Calibrating NTH method for ϕ′ in clayey soils using centrifuge CPTu

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ABSTRACT: An existing effective stress limit plasticity solution for piezocone penetration tests (CPTu) developed at the Norwegian Institute of Technology (NTH) is calibrated to evaluate the effective stress friction angle ϕ′ for clayey soils subjected to centrifuge model testing. Results from previously conducted in-flight mini-piezocone tests by various institutes were compiled for study, including readings taken from 13 series of centrifuge chamber tests on artificially prepared clays, mainly kaolin and kaolinitic-silica mixtures. Effective stress friction angles from companion triaxial compression tests (CAUC or CIUC) and/or direct simple shear (DSS) tests on these soil deposits were adopted as the benchmark reference to verify the reasonableness of the NTH method in assessing ϕ′ at constant penetration rates, as well as a few special tests conducted at variable rates.

1 INTRODUCTION

The use of laboratory testing and artificially-prepared soils helps mitigate the issues of inherent variability and scatter from natural soil deposits when evaluating results from field tests. Also, it is possible to minimize the uncertainty involved in interpreting in-situ test results by verifying, in a calibration chamber, any analytical, theoretical numerical, or empirical relationship between a measured quantity and the reference soil parameters (Ouyang & Mayne 2016).

This study illustrates the interpretation of ϕ' from clays in centrifugal model chamber tests containing artificially-prepared soils under various accelerations and subjected to mini-piezocone penetration tests (CPTu). Results from a total of 13 centrifuge model test series on manufactured clayey soils, mainly kaolinitic clay deposits and silica-kaolin mixtures.

The data are taken from in-flight mini-piezocone penetrometer testing at constant penetration rates, as well as a few variable penetration rate tests (twitch testing). The total cone tip resistance (q_t) and penetration porewater pressure (u_2) at the shoulder position from the miniature penetrometers were recorded. Details on centrifuge model test dimensions, accelerations, piezocone diameters, test rate and soil parameters such as moisture content, liquid limit, plasticity index, and stress history were reviewed and tabulated.

The interpretation of the effective stress friction angle ϕ′ from CPTu is carried out using an existing undrained limit plasticity solution from the Norwegian Institute of Technology (Senneset et al. 1989, Senneset & Janbu 1985). The evaluated effective stress friction angle ϕ′ from the centrifuge CPTu soundings are compared with benchmark values primarily obtained from laboratory CAUC and/or CIUC triaxial tests on the corresponding soils to examine the validity of the solution.

2 CENTRIFUGE MODEL TESTING

2.1 *Principles of centrifuge modeling*

The geotechnical centrifuge is a useful tool to study the mechanical behavior of soils for very large physical structures in order to allow modelling at large strains where failure is too costly to conduct at full scale (Schofield 1980). The centrifuge applies an increased gravitational acceleration to small-scale physical models to produce identical self-weight stresses in the model that simulate those in the prototype. Thus, results from the centrifuge model tests can be utilized to validate and calibrate analytical and/or numerical methods. Details on the principles and operations of the centrifuge, scaling laws, equipment, and procedures are given by Springman et al. (2010).

2.2 *Geomaterials used in centrifuge tests*

The centrifuge series reviewed in this study were collected from laboratory programs established at the University of Western Australia, Cambridge University, National University of Singapore, University of Colorado Boulder, and Zhejiang University, which have different equipment, acceleration capacities, and dimensions.

For this study, the focus was on clayey type soils and the geomaterials that were subjected to centrifuge modeling are mainly kaolinitic type clay deposits and silica-kaolin and or clay-sand mixtures, which are prepared initially as a slurry and then consolidated in the model chambers. For the majority of the soils studied in this paper, the stress histories applied in the chamber tests focused on normally consolidated (NC) to lightly-overconsolidated (LOC) clay deposits. A special series of tests by Cinicioglu et al. (2006) investigated a range of tests with $1 \leq$ OCRs ≤ 150, where OCR = σ_p'/σ_{vo}' = overconsolidation ratio.

Table 1 shows the summary information on the centrifuge series including accelerations, clay types, and their data reference sources.

Table 2 illustrates the geotechnical index parameters of the clay deposits which was prepared, such as water content, liquid limit, plasticity index, and overconsolidation ratio. The initial water contents (w_n) of the soils before the consolidation stage ranged from 30% to 136%, the liquid limit (LL) was between 27% to 80%, and the plasticity index (PI) varied around 2% to 35%.

Table 1. Centrifuge model test series reviewed in this study

No.	a_g	Clay type	Reference
1	100	Kaolin 1	Teh et al (2007)
2	100	Sandy Kaolin	Teh et al (2006)
3	160	Kaolin 2	Schneider (2008)
4	110	Kaolin 3	Mahmoodzadeh & Randolph (2014)
5	160	Kaolin 4	Randolph & Hope (2004)
6	100	Pisa Clay 1	Burland et al (2003) [(1)]
7	100	Pisa Clay 2	Burland et al (2003) [(1)]
8	100	Pisa Clay 3	Burland et al (2003) [(1)]
9	150	Speswhite Kaolin	Cinicioglu et al. (2006) [(2)]
10	30	Clayey Sand	Zhou et al (2014)
11	50	Silica flour	Silva & Bolton (2005)
12	100	K75-S25[(3)]	Fitzgerald (2009)
13	75	China Kaolin	Esquivel and Silva (2000)

NOTES: a_g = centrifuge acceleration in g

[(1)] Additional data from Jamiolkowski & Pepe (2001)

[(2)] Additional information from Cinicioglu et al. (2007)

[(3)] Mixture of 75% kaolin + 25% sand

Table 2. Geotechnical parameters of the clayey soils in the centrifuge series

No.	Clay type	Indices			
		w_n (%)	LL (%)	PI (%)	OCR
1	Kaolin 1*	120	61	27	1.0
2	Sandy Kaolin	120	80	35	1.0
3	Kaolin 2	120	61	34	1.0
4	Kaolin 3*	120	61	27	1.0
5	Kaolin 4*	120	61	27	1.0
6	Pisa Clay 1	88	71	29	1.6
7	Pisa Clay 2	88	52	24	1.2
8	Pisa Clay 3	88	56	23	1.1
9	Speswhite Kaolin	136	53	21	1.0
10	Clayey Sand	NA	NA	27	1.0
11	Silica flour	31	27	2	NA
12	K75-S25	92	46	22	NA
13	China Kaolin	106	53	21	1.0

* same type of kaolin used

2.3 *Mini-piezocone penetration tests in centrifuge*

Each of the soil deposits was tested using miniature piezocone penetrometers. Most of the probes had a diameter of d=10mm, except the penetrometers adopted by Zhou et al (2014) and Silva & Bolton (2005) where d=12mm, and Cinicioglu et al. (2006) used a mini cone with d=11.3 mm. The equivalent prototype depth was calculated as the product of the model depth times the acceleration.

Two sets of CPTu test series are analyzed to observe the influence of penetration rate: (a) inflight penetration with a constant push rate test, and (b) a limited series of twitch tests with variable penetration rates. Table 3 lists the details about the centrifuge chamber sizes (rectangular shape chamber/cylindrical chamber), penetrometer probe dimensions, and the corresponding penetration rates that were adopted for analysis in these test series.

A non-dimensional velocity parameter $V = v \cdot d/c_v$, where v= push rate, d = cone diameter and c_v = coefficient of consolidation has been defined to determine the drainage regime of the soils during testing (DeJong et al 2013, Randolph & Hope 2004), where a V>30 indicates undrained penetration. For most of the centrifuge testing series investigated in this paper, it is believed that the geomaterial undergo undrained penetration process, except for the twitch test series studied in the later section of the paper, which simulate different drainage regimes.

Table 3. Chamber sizes and penetrometer information

Soil No.	Equipment and Test Parameters			
	Chamber size [(1)]	d (mm)	v (mm/s)	V
1	650·390·340	10	1	64
2	500·370[(2)]	10	2.5	40
3	650·390·325	10	3	630
4	650·390·325	10	0.0045 to 1	160[(3)]
5	650·390·325	10	1	120
6	850·400[(2)]	10	1	NA
7	850·400[(2)]	10	1	NA
8	850·400[(2)]	10	1	NA
9	606·537[(2)]	11.3	20	400
10	730·350·300	12	1	NA
11	850·400[(2)]	12	2 to 8	>40
12	650·390·325	10	1	62
13	NA	12.7	NA	NA

[(1)] Rectangular chamber: Length · Width · Height (mm)

[(2)] Cylindrical chamber: Diameter · Height (mm)

[(3)] V varies from 1 to 160 based on different push rate

3 EFFECTIVE FRICTION ANGLE FROM CPTU

Soft to firm to stiff intact clays will exhibit excess porewater pressures during penetration tests ($\Delta u > 0$). An effective stress limit plasticity solution from NTH was derived for the CPTu (Senneset & Janbu 1985) towards the evaluation of ϕ' during undrained penetration. The full solution allows for an interpretation of a paired set of effective stress Mohr-Coulomb strength parameters (c′ and ϕ′) for all soil types, including: sands, silts and clays, as well as mixed soils (Sandven 1990).

Ouyang and Mayne (2016) reviewed data from 11 series of 1-g clay chamber tests using miniature cone and piezocone penetrometers and found that the NTH solution gave good evaluations of ϕ' for prepared deposits of clays, mostly having used kaolin and/or kaolinite-sand mixtures in these testing programs. In a larger study, Ouyang and Mayne (2017) helped to verify the limit plasticity NTH solution by calibrating the theory with data from 105 field sites underlain by natural clays and clayey silts that were subjected to both field CPTu and laboratory triaxial testing.

For the specific case (c' = 0, β = 0°), a closed-form version of the analytical solution was derived for calculating the effective stress friction angle ϕ′ for clays, silty clays, and clayey silts in the following mathematical format:

$$Q = \frac{\tan^2(45° + \phi'/2) \cdot \exp(\pi \cdot \tan\phi') - 1}{1 + 6 \cdot \tan\phi' \cdot (1 + \tan\phi) \cdot B_q} \qquad (1)$$

where the original NTH cone resistance number (N_m) is equal to $Q = q_{net}/\sigma_{v0}'$ = normalized cone tip resistance, and $B_q = \Delta u/q_{net}$ = porewater pressure parameter, $q_{net} = q_t - \sigma_{v0}$ = net cone resistance, and $\Delta u = u_2 - u_0$ = measured excess porewater pressure.

A full inversion of Equation (1) is not possible, yet an approximate solution can be developed over an expected range of effective stress friction angles (20° ≤ ϕ' ≤ 45°) and limited values of porewater pressure parameter ($0.1 \leq B_q \leq 1.0$):

$$\phi' \approx 29.5° \cdot B_q^{0.121} [0.256 + 0.336 \cdot B_q + \log Q] \qquad (2)$$

The approximate expression is compared with the actual closed-form analytical solution in Figure 1 and seen to be in reasonable agreement over the specified ranges of ϕ' and B_q.

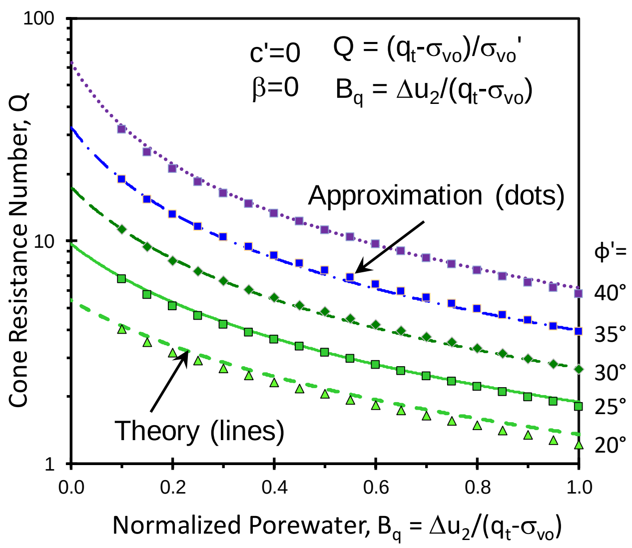

Figure 1. NTH method for evaluating ϕ' from CPTu in intact clays and clayey silts using approximate and exact solutions

4 APPLICATION TO CENTRIFUGE SERIES

Most of the data from in-flight mini-piezocone tests in centrifuge series were taken at constant rates of penetration. In a few special series, termed "twitch tests", the piezocone series recorded the penetration readings at variable rates of penetration. Selected examples are presented in the following subsections to illustrate the application of the NTH method.

4.1 *Constant rate piezocone testing in centrifuge*

Centrifuge testing on kaolin (Soil ID No. 3) was performed using the beam centrifuge at the University of Western Australia (UWA). The clay samples were prepared in 325 mm high strong boxes with plan dimensions of 390mm by 650mm. Normally-consolidated kaolinitic clay having a liquid limit of 61%, plasticity index of 34%, and initial water content of around 55% to 70% was prepared as slurry and consolidated. Afterwards, the deposit was subjected to an acceleration of 160g and inflight piezocone tests made with a constant probe push rate of 3 mm/s. Miniature piezocone penetration test were conducted using a 10mm diameter penetrometer with a 60 degree tip angle, which has a polypropylene filter element behind the 1 mm high cone shoulder to measure u_2. The cone did not have a friction sleeve (Schneider 2008).

Figure 2 illustrates the profiles of the net cone resistance ($q_{net} = q_t - \sigma_{vo}$) and the excess pore water pressures ($\Delta u = u_2 - u_0$) measured during the centrifuge piezocone penetration test. The corresponding profiles of cone resistance number Q and normalized porewater pressure B_q are also shown in the figure.

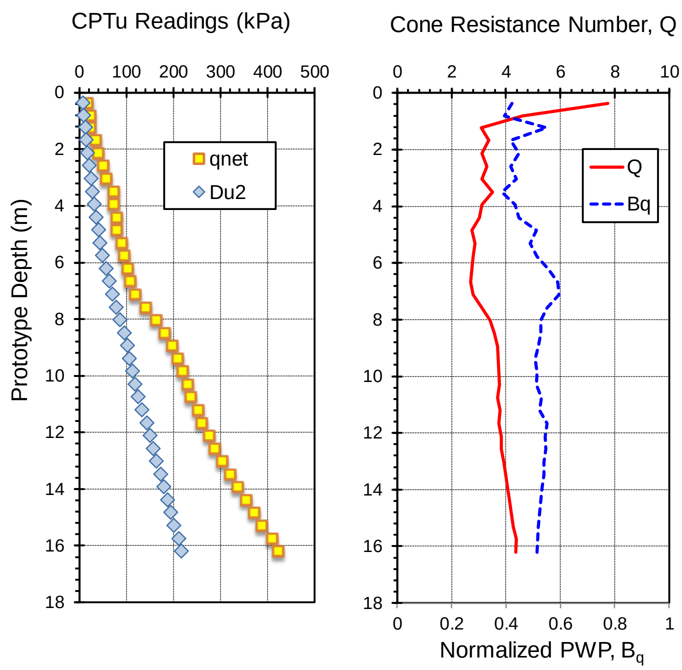

Figure 2. Profiles of q_{net}, Δu, Q and B_q in NC kaolin in centrifuge testing (data from Schneider 2008)

The input parameters Q and B_q for calculating the friction angle ϕ' using the NTH solution can also be found by the following process. The cone resistance number Q is found as the slope from plotting net cone resistance q_{net} vs. effective overburden stress σ_{v0}', as illustrated in Figure 3. In this example, we force the line through the origin (assuming c' =0) to obtain Q =3.88. By the same token, the normalized porewater parameter B_q is determined as the slope of measured excess porewater pressure Δu = (u_2-u_0) versus net cone resistance q_{net}, giving the value of B_q = 0.53 for this sounding, as indicated by Figure 4. The paired Q-B_q are the input for friction angle calculation and according to Figure 1, the evaluated ϕ' from the CPTu sounding is ϕ' = 28.3°. This value compares well with a measured value of ϕ' = 28.6° obtained from laboratory direct simple shear test (DSS) on the same soil, as confirmed by Figure 5.

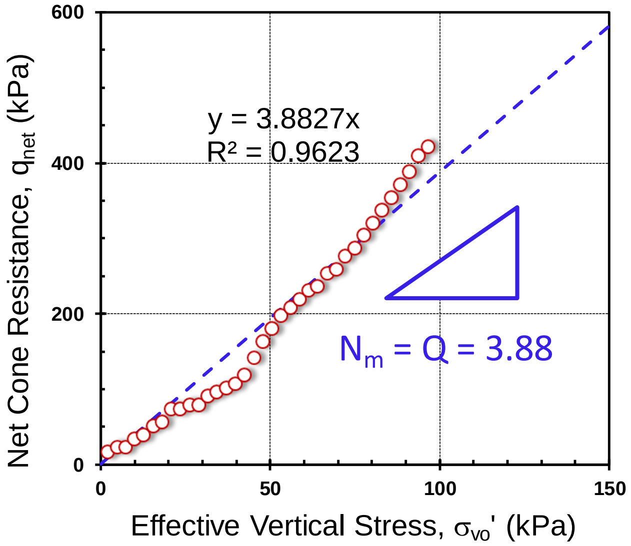

Figure 3. Derivation of the cone resistance number Q for kaolin 2 (data from Schneider 2008)

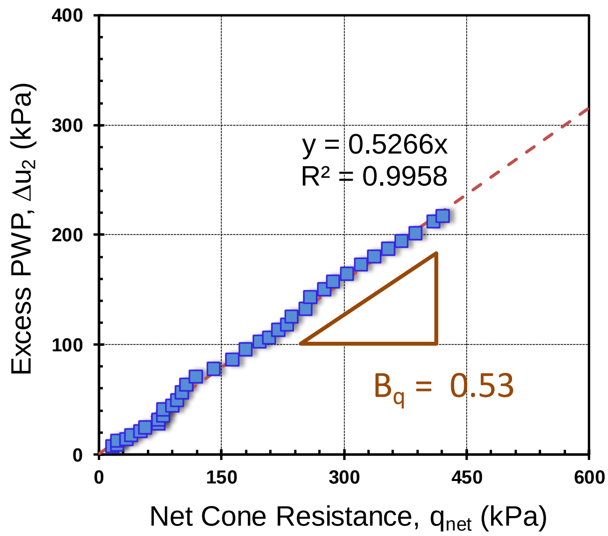

Figure 4. Derivation of porewater pressure parameter B_q for kaolin 2 (data from Schneider 2008)

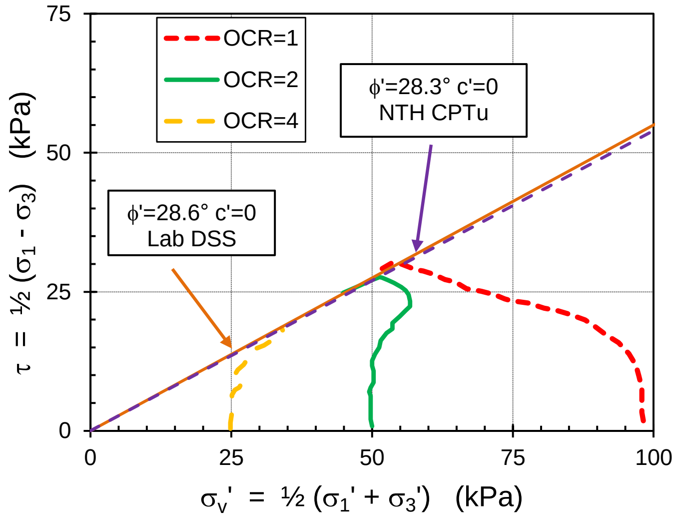

Figure 5. Comparison of NTH evaluated effective friction angle ϕ' from CPTu with lab DSS (data from Schneider 2008)

4.2 *CPTu twitch test at 110g acceleration*

A special series of CPTu soundings that are conducted at variable penetration rates are termed twitch tests (Randolph 2004; DeJong et al. 2013). Twitch testing is known to influence the measured magnitudes of cone resistance q_t and porewater pressure u_2 and was devised to study the quantify the effects of partial drainage, viscous behavior, and dissipation response of soils (Randolph & Hope 2004). In low permeability soils, by varying the CPTu penetration rate during centrifuge testing, one can monitor the consolidation conditions from undrained to partially-drained to fully drained. In this case study, a series of centrifuge CPTu of various probe push rates on normally consolidated kaolin under an acceleration of 110g were done by UWA to examine the sensitivity of the NTH method in evaluating ϕ'.

As reported by Mahmoodzadeh and Randolph (2014), a commercial dry kaolin (clay ID No. 4 in Table 1) was mixed under a vacuum at an initial water content of 120% before being placed above a sand drainage layer in the centrifuge strongbox. Consolidation was applied in steps with the final sample height recorded at 230mm and corresponding to a prototype depth of 25.3m.

Penetration rates for these six twitch test series varied from 1 mm/s to 0.0045 mm/s and the effect of the testing rate on the interpretation of the soil parameters were analyzed. The change of the penetration rate could indicate the change of the drainage condition during the penetration for the kaolin clays subjected to CPTu, with the fastest rate of 1 mm/s to be undrained penetration and the lowest rate 0.0045 mm/s to be drained. Table 4 lists the information about the twitch testing ID, the corresponding penetration rate, the net cone resistance q_{net} at the final test depth, the excess porewater pressure Δu at the final test depth, the cone resistance number Q, the normalized porewater pressure parameter B_q and the evaluated ϕ' using the NTH approximate solution. It is observed that the magnitude of Q increases and B_q decreases as the penetration rate decreases (undrained to drained). However, when the paired sets of Q and B_q are plotted on the NTH solution chart given by Figure 6, they all follow the same friction angle contour (ϕ' = 23°), indicating agreement with the NTH solution for effective stress penetration.

Table 4. Measured q_{net} and Δu plus derived B_q and Q from CPTu centrifuge twitch testing on kaolin (data from Mahmoodzadeh & Randolph 2014)

ID	v *	q_{net} (kPa)	Δu (kPa)	B_q	Q	NTH ϕ'
PC-1	1	207	146	0.71	2.0	22.2°
PC-2	0.45	249	148	0.59	2.4	22.9°
PC-3	0.15	300	126	0.42	2.8	22.6°
PC-4	0.045	405	71	0.18	3.8	21.4°
PC-5	0.015	495	28	0.06	4.7	19.7°
PC-6	0.0045	501	9	0.02	4.7	17.0°

* Piezocone probe push rate in mm/s

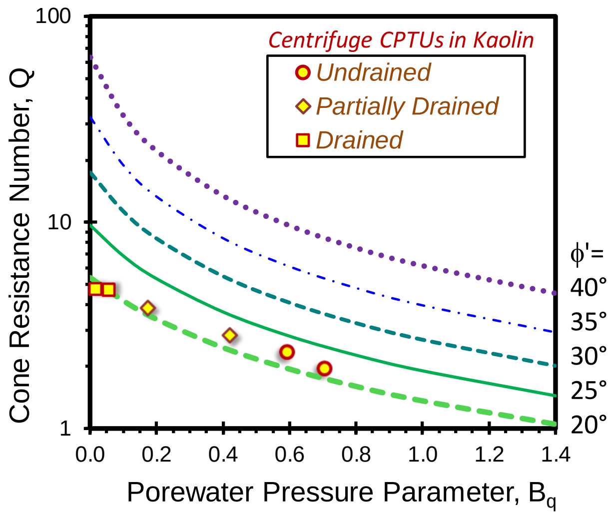

Figure 6. NTH CPTu evaluated ϕ' for kaolin subjected to centrifuge twitch testing (data from Mahmoodzadeh & Randolph 2014)

4.3 *Database Summary*

For all 13 series of CPTu centrifuge tests at constant penetration rates, Table 5 provides the individual cone resistance number (Q) and normalized porewater pressure readings (B_q) with their corresponding NTH effective friction angle ϕ′ and the measured benchmark ϕ′ from laboratory testing.

Figure 7 presents a summary plot for the measured laboratory friction angle values versus the CPTu-determined values from centrifuge tests. Two sets of statistical measures were made on the data set, including: (a) arithmetic statistics, and (b) regression statistics, as indicated on the figure. The measured laboratory ϕ' cover the range from 23.2° to 36.6° and the CPTu-evaluated ϕ' values range from 20.8° to 37.1°. From the arithmetic measures, the ratio of measured/evaluated values ranges from 0.91 to 1.10 with an overall mean of 1.0 and standard deviation = 0.05, giving a corresponding COV (coefficient of variation) = 0.05. From the regression evaluations of laboratory vs. field values, the slope m = 0.99 with a coefficient of determination of r^2 = 0.921 and standard error of the Y-estimate SEY = 1.15 for a best fit line. The above statistics generally support that the NTH method gives a reasonable evaluation of the effective friction angle when compared with the laboratory reference value.

Table 5. Laboratory measured friction angles and NTH parameters from the centrifuge CPTu soundings

No.	Clay type	Lab and CPTu Parameters			
		Lab ϕ′	B_q	Q	NTH ϕ′
1	Kaolin 1	23.0°	0.18	5.35	25.1°
2	Sandy Kaolin	23.0°	0.29	3.73	23.5°
3	Kaolin 2	28.6°*	0.54	3.9	28.3°
4	Kaolin 3	23.0°	0.71	2.0	22.2°
5	Kaolin 4	23.0°	0.57	2.43	23.0°
6	Pisa Clay 1	23.5°	0.34	3.95	25.0°
7	Pisa Clay 2	28.0°	0.71	3.16	28.1°
8	Pisa Clay 3	27.0°	0.59	3.1	26.2°
9	Speswhite Kaolin	25.2°	0.92	1.87	24.4°
10	Clayey Sand	31.0°	0.05	20	32.3°
11	Silica flour	36.6°	0.01	100	37.1°
12	K75-S25	25.0°	0.37	4.22	26.4°
13	China Kaolin	23.0°	0.45	3.46	25.0°

Notes: (a) lab reference ϕ' from triaxial compression tests
(b) *from lab DSS tests shown in Figure 5.

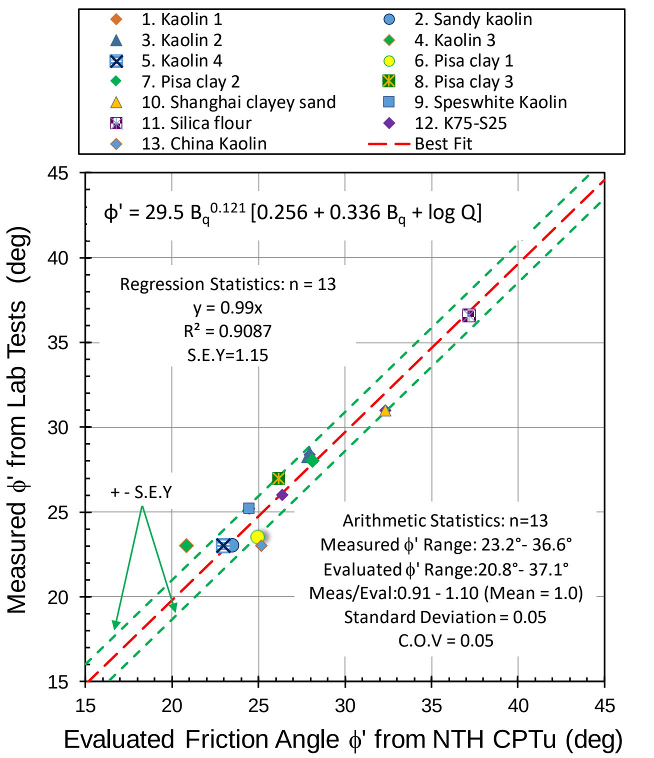

Figure 7. Comparison of laboratory benchmark measured ϕ' versus NTH-evaluated ϕ' from centrifuge CPTu series

5 CONCLUSIONS

Data from 13 series of in-flight mini-piezocone penetrometer tests in centrifuge deposits were reviewed for verifying the NTH limit plasticity solution (Sandven 1990; Senneset et al. 1989) in assessing the effective friction angle of normally consolidated to lightly over-consolidated clays and clayey silts. The majority of artificially-prepared deposits of clays included kaolinites or kaolin-sand mixtures. Primarily, the friction angle ϕ' from laboratory triaxial compression tests served as the reference benchmark value. Results from constant penetration rate CPTu soundings gave good agreement with laboratory determined ϕ'. In addition, one series of CPTu twitch tests on kaolin clay at variable rates showed that as the behavior varied from undrained to partially drained to fully drained, the changes in Q and B_q correspondingly followed the same ϕ' contours established by the NTH solution.

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