

Spherical cavity expansion nexus between CPTu and DMT in soft-firm clays

Nœud de dilatation de la cavité sphérique entre CPTu et DMT dans des argiles soft-firmes

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ABSTRACT: Using cavity expansion solutions for undrained penetration, a theoretical link is established between the cone tip resistance (q_t) and shoulder porewater pressure (u_2) from cone penetration tests (CPTu) in soft to firm clays and the measured contact pressure (p_0) and expansion pressure (p_1) obtained from flat plate dilatometer tests (DMT). Data from 27 paired sets of CPTu-DMT results in a variety of clays are used to support and validate the links. This permits an exchange of interpretations between the two tests, offering a complementary extension of methodologies. Specifically, the established solution using effective stress limit plasticity theory for the assessment of c' and ϕ' in clays from piezocone testing is extended to DMT readings for this purpose. Data from 3 clays located in Sandpoint, Idaho, Washington DC, and Evanston, Illinois are presented as applied case studies.

RÉSUMÉ: L'utilisation de solutions d'extension de la cavité de pénétration non drainée, un lien théorique est établie entre la résistance à la pointe du cône (q_t) et la pression épaule interstitielle (u_2) à partir de tests de pénétration du cône (CPTU) dans doux pour raffermir les argiles et la pression de contact mesuré (p_0) Et la pression de dilatation (p_1) obtenue à partir des essais de dilatomètre plan plat (DMT). Les données provenant de 27 ensembles jumelés de résultats de CPTu-DMT dans une variété d'argiles sont utilisées pour supporter et valider les liaisons. Cela permet un échange d'interprétations entre les deux tests, offrant une extension complémentaire des méthodologies. Plus précisément, la solution établie pour une théorie de plasticité de limite de contrainte efficace pour l'évaluation de c' et ϕ' dans des argiles provenant de tests de piezocones est étendue aux lectures DMT à cet effet. Les données provenant d'argiles situées à Sandpoint, Idaho, Washington DC, et Evanston, Illinois sont présentées comme des études de cas appliquées.

KEYWORDS: cavity expansion, clays, cone penetrometer, dilatometer, effective stress parameters.

1 INTRODUCTION

Geotechnical site investigation is the initial and crucial first step for every geotechnical project in order to establish the stratigraphy and soil engineering properties. Among various practices for subsurface explorations, in-situ tests provide a quick, economical, and reliable assessment of geoparameters for analysis and design. Towards this purpose, cone penetration tests (CPTu) typically give three measurements with depth, namely, the cone tip resistance (q_t), sleeve friction (f_s) and porewater pressure (u_2), often at regular vertical intervals between 1 to 5 cm. Flat dilatometer tests (DMT) provide two readings, the contact pressure (p_0) and the expansion pressure (p_1), at regular intervals of either 20 or 30 cm. Details concerning CPT equipment, procedures, and interpretation method are found in Lunne et al. (1997) and Mayne (2007). Similarly, details on the DMT equipment, test procedures and interpretation can be found in Marchetti (1980).

Using cavity expansion solutions for undrained penetration, a theoretical link is established between these two in-situ tests for soft to firm clays. This nexus permits an exchange of several theoretical, analytical, and empirical solutions between the two tests. Of specific interest, herein, is the extension of an existing solution for effective stress penetration that permits the effective stress friction angle (ϕ') of clays to be evaluated from DMT results.

1.1 Friction angle from CPTu

For the CPTu, the evaluation of the effective stress friction angle ϕ' for undrained conditions for a variety of soils ranging from sands to silts to clays are evaluated by an effective stress limit plasticity solution, developed by the Norwegian Institute of Technology (NTH) and detailed by Senneset & Janbu (1985), Senneset et al. (1989), and Sandven (1990). The size of the failure region is established by the angle of plasticification (β)

which herein takes on a value for the classical case ($\beta = 0$) that is commonly assumed for deep foundations.

For the case of soft to firm clays ($c' = 0$), the closed-form theoretical expression for assessing the effective stress friction angle ϕ' is given as (Mayne 2016):

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

where $Q = (q_t - \sigma_{vo})/\sigma_{vo}'$ is the normalized cone tip resistance and $B_q = (u_2 - u_0)/(q_t - \sigma_{vo})$ is the normalized porewater pressure parameter.

An approximate equation for directly assessing the value of ϕ' from the above theoretical solution is expressed (Mayne 2007):

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

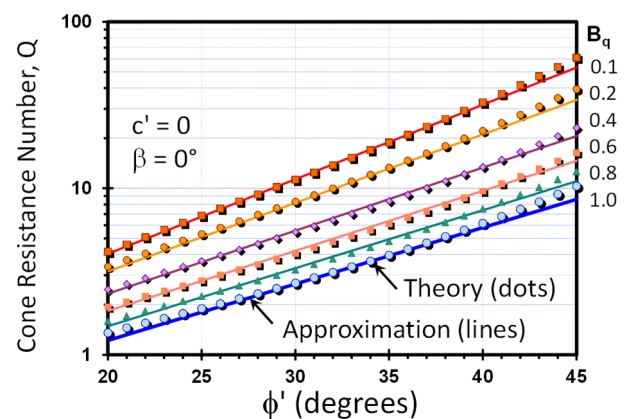


Figure 1. NTH graphical solution for ϕ' from CPTu data when $c' = 0$.

The resulting relationships for ϕ' in terms of Q and various values of B_q from equations (1) and (2) are presented in a graphic form presented in Figure 1.

1.2 Case study: CPTu at Sandpoint, Idaho

A case study from Sandpoint, Idaho is presented to show the process of interpreting effective friction angle using the NTH method. The Idaho Dept. of Transportation required soils information for design of approach embankments and a new bridge for State Route 95 highway. Figure 2 shows a representative CPTu at the site indicating over 80 m of soft silty clays, with occasional sand layers, lenses, and seams.

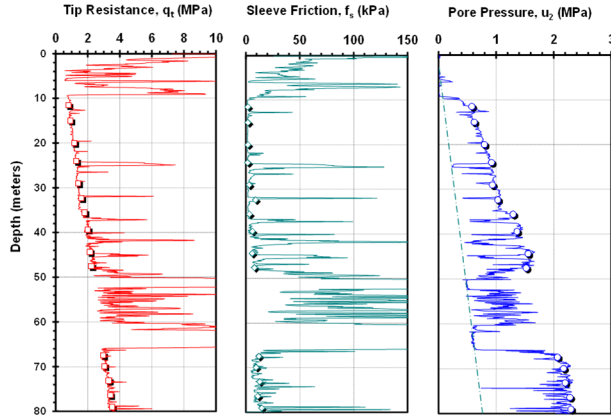


Figure 2. Deep CPTu profile at Sandpoint, Idaho with select data points for analysis.

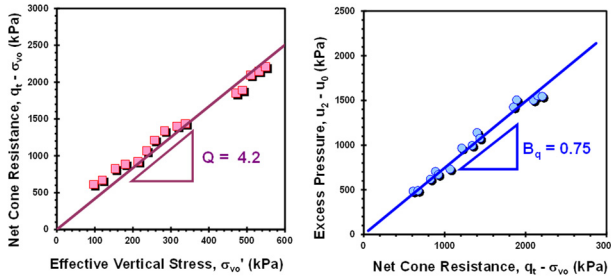


Figure 3. NTH post-processing of CPTu data for Q and B_q at Sandpoint

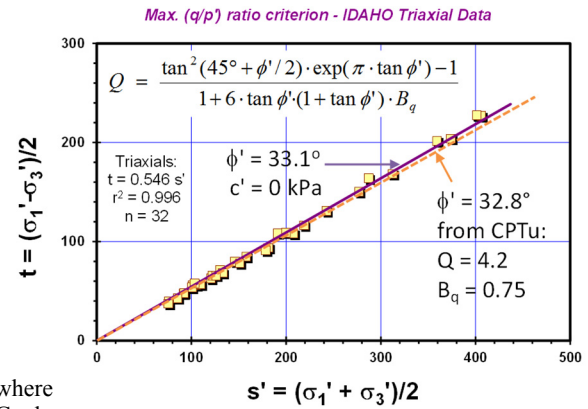
Figure 3 shows the procedure for determining Q and B_q . The parameter Q is found as the slope from plotting net cone resistance vs. the effective overburden stress. In this example, we force the line through the origin (assuming $c'=0$) to obtain $Q=4.2$. By the same token, the porewater parameter B_q is determined as the slope of the Δu versus q_{net} , giving the porewater parameter $B_q=0.75$ for the Sandpoint site.

Results from 32 laboratory CIUC triaxial compression tests on undisturbed samples taken from 5 to 80 m depths are used as the reference benchmark values. Figure 4 shows the laboratory s - t space of the triaxial tests that provided a lab friction angle of 33.1° . The NTH CPTu outputs an interpreted friction angle of 32.8° that is in excellent agreement.

2 THEORETICAL NEXUS BETWEEN DMT AND CPTU

2.1 Cavity expansion solution for piezocone

For CPTu results, the net cone tip resistance ($q_{net} = q_t - \sigma_{vo}$) could be expressed as a function of the undrained shear strength (s_u) that corresponds to triaxial compression mode and the rigidity index of the soil (I_r), which is defined as the G/s_u ,



where
 G =shear

Figure 4. Laboratory triaxial effective stress friction angle ϕ' versus interpreted ϕ' from NTH using CPTu data at Sandpoint

modulus, from spherical cavity expansion theory in the following mathematical form (Vesić 1972, Vesić 1977):

$$q_{net} = s_u \cdot \{ 4/3 \cdot [\ln(I_r) + 1] + \pi/2 + 1 \} \quad (3)$$

At the shoulder filter position, the measured excess porewater pressures (Δu_2) are due to: (a) increases in octahedral stress changes, and (b) shear-induced effects (Burns & Mayne 2002). In the case of normally-consolidated to lightly-overconsolidated clays, shear induced values are rather small compared to the octahedral portion and thus can be neglected. Then, excess porewater pressure from the piezocone can be expressed as:

$$\Delta u = u_2 - u_0 = s_u \cdot 4/3 \cdot \ln(I_r) \quad (4)$$

2.2 Cavity expansion solution for dilatometer

Studies by Mayne & Bachus (1989) showed that the contact pressures (p_0) measured by the flat dilatometer tests (DMT) are quite similar in magnitude to that of the porewater pressures (u_2) measured at the cone shoulder position by piezocone tests, specifically: $p_0 \approx u_2$. Therefore, equation (4) can also be used in the following manner to give an equivalent excess porewater pressure from the DMT:

$$\Delta u_{DMT} = p_0 - u_0 = s_u \cdot 4/3 \cdot \ln(I_r) \quad (5)$$

The Vesić (1972, 1977) solution also provides the magnitude of change in horizontal stress:

$$\Delta \sigma_h = s_u \cdot 4/3 \cdot [\ln(I_r) + 1] \quad (6)$$

The increase in horizontal stress can be assumed to relate to the DMT expansion pressure (p_1), specifically the net expansion pressure ($p_1 - u_0$) as expressed:

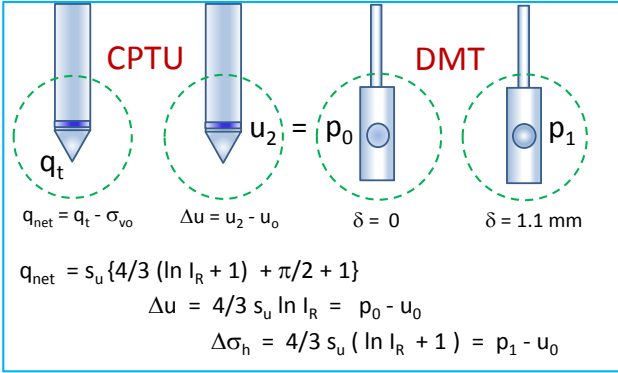
$$\Delta \sigma_h = p_1 - u_0 \quad (7)$$

Substituting the spherical cavity expansion terms from (5), (6) and (7) into (3) gives an equivalent net cone tip resistance (q_{net}) from the dilatometer results

$$q_{netDMT} = 2.93 \cdot p_1 - 1.93 \cdot p_0 - u_0 \quad (8)$$

Equation (8) gives a new approach that expresses the q_{net} resistance from CPTu readings to an equivalent value from the DMT pressures. This nexus provides a link between the two tests for soils that are characterized as normally-consolidated to lightly-overconsolidated clays. The above expressions and associated CPTu-DMT relationships for soft to firm clays are summarized in graphic form in Figure 5.

Figure 5. Summary of the nexus between CPTu and DMT readings in



soft to firm clays using spherical cavity expansion solutions.

2.3 CPTu-DMT database in soft to firm clays

In order to verify the aforementioned relationships between CPTu and DMT readings, a special database was compiled. Paired sets of piezocone and flat dilatometer tests taken at 27 different clay sites were matched at respective elevations for the study (Ouyang & Mayne 2016). The individual symbols for each site are shown in the top half of Figure 6. In the lower portion of Figure 6, the measured excess porewater pressures from the CPTu soundings are shown to be comparable magnitude and in very good agreement with the calculated equivalent excess porewater pressures obtained from the DMT contact pressure, specifically $\Delta u \approx (p_0 - u_0)$ cited by equation (5).

Similarly, a plot of the CPTu-measured net cone resistance is shown to be in rather good agreement with the DMT equivalent resistance given by equation (8), as illustrated in Figure 7.

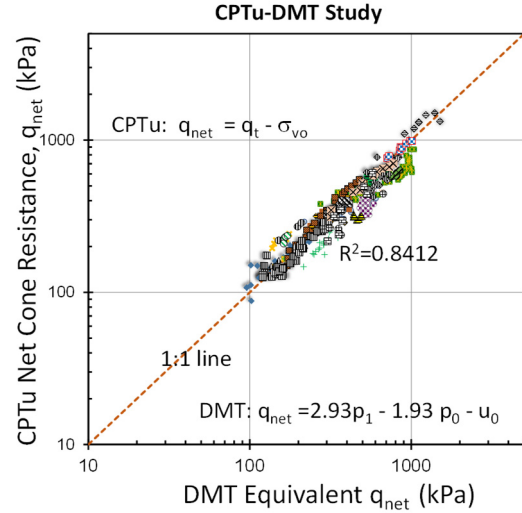


Figure 7. Net cone resistance q_{net} from piezocone versus DMT equivalent q_{net} for 27 clays

3 CASE STUDIES

3.1 Anacostia Naval Air Station, Washington, DC

Figure 8 shows a DMT sounding profile at the Anacostia NAS located at the confluence of the Potomac and Anacostia Rivers, Washington, DC. The site is underlain by soft alluvial clays that extend up to 30 m deep. Index parameters of the soft clay include: $w_n = 68 \%$, $LL = 83\%$; and $PI = 37\%$.

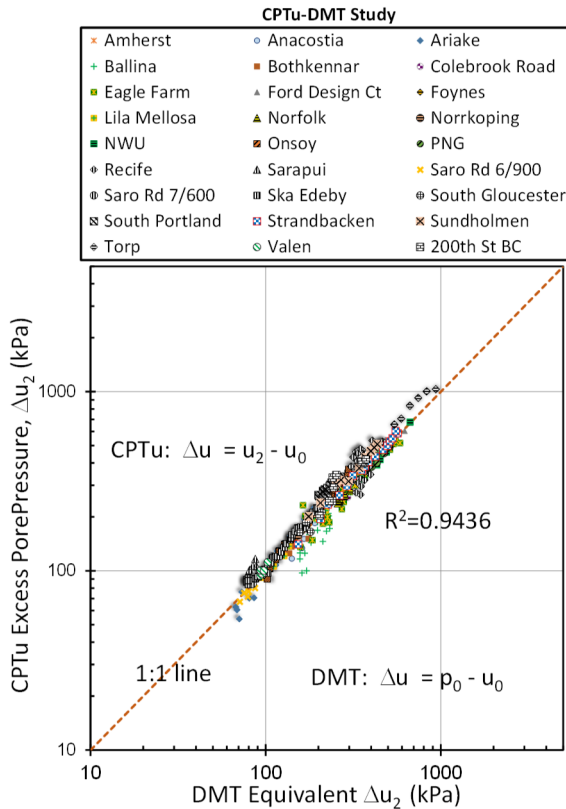


Figure 6. Excess porewater pressure from piezocone versus DMT equivalent Δu for 27 clays

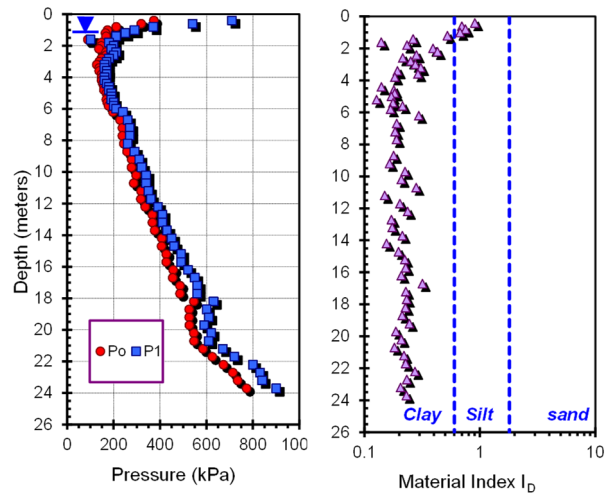


Figure 8. DMT profiles for Anacostia NAS clay site

The DMT-equivalent Q is found as the slope from plotting the equivalent net cone resistance vs. the effective overburden stress, specifically: $Q = 4.5$. By the same token, the DMT equivalent porewater parameter B_q is determined as the slope of the Δu_{DMT} versus q_{netDMT} , giving the DMT equivalent $B_q = 0.92$ for the Anacostia site, as indicated by Figure 9.

These values are inputs to the solution chart in Figure 1, giving an NTH-interpreted effective friction angle of $\phi' = 35.2^\circ$ for the Anacostia clay. This is very comparable to the laboratory ϕ' from CIUC triaxial tests (consolidated isotropic undrained triaxial compression tests) and shows an excellent match as indicated in Figure 10.

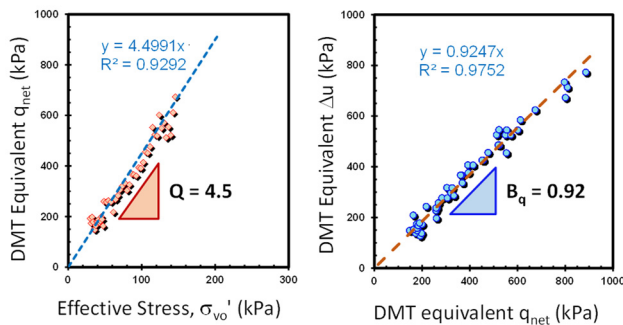


Figure 9. NTH post-processing of DMT data at Anacostia for DMT equivalent Q and DMT equivalent B_q

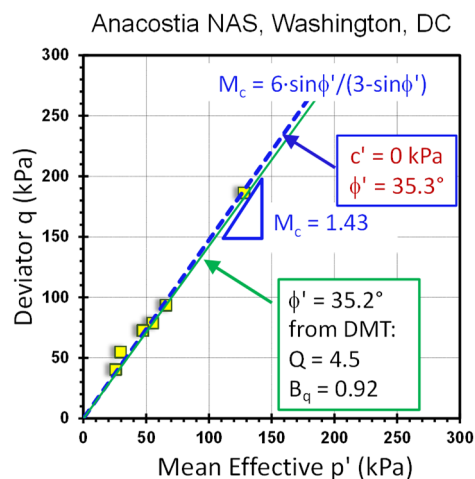


Figure 10. Laboratory triaxial test ϕ' versus interpreted ϕ from NTH using DMT data at Anacostia

3.2 Northwestern University, Evanston, Illinois

The National Geotechnical Experimentation Site (NGES) located at Northwestern University (NWU) is used to verify the approximate NTH method given by equation (2). The upper layer of this site consists of 6 m of sand underlain by soft clay strata. Results of laboratory CAUC tests (consolidated anisotropic undrained triaxial compression tests) are shown in Figure 11, which determines an effective friction angle of 28.3° (Chung & Finno 1992). In this study, the intermediate clay stratum from around 10 to 20 meters is adopted for analysis. The effective friction angle profile ϕ' calculated from equation (2) is shown by Figure 12, indicating extraordinary agreement compared with the lab triaxial data.

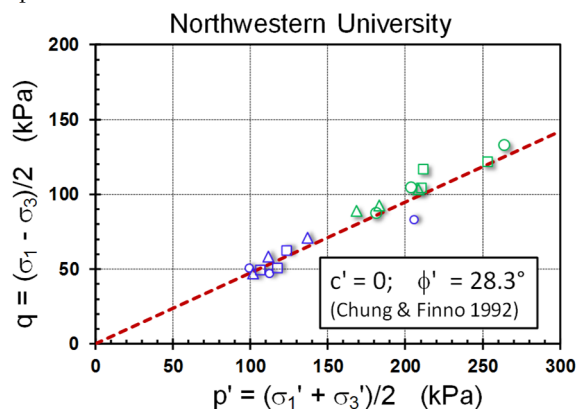


Figure 11. Laboratory CAUC test stress path at Northwestern University (data from Chung & Finno 1992)

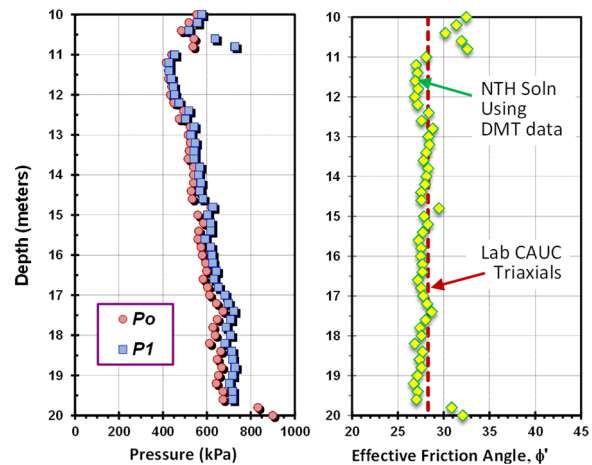


Figure 12. DMT data and comparison of NTH ϕ' and lab ϕ' at NWU

4 CONCLUSIONS

Links between CPTu and DMT in soft to firm clays are generated through spherical cavity expansion theory. The effective stress friction angle for soft clays is calculated from these in-situ tests using a limit plasticity solution by Sandven (1990) and Senneset et al. (1989). The friction angle ϕ' from laboratory triaxial testing was used as the reference benchmark value to compare predicted friction angles from DMTs at two sites in the USA.

5 ACKNOWLEDGMENTS

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