# Modified NTH solution for overconsolidated fissured clays

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**ABSTRACT:** The effective stress limit plasticity solution for piezocone penetration tests (CPTu) developed at the Norwegian Institute of Technology (NTH) is modified to allow the evaluation of the effective stress friction angle $\phi'$ for overconsolidated fissured clays. The modified NTH solution is adjusted to reflect stress history effects on the cone resistance number, specifically using the overconsolidation ratio (OCR). Fissured clays are identified by their porewater pressure response where the normalized $B_q$ parameter is close to zero. Results from CPTu soundings in stiff fissured Beaumont clay from Baytown, Texas, and fissured London clay at Brent Cross are presented to detail the modified NTH post-processing procedure. Benchmark values of effective stress friction angle $\phi'$ interpreted from triaxial compression tests are used to verify the CPTu $\phi'$ value from the modified NTH solution, obtaining reasonable agreement.

**Keywords:** cone penetration, limit plasticity theory, overconsolidation, fissured clays, effective friction angle

## 1. Introduction

The piezocone penetration test (CPTu) obtains three separate readings with depth, including: measured cone tip resistance ($q_c$), sleeve friction ($f_s$), and porewater pressure at the shoulder ($u_2$). The measured cone tip resistance ($q_c$) is converted to total cone resistance ($q_t$) using $q_t = q_c + (1 - a_{net}) \cdot u_2$, where $a_{net}$ is defined as the net area ratio [1].

During geotechnical site investigations that encounter clay deposits and layers, results from CPTu are traditionally interpreted using a total stress analysis, and consequently the evaluation focuses on the undrained shear strength ($s_u$). Yet, the fundamental strength of clays is actually governed by effective stress conditions, specifically the effective stress friction angle ($\phi'$) which is required for stress path analyses, critical state soil mechanics (CSSM), and the prediction of pore pressures during construction using finite element analyses.

Towards this purpose, an existing effective stress limit plasticity developed at the Norwegian Institute of Technology (NTH) has been calibrated and verified to provide sound and reliable interpretations of the effective stress friction angle ($\phi'$) from CPTu data in clays and clayey silts which are normally consolidated (NC) to lightly-overconsolidated (LOC) in nature [2-5].

In this paper, a modification to reflect the stress history effect in terms of overconsolidation ratio (OCR) is made to the aforemention limit plasticity solution towards the evaluation of the effective stress friction angle $\phi'$ for overconsolidated fissured clays.

## 2. Friction angle of fissured clays from CPTu

The limit plasticity solution using CPTu data to evaluate effective stress friction angle ($\phi'$) using CPTu data in intact clays and clayey silts with OCR<2.5 is given as below:

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

where $N_m = (q_t-\sigma_{vo})/\sigma_{vo}'$ is the cone resistance number 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 $\phi'$ from the above theoretical solution is expressed [5]:

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

which is restricted to the following applicable ranges: $18° \le \phi' \le 45°$ and $0.05 \le B_q \le 1.0$. This expression is considered valid for intact clays and clayey silts that are soft to firm with OCRs < 2.5.

For overconsolidated clays, a modification to the original NTH solution is necessary in order to account for stress history effects on the measured CPTu data [6, 7]. A revised definition of Eq. (1) gives the revised cone resistance number ($N_{mc}$):

$$N_{mc} = \frac{q_t-\sigma_{vo}}{\sigma_e'} \quad (3)$$

in which $\sigma_e'$ is called the equivalent stress and determined from:

$$\sigma_e' = \sigma_{vo}'\cdot OCR^{\Lambda} = \sigma_p'^{\,\Lambda}\cdot\sigma_{vo}'^{\,(1-\Lambda)} \quad (4)$$

where $OCR = \sigma_p'/\sigma_{vo}'$ = overconsolidation ratio, $\sigma_p'$ = effective preconsolidation stress, $\Lambda = 1 - C_s/C_c$ = plastic volumetric strain potential, $C_s$ = swelling index, and $C_c$ = virgin compression index.

The concept of equivalent stress is detailed by [8] and found within the framework of critical state soil mechanics [9, 10]. The revised cone resistance number requires knowledge of the overconsolidation ratio (OCR) which should be determined from a series of laboratory consolidation tests, or alternatively from the interpretation of triaxial data [11]. For natural clays, a representative value for $\Lambda \approx 0.80$ is often cited that corresponds to direct simple shear (DSS) testing [12]. For remolded, compacted, and artificially prepared clays, the observed value of $\Lambda$ is lower and in the range of 0.5 to 0.7 [11]. Further discussion on the stress exponent $\Lambda$ is given by [13].

The relationship between the original cone resistance number $N_m$ and the revised cone resistance $N_{mc}$ is simply:

$$N_{mc} = N_m \cdot OCR^{\Lambda} \quad (5)$$

Thus, the modified NTH method is identical to the original NTH solution when the soils are normally consolidated (OCR=1), and Eq. (1) and (2) can be used directly to determine $\phi'$ by substituting $N_m = N_{mc}$ from CPTu soundings advanced into NC and OC intact clays. Both the closed-form solution and its corresponding approximate equation are shown in Fig. 1.

In fissured overconsolidated fine-grained soils, the porewater pressure $u_2$ registered by CPTu often demonstrates a near zero magnitude, $u_2 \approx 0$ [14-17]. To interpret the value of effective stress friction angle $\phi'$ in OC fissured clays, a practical solution is to take $u_2 = 0$ , as recommended by [18]. Therefore, when $B_q < 0.05$, the approximation to the NTH solution is given by the following equation:

$$\phi' \approx 8.18 \cdot \ln(2.13 \cdot N_{mc}) \quad (6)$$

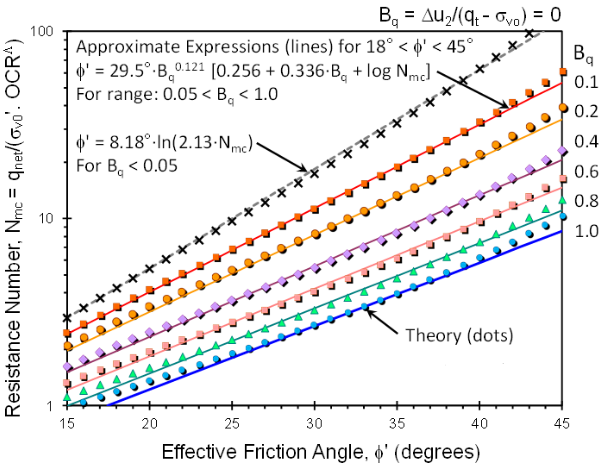


**Figure 1.** NTH method for evaluating $\phi'$ from CPTu using analytical and approximate solutions.

## 3. Case Study

To illustrate the modified NTH solution in overconsolidated fissured clays, two case studies involving piezocone penetration tests in OC fissured clays are demonstrated herein, including: (a) fissured Beaumont clay in Texas and (b) fissured London clay in England. Magnitudes of the effective stress friction angle $\phi'$ measured from series of laboratory triaxial tests are adopted as the benchmark reference to examine the reasonableness of the evaluation.

### 3.1. CPTu in Baytown, Texas

A comprehensive exploration program including series of piezocone penetration tests and soil borings with samples collected for laboratory testing was carried out in Baytown, Texas by Stuedlein [19]. The soil unit at the test site, known locally as the Beaumont clay formation, is overconsolidated by desiccation. The upper clay layers contain numerous fissures and occasional slickensides, with a interbedded loose nonplastic sandy silt to silty sand at a depth around 4.5m. A lower clay layer, was encountered at an average depth of 4.5 m and consisted of stiff slightly silty fat clay. The average moist unit weight of the fissured clay layer is 19.7 kN/m$^3$ and the plasticity index (PI) ranges from 18 to 52 for upper 4.5m of soil profile.

Fig. 2 shows a representative CPTu sounding at Baytown, Texas and for the fissured clay investigated, the porewater pressure $u_2$ from the testing output essentially zero down to z=4.5m.

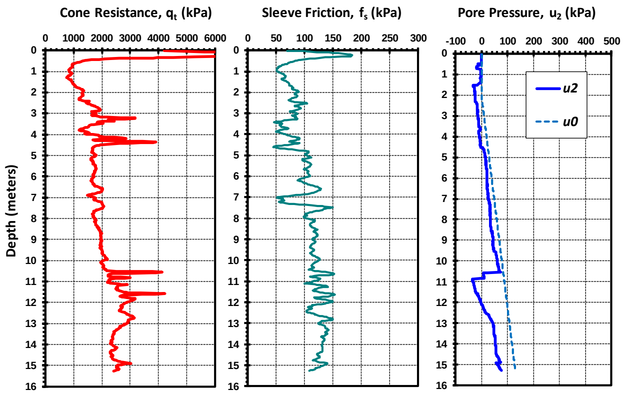


**Figure 2.** Representative CPTu sounding is stiff fissured Beaumont clay at Baytown, Texas (data from [19])

Data from istropically consolidated undrained triaxial compression test (CIUC) are shown by Fig. 3 and the effective stress friction angle $\phi'$ can be interpreted as $\phi' = 24°$ with cohesion intercept $c' = 0$.

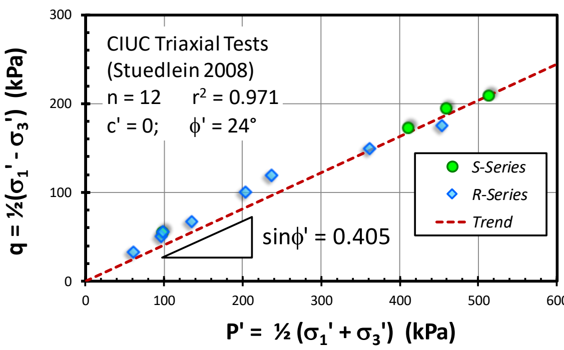


**Figure 3.** CIUC Triaxials on stiff fissured Beaumont clay at Baytown, Texas (data from [19])

In order to apply the modified NTH solution using the CPTu data, a knowledge of the overconslidation ratio is required. For the fissured clay under investigation at Baytown, Texas, a series of laboratory consolidation tests was carried and the profile of preconsolidation stress $\sigma_p'$ is shown by Fig. 4. Also, shown is an estimate of the apparent preconsolidation stress profile made using the CPT data [19].

Applying Eq (4) with a value of $\Lambda = 0.6$ for this site, the equivalent stress $\sigma_e'$ can be calculated and the revised cone resistance number $N_{mc}$ is determined using Eq (3) with the CPTu sounding. The effective stress friction angle $\phi'$ is calculated using Eq (6) from the modified NTH solution for OC fissured clays and the result is illustrated by Fig. 4.

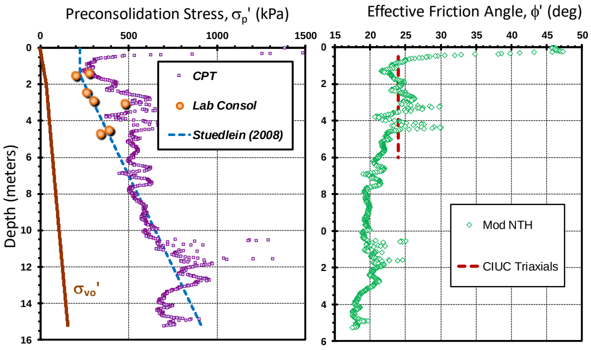


**Figure 4.** Profiles of preconsolidation stress $\sigma_p'$ and $\phi'$ for stiff Beaumont clay at Baytown, Texas (data from [19])

The depth profile of calculated $\phi'$ from modified NTH is put in direct comparison with the $\phi'$ interpreted from CIUC triaxial tests at their respective sampling depths. Overall, the values from CIUC results are in good agreement with those from CPTu using the modified NTH solution.

## *3.2. CPTu in fissured OC London Clay*

London Clay is an overconsolidated Eocene marine formation that is notable for the presence of discontinuities in the form of extensive fissures and cracks [14]. Fig. 5 illustrates a representative piezocone penetration sounding at Brent Cross with porewater pressure measuring elements at both the cone tip ($u_1$) and the shoulder of the cone ($u_2$). Whereas the u1 readings are positive and about one-half the magnitude of qt, it can be observed that $u_2$ measurements are slightly negative and herein taken as zero through out the sounding. The specific site is heavily overconsolidated due to uplift and erosion [20] with as much as 200 to 300 m of overburden soils removed, as shown by Fig. 5.

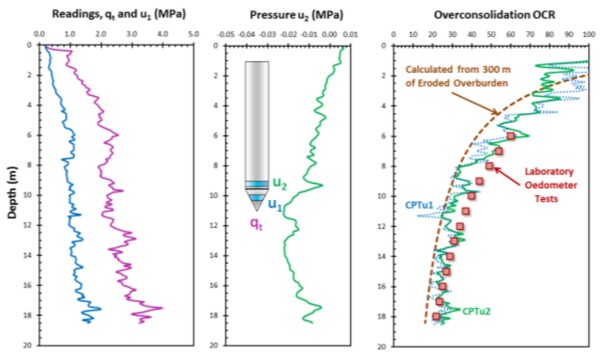


**Figure 5.** Profiles of London Clay at Brent Cross: (a) $q_t$ and $u_1$; (b) $u_2$, and (c) OCR (data from [14])

Laboratory testing on the London clay at Brent Cross shows a representative total unit weight $\gamma_t$ =20 kN/m$^3$, natural water contents ≈ 28%–32%, liquid limits in the range of 65%–85%, and values of plasticity index (PI) between 55% and 65%. Representative triaxial stress paths and effective strength envelope for the London clay are illustrated in Fig. 6, indicating an overall effective friction angle of $\phi'$ = 19.5° with c' = 0 can be assigned to these fissured clays between depths of 2 to 12 m [21].

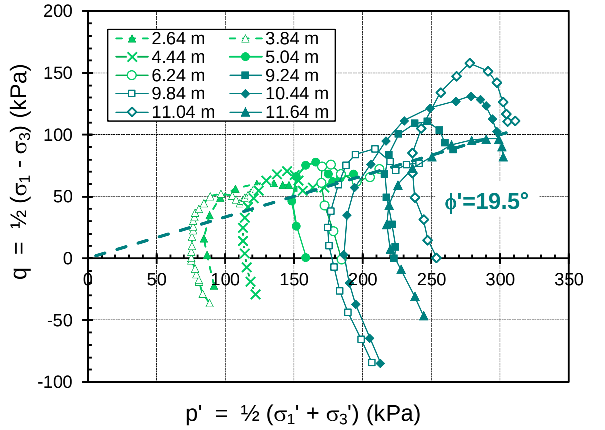


**Figure 6.** Triaxial stress paths for London clay at Brent Cross. (data from [21])

Fig. 7 shows the profiles of the revised cone resistance number $N_{mc}$ and the normalized porewater pressure $B_q$ by applying the modified NTH solution (using Λ=0.6 and the OCR information from Fig. 6). It is observed that the value of $B_q$ is essentially zero throughout the entire profile, which again is indicative of a fissured clay. The modified NTH solution using the approximate expression Eq (6) for $B_q \approx 0$ appears in good agreement with the laboratory triaxial interpretation of the effective friction angle at their corresponding elevation.

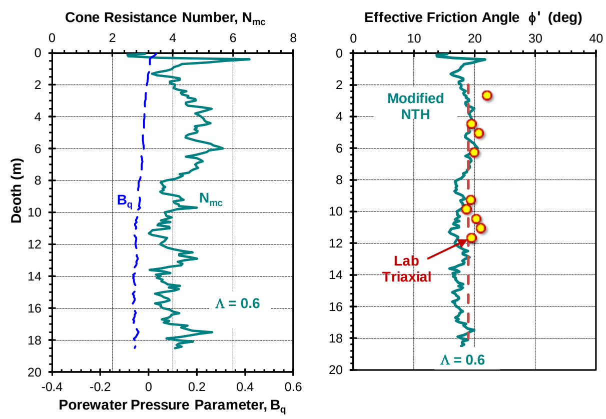


**Figure 7.** Profiles of $N_{mc}$, $B_q$, Modified NTH $\phi'$ and CAUC triaxial $\phi'$ for fissured London clay at Brent Cross: (data from [14])

## *4. Summary and Conclusions*

A modified NTH effective stress limit plasticity solution for evaluating the effective stress friction angle ($\phi'$) in overconsolidated fissured clays from piezocone penetration tests (CPTu) is presented in which the cone resistance number is adjusted to reflect stress history effects, i.e., OCR. Fissured clays are identified when the normalized porewater pressure parameter $B_q \approx 0$. Two case studies involving fissured OC clays in the USA and UK are presented to detail the modified NTH post-processing procedure in determining the profiles of $\phi'$ with depth. The results have shown good agreement with benchmark $\phi'$ measured from laboarotory triaxial tests.

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