Exploring the effect of clay permeability on CPTu metrics through numerical modeling

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ABSTRACT: The cone penetration test (CPTu) is one of the most widely used geotechnical site investigation method and research on the interpretation of the test began once the instrument became available. Traditionally, permeability has been obtained using dissipation tests, which are frequently slow and only link permeability through compressibility measurements. On-the-fly methods are an alternative, in which permeability is directly linked to CPTu penetration measurements. Several on-the-fly techniques have been proposed and their applicability and advantages are not fully clear. In this work, previous knowledge on CPTu in partially drained conditions is used to clarify the parameters that appear on these on-the-fly techniques and also to note that these techniques are only reliable on partially drained conditions. The performance of on-the-fly techniques to infer soil permeability is demonstrated employing results from effective stress numerical analyses.

Keywords: cone penetration test; in situ testing; permeability; numerical modelling; PFEM

1. Introduction

The cone penetration test (CPTu) is one of the most widely used geotechnical site investigation methods. During the test an instrumented cone is pushed into the ground at a controlled rate. Tip resistance and sleeve friction are always recorded and, very frequently, the pore water pressure at several standard positions is also measured. From these measurements, stratigraphy and constitutive soil parameters are estimated based mostly on empirical correlations (see Robertson [1]).

Traditionally, the evaluation of coefficients of consolidation of fine grained soils has been of much interest for geotechnical design. CPTu based methods for obtaining consolidation coefficients were researched intensively almost since the instrument became available. In a dissipation test, the CPTu penetration is halted and the pore-pressure decay in time is registered. The duration of a dissipation test is usually established as the required to achieve a 50% reduction of the excess pore pressure registered just before the stoppage. This time is denoted t_{50}.

There exist direct correlations between t_{50} and permeability, k, (Parez and Fauriel [2], Mayne [3]). Nevertheless, dissipation tests are most frequently interpreted by means of normalized dissipation curves proposed by The and Houslby [4].

Elsworth & Lee [5,6] proposed an alternative method in which permeability could be directly estimated from the CPTu data stream without the need for any stoppage. This work was restricted to materials, like silts, in which CPTu penetration was partially drained. Latter works [7,8] has sough to extend that approach to more impermeable materials. These methods are attractive, although some difficulties in application have been reported (see Vessia et al. [9]). These methods have a number of fitting parameters, whose meaning is not clear, and some authors state that the technique is only suitable to partially drained penetration [6], whereas others disregard this limitation.

In a previous work [10], the authors clarified the range of applicability of the method and the meaning of the fitting parameters that appear on the on-the-fly techniques by establishing a link between these techniques and previous knowledge on the effect or partial drainage on cone metrics. The performance of the technique was evaluated with results obtained through numerical modeling. One of the downsides of that proposal is that a number of the clay constitutive parameters were required, which are only available in the case that database comes from numerical modelling. In this work, the technique is extended so that permeability may be directly estimated only with cone metrics.

This work is organized as follows: first, a numerical dataset with cases ranging from undrained to drained conditions is presented. After a brief description of on-the-fly techniques, the proposed approach is fully described and assessed with the numerical database. Finally, some conclusions are drawn.

2. Numerical database

In this work, a database of numerical results of the simulation of the CPTu is used. One set has been obtained through the Material Point method (Ceccato et al. [11]), whereas the others employing the Particle Finite Element method (PFEM) [12-14]. In all these simulations the material has been described by the Modified Cam Clay and an overconsolidation ratio close to one has been used. Every set has been obtained with exaclty the same constitutive parameters with the exception of the permeability, which has been varied several orders of magnitude. Except for Series 1, in which all simulations take place in practically undrained conditions, all the other set of simulations cover the full range of permeabilities, ranging from undrained to drained conditions. Tables 1 and 2 reports the soil constitutive parameters, the initial stress state, the range of permeabilities considered and also the interface friction between the cone and the soil.

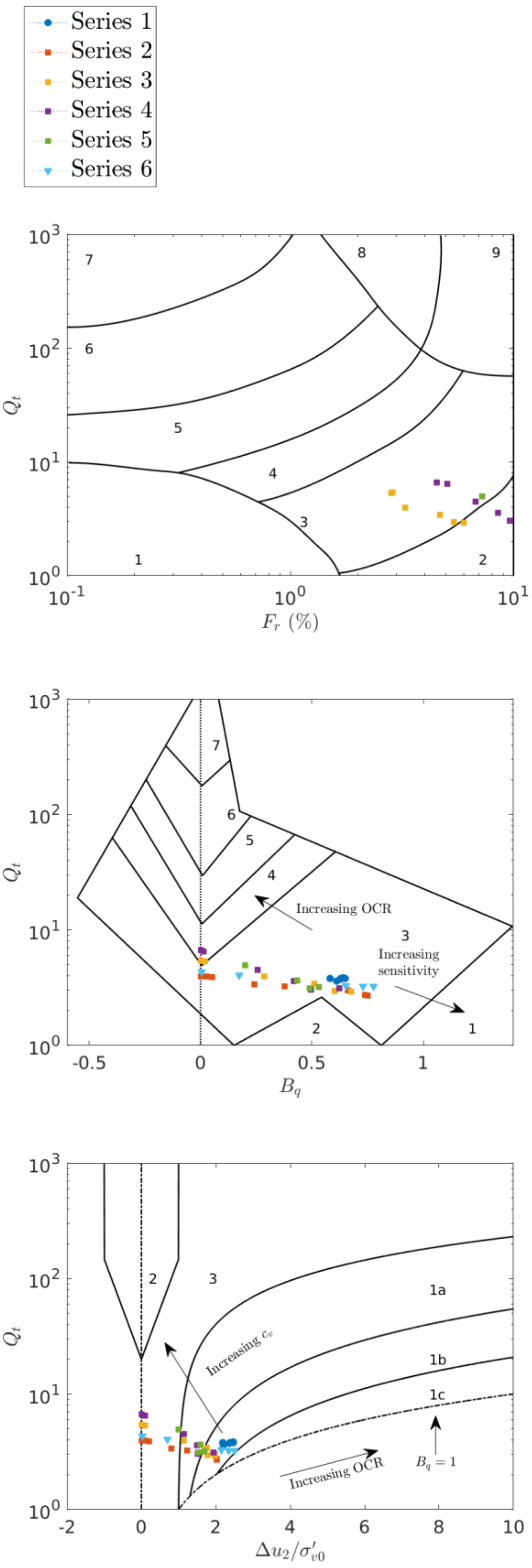

Figure 1. Numerical results depicted in current practice interpretation charts: Robertson [17] and Schneider et al [18].

Results in custom interpretation charts are presented in Fig. 1. Undrained conditions correspond to the lowest cone resistance, that increase as it does the permeability. On the contrary, the excess water pressure at the u_2 position and the normalized excess water pressure, B_q, decrease as largest permeabilities are considered. The friction ratio decreases as permeability increases.

Table 1. Modified Cam Clay constitutive parameters

Set	κ	λ	e_0	OCR	M	ν
1 [13,14]	0.02	0.2	1.94	1.1	1.07	0.2
2-5 [12]	0.05	0.3	2	1.21	1	0.33
6 [11]	0.04	0.205	1.41	1	0.92	0.25

Table 2. Initial stress state, permeability and interface friction angle

Set	σ'_{v0} (kPa)	K_0	k (m/s)	δ (º)
1	100	0.765	$10^{-7} - 10^{-12}$	0
2	57.8	0.5	$10^{-3} - 10^{-8}$	0
3	57.8	0.5	$10^{-3} - 10^{-8}$	10
4	57.8	0.5	$10^{-3} - 10^{-8}$	20
5	57.8	0.5	$5 \cdot 10^{-6} - 10^{-8}$	25
6	50	0.68	$1.2{\cdot}10^{-2} - 2.4 \cdot 10^{-8}$	0

In these graphs all the cases (and specially those in undrained conditions) plot in the areas where they are expected, namely, normally consolidated, unsensitive clays.

2.1. CPTu in partially drained conditions

The effect of partial consolidation during cone penetration has been extensively studied through field and centrifuge datasets and, more recently, through numerical modeling. DeJong and Randolph [15] observed that the general trend that follows the net cone resistance, q_n, and the excess water pressure at the u_2 position may be expressed as:

$$q_n = q_n^{und}\left(1 + \frac{\frac{q_n^d}{q_n^{und}}+1}{1+\left(\frac{V}{V_{50}}\right)^c}\right) \quad (1)$$

$$\Delta u_2 = \Delta u_2^{und}\left(1 - \frac{1}{1+\left(\frac{V}{V_{50}}\right)^c}\right) \quad (2)$$

where q_n^{und} and Δu_2^{und} are the net cone resistance and excess water pressure in undrained conditions, $\frac{q_n^d}{q_n^{und}}$ is the ratio between drained and undrained net cone resistance, V_{50} and c are two parameters of the model whereas V is the normalized cone velocity, which is defined as:

$$\mathrm{V} = \frac{2\,\mathrm{v}\,\mathrm{r}}{\mathrm{c_v}} = \frac{2\,v\,r\,\gamma_w}{M\,k} \quad (3)$$

where v is the cone velocity, r its radius and c_v is the soil coefficient of consolidation.

Fig. 2 reports the variation of the cone resistance and excess water pressure for the numerical database. The agreement between the numerical results and the curve proposed by DeJong and Randolph is excellent, specially for the excess water pressure. Of course, the ratio of the net cone resistance in drained and undrained conditions depends on soil constitutive parameters and the roughness of the contact. However, numerical results show the same trend than the backbone curve.

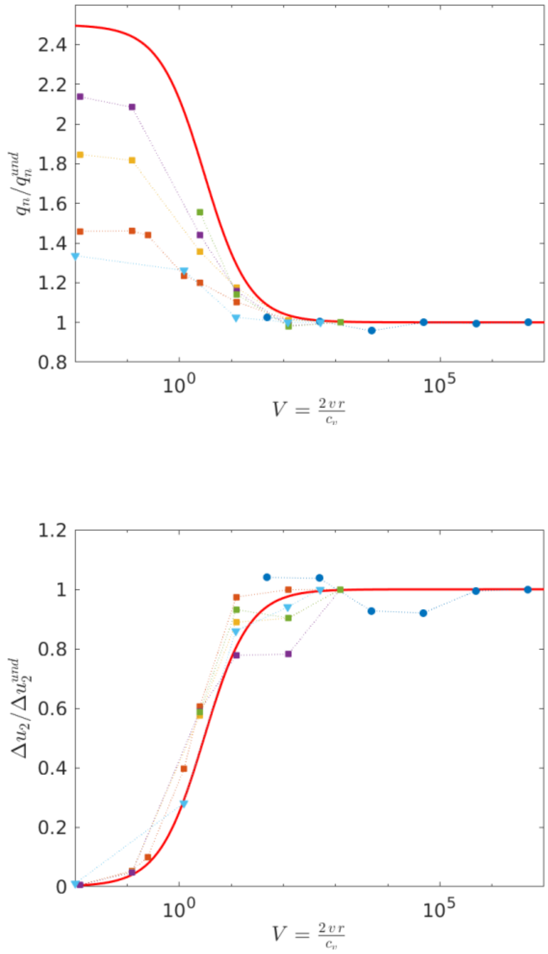

Figure 2. Effect of the normalized cone velocity to the net cone resistance (on top) and excess water pressure (bottom). The red line corresponds to the backbone curve proposed by DeJong and Randolph [15].

3. On-the-fly techniques

Elsworth and Lee [5,6] proposed a technique to estimate the permeability of the soil during cone penetration. Based on that seminal work, several proposals have been made to extend the technique to more undrained conditions and also to clarify the meaning of the parameters involved in the technique.

In this section, first the seminal work of Elswoth & Lee [5,6] is breafly described. Afterwards, the similitude of the backbone curve of DeJong and Randolph [15] with on-the-fly techniques is noted, which allows us to generalize the technique. After breafly describing how to estimate the parameters of the new generalization, the proposal is assessed against the numerical database.

3.1. Elsworth & Lee

Elsworth & Lee [5] analyzed the flow induced by a finite-size penetrometer as a moving steady-state flow problem. Combining dislocation and cavity exansion analysis and assuming negligible local storage they used continuity and Darcy's law to obtain the following relation between the product of cone metrics and a dimensionless permeability:

$$B_q Q_t = \frac{\Delta u_2}{\sigma'_{v0}} = \frac{v\, r\, \gamma_w}{4\, k\, \sigma'_{v0}} = \frac{1}{K} \quad (4)$$

where the symbol K represents a dimensionless permeability ratio.

Therefore, Equation (4) implies that permeability may be directly computed from the product of cone metrics $B_q Q_t$, since

$$K = 1/(B_q Q_t) \quad (5)$$

In a subsequent work, Elsworth & Lee [6] noted that the method should not be applied below a certain undrained limit. In other words, in cases where the product of metrics $B_q Q_t$ is between 1.2 and 5.6, undrained conditions prevail and the permeability may no longer be estimated. Also, through statistical fitting with a well documented database, they updated Equation (5):

$$K = 0.65/\left(B_q Q_t\right)^{1.6} \quad (6)$$

Expressions (5) and (6) are graphically depicted in Figure 3 in the $K - B_q Q_t$ space typically used on on-the-fly techniques.

Subsequent works disregard the undrained limit (see, for instance, Chai et al. [7] and Shen et al. [8]) and made different geometric assumptions to derive the basic formula. Therefore, each author propose different slopes of the straight lines in the interpretation graph shown in Fig. 3 and also vary the intersection point between both straight lines (see Monforte et al. [10]). Consequently, there are several on-the-fly techniques available, that depend on some parameters whose meaning is not fully understood.

3.2. Relation with DeJong and Randolph

As commented in the previous paragraph, each on-the-fly technique has different parameters -compare, for instance, Equation (5) and (6)- but its physical meaning is not fully understood.

A way to clarify the meaning of the parameters that appear on the on-the-fly techniques is through the backbone curve. As shown previously, DeJong & Randolph [15] proposed an expression that relates the permeability (through the normalized penetration velocity) with the excess water pressure, Equation (2). This expression may be rewritten by introducing K, defined in Equation (4). Therefore:

$$B_q Q_t = \left(B_q Q_t\right)^{und} \left(1 - \frac{1}{1 + \left(\frac{1}{K}\frac{8}{V_{50}}\frac{\sigma'_{v0}}{M}\right)^{c}}\right) \quad (5)$$

where $\left(B_q Q_t\right)^{und}$ is the product of cone metrics during undrained penetration.

Expression (5) is graphically depicted in Figure 3, where it can be seen that it incorporates the undrained limit (the curve is almost flat for normalized permeabilities lower than 10^{-2}) and for higher permeabilities has a slope of 1, which is in accordance with the seminal work of Elsworth and Lee [5].

The curve has 4 different parameters that need to be estimated. On the one hand, c and V_{50} are those of DeJong and Randolph [15]; in the referred work $c = 1$

and $V_{50} = 3$ are recomended as mean values and are adopted here, since a good agreement with the numerical data has been observed in Figure 1. A parametric analysis on how these values affects the backbone curve and also the interpretation graph may be found in Monforte et al. [10]. On the other hand, $(B_q Q_t)^{und}$ and M may linked to cone metrics. The former performing a CPTu in undrained conditions whereas the latter through the formula proposed by Robertson [16] (valid for $Q_t < 14$):

$$M = \sigma'_{v0}\, Q_t^2 \tag{6}$$

Consequently, introducing this expression to Equation (5), the generalized expression becomes:

$$B_q Q_t = (B_q Q_t)^{und} \left(1 - \frac{1}{1 + \left(\frac{1}{K} \frac{8}{V_{50}} \frac{1}{Q_t^2} \right)^c} \right) \tag{7}$$

From this last expression, an explicit equation for permeability may be directly obtained

$$k = \frac{2\, v\, r\, \gamma_w}{4\, \sigma'_{v0} V_{50} Q_t^2} \left(\frac{(B_q Q_t)^{und}}{B_q Q_t} - 1 \right)^{\frac{1}{c}} \tag{8}$$

Of course, as in Monforte et al. [10], Equation (5) may be expressed in terms of Cam Clay constitutive parameters. For instance, the constrained modulus M may be written in terms of the slope of the normal compression, the void ratio and the effective pressure, whereas $(B_q Q_t)^{und}$, assuming the results of cavity expansion, may be expressed in terms of the undrained shear strength and the rigidity index. On the contrary, it is more straightforward to link all quantities to cone metrics. Therefore, a CPTu in undrained conditions is necessary to evaluate the term $(B_q Q_t)^{und}$.

3.3. Numerical assessment

Figure 3 depicts the numerical results in the $K - B_q Q_t$ plane. Results of Series 1, in which all simulations take place in practically undrained conditions, plot in a straight line: the excess water pressure is insensitive to permeability. Therefore, on-the-fly techniques are only suitable to partially drained cases.

The figure also includes the the interpretation lines proposed by Elsworth & Lee [5,6], along with the generalization proposed in Equation (8), particularized for Series 2. It is clear that the agreement between the numerical data and the proposed interpretation line is perfect. In partially drained conditions, the agreement with the first interpretation line proposed by Elsworth & Lee [5] is good; numerical results do not support the idea of having a line with a slope different than one, as proposed by Equation (6).

Finally, Figure 4 compares the input permeability to the numerical model with that retrieved from Equation (8) for cases in partially drained conditions; that is, normalized cone velocities V > 1000. The performance of the proposed equation is excellent.

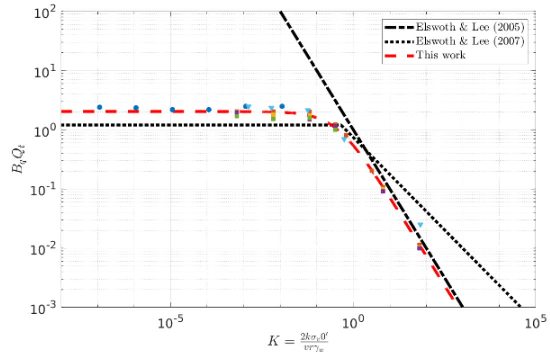

Figure 3. Interpretation chart of Elsworth & Lee, Equation (7) and numerical results.

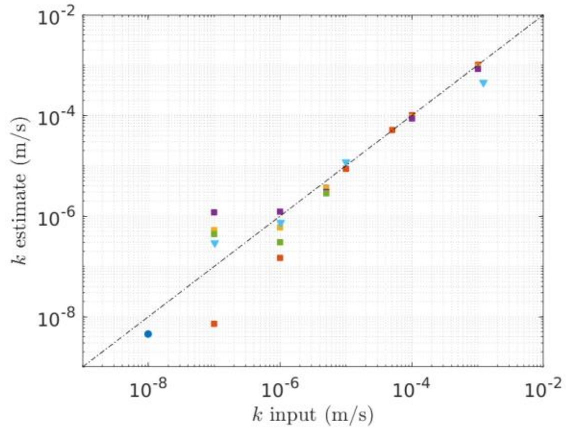

Figure 4. Comparison of input permeability to the numerical calculations and that deduced from the proposed on-the-fly technique.

4. Conclusions

For partially drained penetration CPTu, the on-the-fly method appears to offer a good approximation to the evaluation of permeability in compressible soils. The continuous generalization proposed here offers a clear connection with studies on partially drained penetration and clarifies the meaning of the adjustment parameters.

Acknowledgement

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References

[1] Robertson, P.K. “Interpretation of cone penetration tests – a unified approach”, Canadian Geotechnical Journal, 46(11), pp. 1337-1355, 2009. http://doi.org/10.1139/T09-065

[2] Parez, L., Fauriel, R. “Le piezocone ameliorations apportees a la reconnaissance des sols”, Revue Francaise Géotechnique., 44, pp. 13-27, 1988.

[3] Mayne, P.W. “Cone penetration testing” Transportation Research Board, 2007.

[4] Teh, C. I., Houlsby, G. T. “An analytical study of the cone penetration test in clay”, Géotechnique, 4(1), pp. 17-34, 1991. http://doi.org/10.1680/geot.1991.41.1.17

[5] Elsworth, D., Lee, D.S. “Permeability determination from on-the-fly Piezocone sounding”, Journal of Geotechnical and Geoenvironmental Engineering, 131(5), pp. 643-653, 2005. http:/doi.org/10.1061/(ASCE)1090-0241(2005)131:5(643)

[6] Elsworth, D., Lee, D.S. "Limits in determining permeability from on-the-fly uCPT sounding", Géotechnique, 57 (8), pp. 679-685, 2005. http://doi.org/10.1680/geot.2007.57.8.679
[7] Chai, J.C., Agung, P.M.A., Hino, T., Igaya, Y., Carter, J.P. "Estimating hydraulic conductivity from piezocone soundings", Géotechnique, 61(8), pp. 699-708, 2011 http://doi.org/10.1680/geot.10.P.009
[8] Shen, S.-L., Wang, J.-P., Wu, H.-N., Xu, Y.-S., Ye, G.-L., Yin, Z.-Y. "Evaluation of hydraulic conductivity for both marine and deltaic deposits based on piezocone testing", Ocean Engineering, Part A 110, pp. 174-182, 2015.http://doi.org/10.1016/j.oceaneng.2015.10.011
[9] Vessia, G., Casini, F., Springman, S.M. "DISCUSSION: Estimating hydraulic conductivity from piezocone soundings", Geotechnique, 62(10), pp. 955-956, 2012. http://doi.org/10.1680/geot.12.D.001
[10] Monforte, L., Arroyo, M., Gens, A., Carbonell, J.M. "Hydraulic conducitivy from piezocone on-the-fly: a numerical evaluation", Géotechnique Letters, 8 (4), pp. 268-277. https://doi.org/10.1680/jgele.18.00108
[11] Ceccato, F., Beuth, L., Simonini, P. "Analysis of piezocone penetration under different drainage conditions with the two-phase material point method", Journal of Geotechnical and Geoenvironmental Engineering, 142 (12), pp. 04016066, 2016. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001550
[12] Monforte, L., Arroyo, M., Carbonell, J.M., Gens, A. "Coupled effective stress analysis of insertion problems in geotechnics with the Particle Finite Element Method", Computers and Geotechnics, 101, pp. 114-129, 2018. http://doi.org/10.1016/j.compgeo.2018.04.002
[13] Parolini, C. "CPT and dissipation test simulation through PFEM", 2006. Master Thesis, Politecnico di Milano.
[14] Monforte, L., Arroyo, M., Gens, A., Parolini, C., "Permeability estimates from CPTu: A numerical study", In: CPT18 - 4th International Symposium on Cone Penetration Testing, Delft, the Netherlands, June 21-22 2018, pp 455-460. https://doi.org/10.1201/9780429505980
[15] DeJong, J.T., Randolph, M. "Influence of partial consolidation during cone penetration on estimated soil behavior type and pore pressure dissipation measurements" Journal of Geotechnical and Geoenvironmental Engineering, 138 (7), pp. 777-788, 2012. http://doi.org/10.1061/(ASCE)GT.1943-5606.0000646
[16] Robertson, P.K. "Estimating in-situ soil permeability from CPT & CPTu", 2nd International Symposium on Cone Penetration Testing, 2010.