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# Some comments on the CPTu and DMT dissipation tests

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ABSTRACT: Some $u_2$ and some DMT dissipation test data, measured at the Ballina soft clay test site, are compared. The DMT tests are evaluated using the Flex method which is based on the assumption that the $t_{50}$ is related to the inflexion point of the total stress-time curve. The $u_2$ dissipation tests are evaluated by two previously suggested, mathematically-precise methods and by the Teh-Houlsby method. Results show that the testing time can be considerably reduced by applying the mathematically-precise methods.

## 1 INTRODUCTION

The cone penetrometer test can be made either in continuous or in rheological testing modes. In the rheological or dissipation tests (Table 1) the time variation of a stress variable is measured on the penetrometer, after steady penetration is stopped. These tests can be used to assess the in situ permeability of soils if a suitable evaluation method is available.

The goal of the research is to get more information from shorter dissipation tests using optimal measuring system and proper evaluation methods. The research plan includes the following general steps. (i) Selection of in situ test sites with known properties: soft soil sites in Australia and Hungary (Szeged) are used. (ii) some preliminary tests are undertaken. (iii) possible modifications in the measuring and evaluation system are considered.

In this work some new $u_2$ and DMT dissipation tests were performed, at a soft clay test site in an Australian estuary, according to the present standards. The long $u_2$ data were evaluated with the one-point fitting method of Teh-Houlsby and two precise evaluation methods, a slow (A) and a fast (B) method. Some truncated short $u_2$ data were evaluated with the precise methods. The long DMT tests were evaluated with the Flex method (Totani, et al. (1998)).

First results show that the $t_{50}$ dissipation time is longer for the DMT than for the CPTu for low permeability soils. The necessary testing time is considerably shorter than the $t_{50}$ time if mathematically-precise – several point-fitting type – evaluation methods are used.

## 2 METHODS

### 2.1 *One-point fitting evaluation of dissipation*

At present, the measured and the theoretical dissipation curves are fitted in one point. For example, the coefficient of consolidation $c_{T\text{-}H}$ is determined by Teh and Houlsby (1991) as follows:

$$c_{T-H} = \frac{T_{50}^{T-H}}{t_{50}} r_0^2 \; I_r^{\;1/2} \tag{1}$$

where $r_0$ is radius of the rod, $t_{50}$ is measured time for 50% dissipation, $I_r$ is rigidity index, $T^{T\text{-}H}_{50}$ is an approximate time factor based on the observation that the dissipation curves can approximately be normalized.

Using total stress data measured in DMT, the coefficient of consolidation $c$ is determined with the following one-point fitting equation:

$$c_{DMT} = \frac{F}{t_{50}} \tag{2}$$

Table 1 Measured variables of some dissipation tests

| CPTu dissipation test* | CPT Piezo-lateral stress cell test, DMT dissipation test** | CPT dissipation test*** |
|---|---|---|
| pore water pressure on the shaft or the tip | total stress on the shaft | local side friction and the cone resistance on the usual shaft and tip position |

*Lunne et al (1992) ** Totani, et al. (1998), *** Imre et al (2014, 2014b) where $F$ is between 7 and 12 cm$^2$ (Totani et al, (1998)). It is assumed that the $t_{50}$ dissipation time of the pore water pressure and the inflexion point of the total normal stress dissipation curve coincide.

## 2.2 *Model for the precise CPTu evaluation*

### 2.2.1 *Differential Equation*

The pore water pressure variation with time is either monotonic or non-monotonic, determined by the initial pore water pressure distribution $u_o$.

In this work, the solution of a coupled model was used with a fixed $r_1$ (influence radius), as follows, for the pore water pressure (Imre et al, 2010):

$$u(t,r)= \sum_{k=0}^{\infty} \lambda_k C_k e^{-\gamma_k^2 \cdot c_h \cdot t} \begin{Bmatrix} [I_0(\lambda_k r)+\mu_k Y_0(\lambda_k r)] \\ -[I_0(\lambda_k r_1)+\mu_k Y_0(\lambda_k r_1)] \end{Bmatrix} \quad (3)$$

where $J_p$ and $Y_p$ are Bessel functions of first and second kind, order of $p$, $\lambda_k$, $\mu_k$ are roots of the boundary condition equations depending on $r_1$; $C_k$ ($k$=1...∞) are Bessel coefficients and $c(= k\ E_{oed}/\gamma_v)$ is coefficient of consolidation.

### 2.2.2 *The initial condition, boundary condition*

The $C_k$ ($k$=1...∞) were determined from the initial condition in two different ways. In one approach, a few $C_k$ ($k$=1...$n$) were identified during the inverse problem solution (fast model). If the value of $n$ was 1, the initial condition was monotonic, valid after undrained penetration. If the value of $n$ was greater than 1, the initial condition was non-monotonic but not necessarily realistic.

Alternatively, the parameters $C_k$ were determined beforehand for various shape functions, and the shape functions were identified (slow method). This resulted in some additional non-linearly dependent parameters, the model fitting was very slow.

The shape functions were defined as follows. The initial pore water pressure distribution $u_o$ may monotonically decrease with distance away from the shaft or it may increase initially over a short distance, (possibly from a negative value) due to interface shear in a thin shear zone of thickness $t_s$, between radii of $r_o$ and $r_s$.

Within the shear zone ($r_o \leq r \leq r_s$), the increasing initial pore water pressure function was assumed to be linear, having one of five prescribed values at $r_o$, called relative negativities, denoted by $n_1$ ($0 \leq n_1 \leq 4$) corresponding in Figure 1 to the distributions I to V.

The pore pressure decreasing part of the initial condition is a curve denoted by an integer parameter $n_2$ ($0 \leq n_2 \leq 9$) with an increasing mean ordinate, shown in Figure 1 as distributions 1 to 10.

The two parts of the initial condition ($n_1$, $n_2$) were combined to give $n = n_1 n_2$ ($0 \leq n \leq 49$), there were 50 different initial conditions (shown in Figure 1). A variable, the relative thickness of the interface shear zone $s$, was defined as $t_s/r_o$. was also used. The possible range of $s$ was covered by seven different values ($0.05r_o < t_s < 1.92r_o$), denoted by $s$ in Table 2.

In the evaluation method $r_1$ = 37 $r_0$ (valid in filter position E; Imre et al, 2010) is used. The identified $c$ values are greater by a factor of 4.5-6.5 if the measured data are related to other filter positions. A correction factor can be determined by using the model law (see Section 4). In this work 0.5 was used.

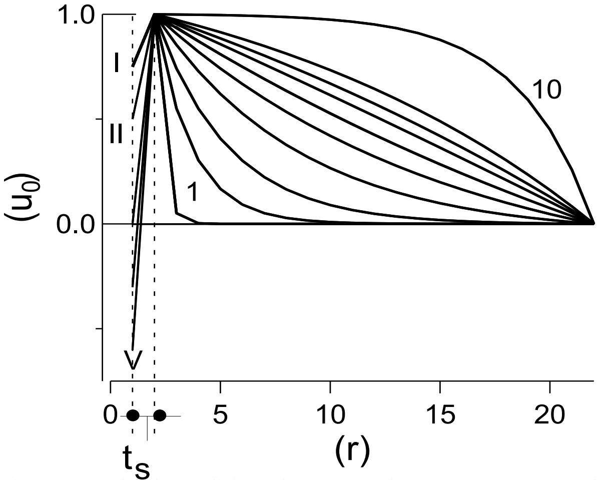


Figure 1. Initial condition shape functions from $r_o$ to $r_1$, the sheared zone extends from $r_o$ to $r_s = r_o + t_s$ where lines are labelled I to V, outside the curves are labelled 1 to 10.

Table 2 Specified thickness values of the interface shear zone ($r_o$ and $r_s$ is the radius of the CPT and the sheared zone, resp.)

| *s number* [-] | $t_s$ [cm] | $r_s = r_o + t_s$ [cm] | $t_s/r_o$ [-] |
|---|---|---|---|
| 1 | 0.1 | 1.85 | 0.05 |
| 2 | 0.21 | 1.96 | 0.12 |
| 3 | 0.42 | 2.17 | 0.24 |
| 4 | 0.84 | 2.59 | 0.48 |
| 5 | 1.89 | 3.64 | 1.08 |
| 6 | 2.94 | 4.69 | 1.68 |
| 7 | 3.36 | 5.11 | 1.92 |

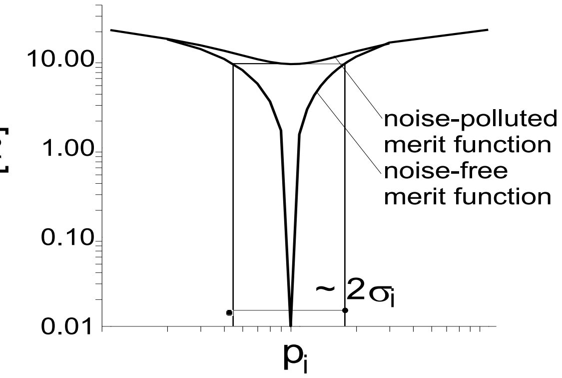


Figure 2. The clever section of the merit function and the geometrical concept of the parameter error domain for $p_i$.

### 2.3 *The inverse problem solution, precise evaluation*

Concerning the minimisation of the least squares objective function, the following concepts were used (Imre et al, 2010 and 2013): (i) the elimination of the linearly dependent parameters by sub-minimisation, (ii) the closest noise-free merit function (called follower function), (iii) the "deepest" or "clever section" section of the merit function, with respect to a parameter. The clever section contains the global minimum and gives information on the maximum error of the respective parameter (Figure 2).

The merit function was minimised such that a convex sublevel set - called an error domain – of the follower merit function was bracketed with a predetermined mesh generated in the subspace of the non-linearly dependent parameters, the linearly dependent parameters were eliminated. The clever sections for each non-linearly dependent parameter were determined on the basis of grid computations.

## 3 RESULTS

### 3.1 *CPTu and DMT measurements*

The soft clays associated sediments in the coastal estuaries has been extensively investigated in the Richmond River estuary (Bishop, 2009).

The Upper Clay is sensitive, has a liquid limit of around 100%, a plastic limit of 40% and a natural water content of 80%, with a unit weight of around 14.2 kN/m$^3$. The shear vane strength is low; around 25kPa. CPTu $u_2$ dissipation curves made in this layer are generally non-monotonic (Bates et al, 2014). From a geotechnical perspective, in the highly sensitive clays the organic substances lead to some physical stabilization in "normally consolidated" clays at high void ratio. This clay has a metastable structure.

The Lower Clay is not sensitive, has a liquid limit of around 80%, a plastic limit of 25% and a natural water content of 60% with a unit weight of around 16.4 kN/m$^3$. The shear vane strengths are higher; around 70kPa. The dissipation curves made in this layer are generally monotonic (Bates et al, 2014).

The site from which the data presented in this paper has been obtained is located on the Ballina coastal plain of eastern Australia (Figs 3 to 5). The main feature of the profile is the 3-4m thick sand layer that separates the upper Holocene estuarine clays from the lower Pleistocene estuarine and deeper clays. Two test -pairs are presented in this paper.

The CPTu tests were undertaken by the "NEWSYD" 200kN truck-mounted penetrometer facility using a 50MPa compression cone with the filter in the $u_2$ position. The same facility also performed the DMT tests.

The dissipation tests were conducted in the two clay layers (Fig. 5). According to the expectations, the lower clay has monotonic behavior while the upper clay has a non-monotonic response.

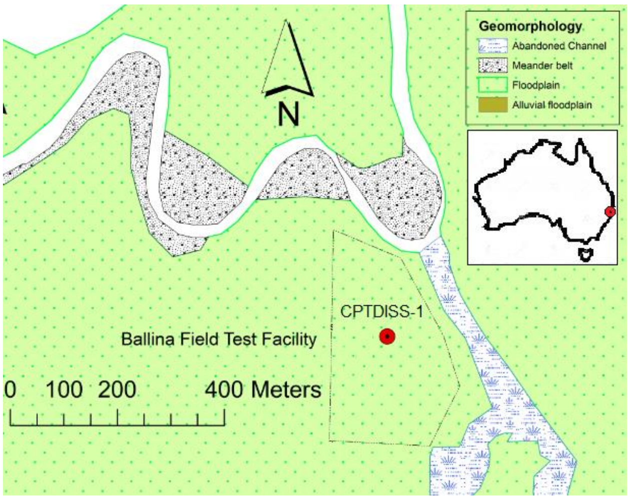


Figure 3. CPTDISS-1 at Ballina soft soils test site.

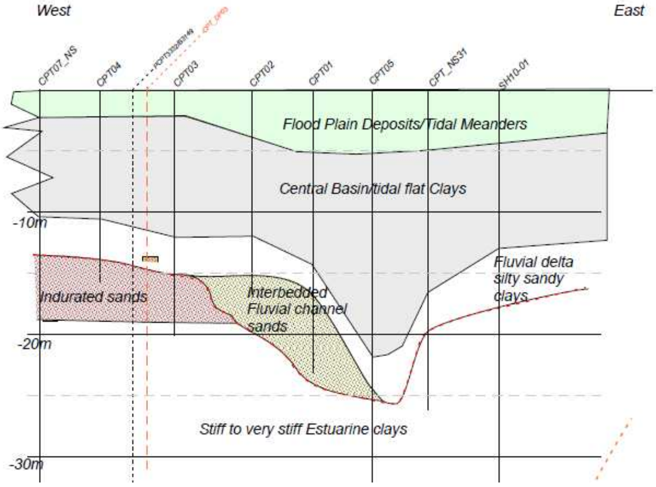


Figure 4. Section at Ballina soft soils test site.

Table 3 Identified c [cm$^2$/s] (uncorrected/corrected values)

| Test Depth [m] | 5 | 23 |
|---|---|---|
| Method A ($c_A$) | 5E-3/2.5E-3 | 0.4/0.2 |
| Method B ($c_B$) | 2E-2/1E-2 | 0.4/0.2 |
| DMT ($c_{DMT}$) | 3E-04 | 1.8E-01 |
| Teh-Houlsby ($c_{T\text{-}H}$) | 4E-04 | 3E-02 |

Table 4 Test duration data [min]

| Test Depth [m] | 5 | 23 |
|---|---|---|
| CPTu duration | 218 | 14.5 |
| CPTu $t_{50}$ | 120 | 4.16 |
| DMT $t_{50}$ | 340 | 0.65 |
| DMT duration | 450 | 240 |
| Method A minimum* | 5 | 4 |
| Method B minimum* | 20 | 2 |

* minimum test length from truncated tests

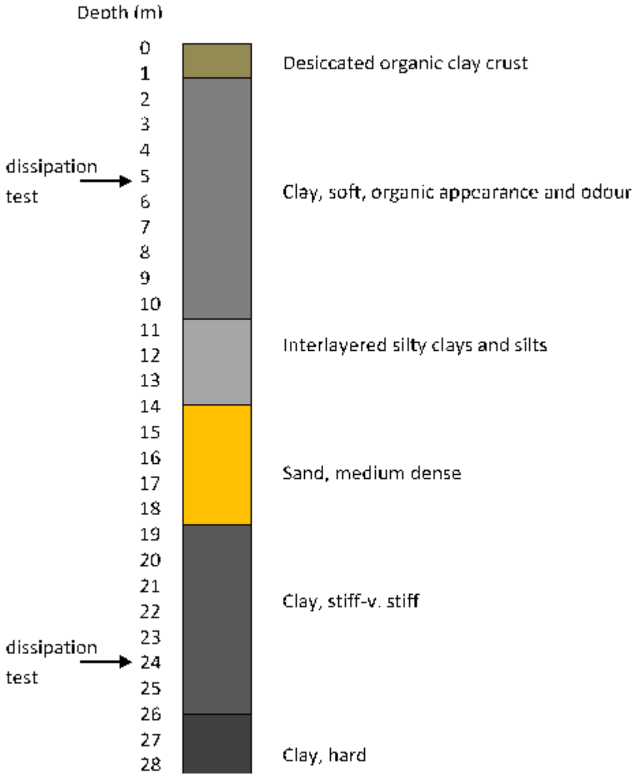


Figure 5. CPT profile showing dissipation tests: 5m, 7m and 23 m in estuarine clay from the Holocene and Pleistocene, resp.

## 3.2 *Evaluation results*

The results are shown in Figures 6 to 10 in Tables 3 to 4. Measured and fitted data in Figure 6 show good agreement. The identified coefficient of consolidation *c* can be characterized as follows.

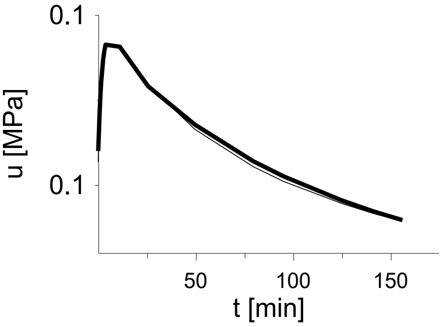
In the upper clay where the CPTu $t_{50}$ was 120 min and the DMT $t_{50}$ was 340 min, the coefficient of consolidation *c* identified with the Flex method was close to the one identified with the Teh-Houlsby method $c_{DMT} \approx c_{T\text{-}H}$ and $c_{T\text{-}H} < c_A < c_B$ was observed which is a previously observed experience (see e.g. Imre et al, 2014 and 2014b).

In the lower clay where the CPTu $t_{50}$ was 4.16 min and the DMT $t_{50}$ was 0.65 min, the coefficient of consolidation *c* identified with the Flex method was close to the precise method value $c_{DMT} \approx c_A \approx c_B$ and was larger than the one identified with the Teh-Houlsby method $c_{T\text{-}H} < c_{DMT} \approx c_A \approx c_B$.

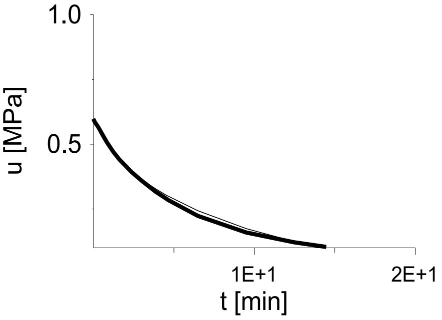
According to the clever sections of the merit functions for parameter *c* (Figures 7 and 8), the results of the precise method indicate reliable solutions in each case for the long tests. This is because the solution was unique, since the global minimum of the clever section was single, non-degenerated and the local minima were not 'too deep' (e.g. not deeper than global minimum of the real-life merit function).

The solution of the inverse problem was acceptably precise since the error domain of the solution on the clever sections was situated within the physically admissible parameter domain.

The evaluation of the short tests was made with methods A and B for each test, and the variation in the determined *c* values is shown in Figure 9. It is apparent that consistent values of *c* can be obtained as the data record is shortened by a great amount.

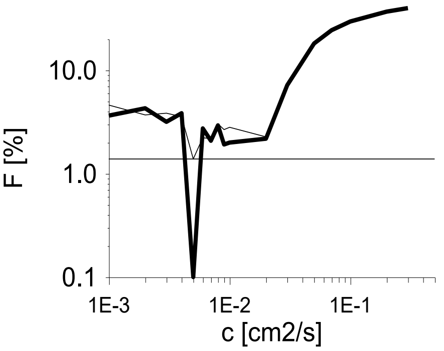


(a) CPTu test 5m

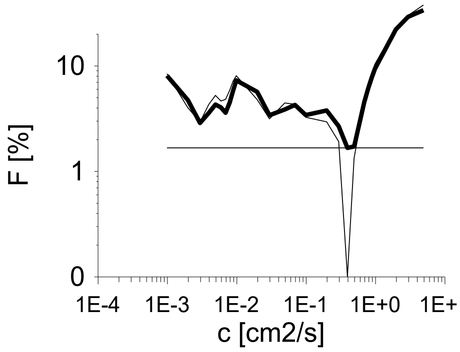


(b) CPTu test 23m

Figure 6. Measured – fitted data, slow method A

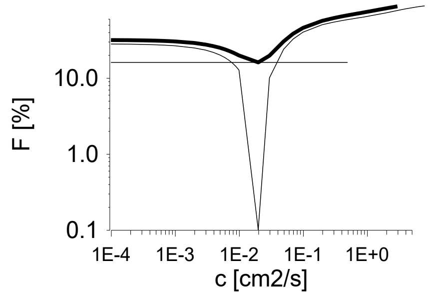


(a) CPTu test 5m

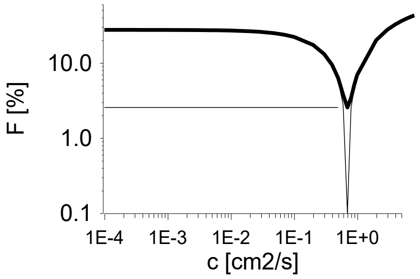


(b) CPTu test 23m

Figure 7. Clever section of the merit functions of *c*, method A.

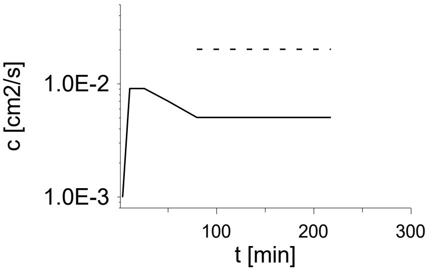


(a) CPTu test 5m

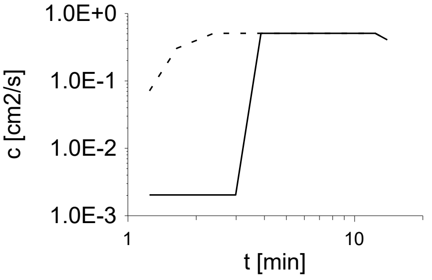


(b) CPTu test 23m

Figure 8. Clever section of the merit functions of *c*, method B.



(a) CPTu test 5m



(b) CPTu test 23m

Figure 9. Identified *c* and testing time (method A and B are indicated in solid and dashed lines, resp.)

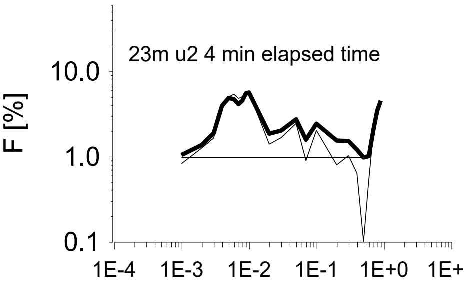


Figure 10. CPTu 23 m, method A, too short data (4 min elapsed time, see Fig. 7 for long test with unique solution).

By representing the clever sections of the short data series (Fig. 10), it can be seen that in the initial, inconsistent part of the *c-t* diagrams the solution is not unique. The value of *c* is only consistent for data longer than 20 minutes elapsed time for the upper clay where the solution of the inverse problem became unique.

## 4 DISCUSSION

### 4.1 *Time factor concept*

#### 4.1.1 *The $t_{50}$ relationship*

The relation of the $t_{50}$ of CPT and DMT can be expressed by combining Equations (1) and (2):

$$\frac{t_{50,CPT}}{t_{50,DMT}} = \frac{T_{50}^{T-H}}{F} r_0^2 \; I_r^{1/2} \qquad (4)$$

It is clear from approximate Equation (3) that the $t_{50}$ dissipation time ration for the DMT and CPT may be dependent on the rigidity index $I_r$.

#### 4.1.2 *The use of rigidity index*

An approximate time factor can be derived from the analytical solution (3) (Imre et al., 2014 and 2014b):

$$T = \frac{ct}{\left(r_1 - r_o\right)^2} \qquad (5)$$

Combining Equations (1) and (5) gives:

$$r_1 - r_0 = r_0 \left(T^{T-H} / T^1\right)^{1/2} I_r^{1/4} \qquad (6)$$

It follows that some information can be collected for the value of $r_1$ using the rigidity index $I_r$. As the rigidity index $I_r$ is smaller, the value of $r_1$ - $r_0$ is less for sands and silts than for clays.

#### 4.1.3 *The model law*

The approximate time factor (5) can be used to derive various model laws (Imre et al, 2010) just as in the case Terzaghi’s model law. One possibility is shown here as follows.

The differences in the dissipation time can be explained by the size of the displacement domain $r_1$ where the in which dissipation extends. This depends on filter position and drainage condition.

Assuming that the same linear model applies for every filter position and the soil is isotropic, the following ‘‘*c* formula” can be derived from the time factor. The ratio of the *c* values from the filter position A and position D depends on the size of the displacement domains:

$$\sqrt{c_E / c_D} = \frac{(r_{D1} - r_{D0})}{(r_{E1} - r_{E0})} \qquad (7)$$

using the $r_1$ value valid for filter position E and D and one corresponding identified *c*.

## 4.2 *Precise method for DMT*

The evaluation of the DMTA dilatometer dissipation test - based on the inflexion point of the measured stress curve (Flex method) -, may not work if no inflexion point can be found.

In this case the dilatometer dissipation test data can be evaluated in the frame of a double parameter sensitivity analysis including not only the Flex method but also the precise pore water pressure dissipation test evaluation method A (Imre et al, 2011).

The double parameter sensitivity analysis can also be used to validate the constant of the DMTA dilatometer dissipation test evaluation (Flex) method.

# 5 CONCLUSIONS

The preliminary results of the evaluation of two test - pairs of CPTu $u_2$ and DMT dissipation tests data, compared in this paper - show some differences in terms of the identified *c* and the $t_{50}$ dissipation time.

The *c* values determined by the one-point fitting method (Teh-Houlsby method) in the upper clay, was smaller than the ones determined by the mathematically precise fitting methods A and B. The difference decreased if a correction factor of 0.5 was used to account for the $u_2$ filter position. The DMT value was the same as the Teh-Houlsby value. Method A gave smaller values than method B. In the lower, assumingly low plasticity soil the opposite was true in the sense that the DMT and the precise methods gave basically the same result, but the Teh-Houlsby value was smaller.

It can be concluded that the *c* values identified with the various $u_2$ methods showed a similar picture – depending on soil plasticity - as in earlier works, e.g. in the case of the Hungarian soft clay site (Imre et al, 2014, 2014a) which need some further research using additional information.

No unique rule was found for the relation of the $t_{50}$ dissipation time of CPT and DMT. The $t_{50}$ in the upper clay was shorter for the CPT than for the DMT (the $t_{50}$ was longer than 100 min for the CPTu and longer than 300 min for the DMT). In the less plastic, lower soil the opposite was true. The difference may be dependent on rigidity index, as derived in this paper and may be influenced by the fact that the dilatometer blade has a different geometry than the CPT cone.

The necessary testing time of the one-point fitting methods (i.e. for the Flex and The-Houlsby method) is equal to the $t_{50}$ time at present. The evaluation results of a series of truncated $u_2$ dissipation test data indicated unique solution for shorter data series even by an order of magnitude.

It follows that the necessary testing time can be decreased with the precise method in plastic clays. The same can probably be true for the DMT if evaluated with the precise method.

Further research is suggested on the $t_{50}$ dissipation time and on the possible decrease in the testing time by using precise – several point-fitting – evaluation methods. In the subsequent, detailed analyses of the data, the laboratory test results, for example rigidity index information is suggested to be included.

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