Vesic 1977):

\[
N_q = \frac{3}{3 - \sin \phi} e^{\left[ \frac{\pi}{2} (3 - \sin \phi) \right]} \tan^2 \left( \frac{\pi}{4} + \frac{\phi}{2} \right) I_v \left[ \frac{4 \sin \phi}{\chi(\sin \phi)} \right]
\]

where \( I_{rr} \) = reduced rigidity index, and for spherical expanding cavity \( I_r \), takes the following form:

\[
I_r = \frac{I_v}{1 + \Delta},
\]

where \( \Delta \) = volumetric strain, \( I_v = \) rigidity index which represents the ratio of the shear modulus of the soil to its initial undrained shear strength. Vesic (1977) estimated \( I_v \) empirically as follows:

\[
I_v = \frac{170}{F_r}
\]

where \( F_r \) = friction ratio previously mentioned. With the friction ratio, both the tip resistance and the sleeve friction of the CPT results can be taken account in the prediction of the soil strength parameters. Chen and Juang (1996) proposed an empirical correlation through regression analyses for \( \Delta \):

\[
\Delta = -0.003 \frac{\sigma_{\text{e}}}{q_c} + 1.554
\]

where \( \sigma_{\text{e}} = \) mean effective confining pressure.

Substituting Eqs. (2–4) into Eq. (1), \( N_q \) and tip resistance could be calculated from a given \( \phi \). Compared with the measured tip resistance, the predicted internal friction angles are obtained through least square method.

In terms of the equations, the internal friction angles are predicted to be 39.6 and 40.3 degree in terms of the results of test No. 1 and No. 2. Consolidated drained triaxial tests of the sand were conducted previously in accordance with ASTM D4767 and determined the internal friction angle to be 39.0 degree. The internal friction angles predicted from the two tests are both close to the value of 39.0 obtained from laboratory tests. In this case, the penetration rate has minor effect on the predicted internal friction angle with cavity expansion theory.

5 SUMMARY

Centrifuge model tests were performed on piezocene penetration in a sand at two penetrating rates. Based on the preliminary results, it can be summarized:

1) The penetration rate has strong but different effects on tip resistance and sleeve friction of the cone penetration response.

2) It is found that at two penetrating rates, the internal friction angles predicted by cavity expansion theory are approximately identical, using the friction ratio to take account the tip resistance and sleeve friction.

3) Further study is needed to clarify whether there is a minor effect of penetration rate on the prediction of soil strength parameters.

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REFERENCES

1) Chen, J.W. and Juang C.H. (1996): Determination of Drained Friction Angle of Sands from CPT, Journal of Geotechnical Engineering, 122(5), 374–381.

2) Giretti, D., Been, K. Fioravante, V. and Dickenson, S. (2018): CPT calibration and analysis for a carbonate sand,
3) Huang, A.B. (2016): The Seventh James K. Mitchell Lecture: Characterization of Silt/Sand Soils, *Australian Geomechanics Journal*, 50(4), 1–23.

4) Jamiolkowski, M., Lancellotta, R., Tordella, L. and Battaglio, M. (1982): Undrained Strength from CPT, *Proc. of 2nd European Symposium on Penetration Testing*, Amsterdam, 599–606.

5) Liu, S.Y. and Cai, Z.Y. (2012): Review of the geotechnical testing, *China Civil Engineering Journal*, 45(3), 151–165.

6) Mayne, P.W. (2007): Cone penetration testing—a synthesis of highway practice, *National Cooperative Highway Research Program (NCHRP) Synthesis 368*, Transportation Research Board, Washington, D.C.

7) Sawada, S. and Towhata, I. (2011): Use of Piezo drive cone for evaluation of subsoil settlement induced by seismic liquefaction, *ISSMGE Bulletin*, 5(1), February 2011, 15–25.

8) Schmertmann, J.H. (1978): Guidelines for cone penetration test: performance and design, *Report FHWA-TS-787-209*, Washington, D.C., USA: Federal Highway Administration.

9) Shen, X.K., Cai, Z.Y. and Cai, G.J. (2016): Applications of In-situ Tests in Site Characterization and Evaluation, *China Civil Engineering Journal*, 49(2), 98–120.

10) Taylor, R.N. (1995): Geotechnical centrifuge technology, *Blackie Academic Press*.

11) Vesic, A.S. (1977): Design of pile foundations, *Synthesis of highway practice*, Transportation Research Board, National Research Council, Washington, D.C.

12) Wang, H. and Zhang, J.H. (2018): Undrained Shear Strength of Clays measured by T-bar Penetrometer in Centrifuge, *The 7th Japan-China Geotechnical Symposium*, March 16–18th 2018, Sanya.