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Size effects in cone penetration tests in sand

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Abstract. Size effects in miniature cone penetration tests (CPTs) are examined by performing a series of 1g laboratory tests using three penetrometers of 3, 6, and 12 mm in diameter (D) in two grades of dry Leighton Buzzard sand respectively. It is found that the size effects primarily depend on three non-dimensional geometrical parameters, including relative penetration depth (H/D), normalised surface roughness of the cone (R_a/d_{50}), and normalized cone size (D/d_{50}). Test results showed that: (1) H/D is a major size factor influencing the cone resistance at relatively shallow depths, and its influence may disappear while a localized failure occurs; (2) the cone resistance may increase with a decreasing value of D/d_{50} in some circumstances, and this effect attenuates in loose sand; (3) the cone resistance is positively related to R_a/d_{50}, especially for cones with an intermediate rough interface. These size dependent behavior are attributed to the dependency of the failure pattern and sand properties on the stress level, strain level, and non-local interactions of underlying microstructures and the dependency of the shearing resistance of sand-cone interface on R_a/d_{50}.

Keywords: Size effect, Cone penetration tests, Experimental analysis.

1 Introduction

As one of the most versatile and reliable in-situ devices, cone penetrometers have been extensively used for soil explorations (e.g., soil classification and characterization) in both geotechnical practices and agricultural investigations. In addition to recommended standard penetrometers (e.g., 12.83mm, 20.27mm, 35.7mm, 43.7mm in diameter [1, 2]), miniature and needle cone penetrometers also attracted growing interests due to their inherent advantages such as: (1) energy-saving as smaller downward thrust needed; (2) higher mobility and site accessibility; (3) higher sensitivity to variations of the soil stratigraphy; (4) lower requirement on the sample size to get rid of the possible boundary effect, which can effectively reduce labour, time, and cost in the sample preparation and make it easier to be integrated with other techniques (e.g., centrifuge, nondestructive testing methods like X-ray CT); and (5) geometrical similarity in modelling the interaction between soil and plant root-tips or earthworms. Considering the wide applications of various small sized cone penetrometers, possible size effects associated with the cone size and the sand particle size in 1g shallow CPTs are experimentally investigated and briefly discussed in this paper.

2 Test description

Two grades of the Leighton Buzzard sand (see **Table 1**) were used in the tests. Reconstituted dry sand samples of different relative densities (Dense: D_r=90%; Medium dense: D_r=65%; Loose: D_r=40%) were prepared by using the air pluviation technique. The repeatability of penetration resistance data has been verified in duplicated tests.

Table 1. Basic sand properties

Sand type	Median grain size d_{50} / mm	Special gravity G_s	Maximum void ratio e_{max}	Minimum void ratio e_{min}	Critical state friction angle φ_{cs}/ °
Fraction C (FC)	0.51	2.65*	0.805	0.55	32*
Fraction E (FE)	0.12	2.65†	1.014†	0.613†	32†

Note:* after Lee [3]. † after Tan [4].

Three sized cone penetrometers of 3mm, 6mm, and 12mm in diameter were designed and used, which all have the same apex angle of 60° and are made from stainless steel with polished surfaces. The penetrometers have an arithmetical mean surface roughness (R_a) of 0.607 um in average measured by the Contour GT-I 3D optical microscope. The cone resistance (q_c) and the average sleeve friction can be measured separately by the 12mm sized penetrometer, equipped with strain gauges in two sections. In tests with the 6mm and 3mm sized probes, only the total load has been measured with a load cell mounted on the top of the probe. The soil resistance during both penetrations and extractions were recorded in all tests.

To minimise the potential lateral boundary effect and the bottom boundary effect [3, 5], a rigid walled cylinder of 490mm in diameter and 500mm in height was used. The smallest diameter ratio of the container over the penetrometer (B/D) is 40.8, and the sand samples were deposited into heights within the range of 315mm-415mm.

The cone penetrometers were driven by a SKF linear actuator (CAHB-10, rated load: 500N, stroke: 300mm) with a speed of approximately 1.5 mm/s. The possible penetration rate effect has been evaluated with moving speeds in the range of 1-4 mm/s, which showed negligible influences in tests with the dry sand samples.

3 Test results and discussion

Measured by the 12mm sized penetrometer, the ratio of the maximum tensile shaft capacity over the maximum shaft capacity during penetrations (Q_{ft}/Q_{fc}) lies in a range of 0.62-0.76 in the tests. The shaft friction experienced by the 6mm and 3mm probes during penetrations are estimated by dividing the Q_{ft} measured by them and the corresponding value of Q_{ft}/Q_{fc}, and thus the cone resistance experienced by them can be obtained by extracting the shaft frictional resistance from the total load.

Dimensional analysis is used to interpret the 1g CPT results. Factors affecting the normalised cone resistance (N_{CPT}) are summarised in Eq.(1).

$$N_{\mathrm{CPT}} = \frac{q_c}{\sigma_{\mathrm{v}}'} = \left\{\frac{\sigma_{\mathrm{v}}'}{p_{\mathrm{c}}'}, \frac{H}{D}, \frac{R_{\mathrm{a}}}{D}, \frac{D}{d_{50}}, \frac{B}{D}, \frac{S}{D}, D_{\mathrm{r}}, \varphi_{\mathrm{cs}}, \text{etc.}\right\} \tag{1}$$

where σ_{v}' is the effective vertical stress. p_{c}' is an index of aggregate crushing strength [6]. S is the distance from the nearest wall boundary to the location of penetration.
All test results of N_{CPT} are presented in **Fig. 1**. The tests are identified with codes comprising the sand fraction, cone diameter and sand density classification.

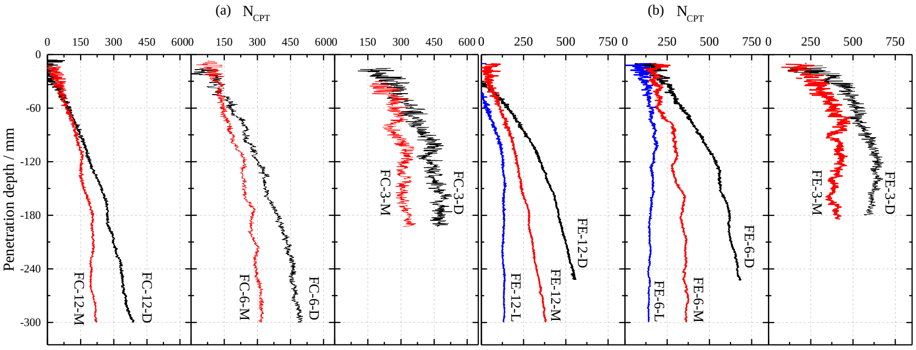

Fig. 1. Normalised cone resistance. (a) Fraction C sand; (b) Fraction E sand

Due to the strong dependency of the friction and dilation angels of sand on the stress level, p_{c}', D_{r}, and φ_{cs} [6], no doubt that N_{CPT} may significantly vary with these factors (e.g., **Fig. 1**). As the maximum q_{c} is less than 3 MPa in the present 1g CPTs, it is anticipated that no significant particle crushing takes place in the tested silica sand [7]. The lateral boundary effect is avoided with $B/D \geq 40.8$. Results of multiple penetrations in the same dense FC sand samples showed negligible difference between tests with $S/D=20.5$ and $S/D=10$. Preserving above factors in the comparison analysis of data in **Fig. 1**, it is observed that: (1) the tip resistance measured in samples of the FE sand are generally higher than that in the FC sand; (2) higher tip resistances are experienced by smaller probes at the same penetration depth, and this phenomenon is more significant in the FC sand and attenuates with an increasing penetration depth. It is found that the size-dependent behaviour of these are mainly due to the combined size effect associated with the normalized geometry sizes of R_{a}/d_{50}, H/D, and D/d_{50} as

(1) The shearing resistance of sand-structure interface may increase with increasing values of R_{a}/d_{50}, especially for interfaces lie in the intermediate rough zone (approximately, $0.001 \leq R_{\mathrm{a}}/d_{50} \leq 0.1$)[8, 9]. As a result, R_{a}/d_{50} may influence the cone resistance. According to the correlated relationship between the critical state interface friction angle (δ_{cs}) and R_{a}/d_{50}, δ_{cs} between the cone surface and the FE sand and the FC sand equals 19.2° and 14.3° respectively [9]. This partly explains the difference between tests in the FC sand and the FE sand while preserving other influencing factors.

(2) Apart from its influence to the sand-cone interaction, the particle size effect is also strongly dependent on the value of D/d_{50} [5, 10], for example, CPTs performed by the 'modelling of model' method suggested $D/d_{50}>20$ to get rid of the particle size effect. The D/d_{50} effect may primarily stem from the dependency of the failure pattern

(e.g., progressive failure along the shear band) and sand properties on the stress level, strain level and strain gradients (non-local contribution of underlying microstructures to the macroscopic response), and this effect may still apply in deep penetrations.

For tests in the same sand, the observed size-dependent behaviour are mainly attributed to the effects of H/D and D/d_{50}. It is observed that values of N_{CPT} measured by different sized penetrometers are in good agreement while plotted against H/D in similar sand samples. It indicates that H/D is a major factor causing the size variation of q_c or N_{CPT} at the same initial stress level in the shallow CPTs at 1g, and this effect attenuates with increasing values of H/D. The critical depth from shallow failure mode to deep failure mode is found around 30-40D in the 1g tests, varying with the sand relative density. It is deeper than that found in CPTs on centrifuge (e.g., 20D [5]) probably due to the dependency of sand properties on the stress level.

4 Conclusion

Evident size effects have been observed in the shallow 1g CPTs with miniature cone penetrometers. The dependency of the failure pattern and sand properties on the stress level, strain level, and non-local contributions of underlying microstructures and the dependency of the shearing resistance along the sand-cone interface on R_a/d_{50} were concluded as the main reasons leading to the size-dependent behaviour in CPTs. These characteristics are closely related to the dimensionless size parameters of H/D, $R_a/d_{50,}$ and D/d_{50}. Hence, particular care should be taken to these size parameters while scaling them in the model test design and interpretations of tests with different scales.

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