

Some Comments on Dissipation Testing of the Soils

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ABSTRACT: In the paper some current topics are highlighted in the field of the dissipation tests made by the CPTu and DMT (pore water pressure, radial total stress, local side friction and the cone resistance), and more particularly those, where some future developments are expected.

1 INTRODUCTION

The static cone penetrometer (CPT or CPTu) or flat dilatometer (DMT) can be used in soil, in municipal landfill waste material and tailings. The rheological testing mode means that the steady penetration is stopped, the penetrometer rod is clamped and the time variation of some stress variable is measured at the penetrometer - soil interface.

The rheological-type cone penetrometer tests, which measure the time dependence of some stress variables on the surface of the penetrometer or DMT after steady penetration is stopped, can theoretically be used to assess the in situ permeability of soils on the condition that a suitable evaluation method is available.

In the paper some current topics are highlighted in the field of the evaluation of the dissipation test made by the CPTu and DMT (pore water pressure, radial total stress, local side friction and the cone resistance). More particularly, some notes are made concerning the total stress dissipation, where some future developments are expected. The reason for this is that the measurement of the total stress dissipation and the local side friction dissipation test could be simpler than the pore water pressure dissipation test in terms of measurement.

2 MEASURED DATA

2.1 *Pore water pressure dissipation test*

In the CPTu pore water pressure dissipation test, the pore water pressure is recorded. The measured dissipation curves are generally either monotonic

or non-monotonic, and these are generally associated with low or high values of OCR, respectively. Significant differences in the shape of the dissipation curve are also observed, depending on where the pore pressure filter is mounted on the penetrometer (Fig. 1 and Table 1).

2.2 *Piezo-lateral stress cell test*

In the piezo-lateral stress cell test the time variation of the radial total normal stress is recorded and the pore water pressure may be measured.

In soft clay the radial total stress may decrease by 73% up to the end of the dissipation.

In the first minutes, the effective stress decreases, then increases up to a final value being about equal to the value before penetration (Fig. 2).

2.3 *Simple test*

In the “simple rheological test” the time variation of the local side friction (350 cm² shaft element) and the cone resistance are measured for a few minutes after the rod is clamped (Fig. 3). The cone resistance and the local side resistance dissipation measurement results generally show an immediate stress drop (or discontinuity) at the stop of the steady penetration, possibly since the loading type changes from basically dynamic to quasi-static.

The increment in the shaft dissipation data and the rate of the cone dissipation data measured afterwards in the first two minutes (with a 350 cm² element for the shaft) are strongly dependent on the soil type (Imre, 1995, Imre et al., 2013).

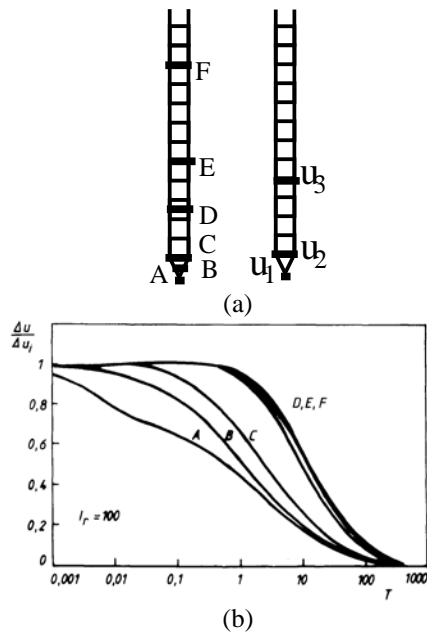


Fig. 1. The pore water pressure dissipation test (a) filter positions on the CPT. (b) The results of a 2D analysis of pore pressures at different positions (from Imre et al, 2010)

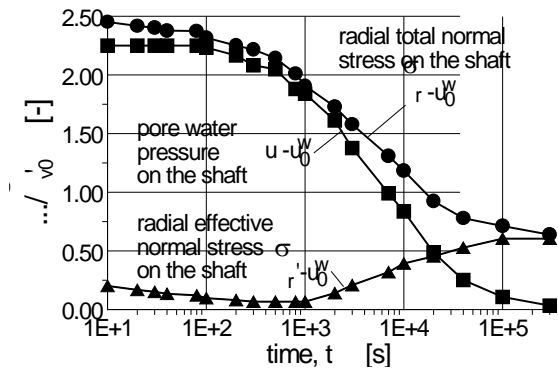


Fig. 2. Piezo-lateral stress cell measurement (from Imre et al, 2010)

Especially, for sands the local side resistance increases with time and for clays it decreases with time (like in the piezo-lateral stress cell test data section 2.3). The variation tendencies are different in agreement with the piezo-lateral stress cell test data (section 2.3, Fig. 3). The rate of the cone resistance dissipation is small in sand and is large in clay. Using these dependences, charts were suggested for the soil type. The cone resistance and the local side resistance dissipation tests can theoretically be used to determine the soil type by charts (see App).

2.4 DMT dissipation test

The dilatometer dissipation test is similar to the CPT dissipation tests (see Fig. 4). In the DMTA test the total stress is measured manually immediately after penetration in the function of the time, (A data). In the DMTC test the stress is

measured manually not only immediately after penetration but also after an inflation and a deflation of the membrane. As a result, a kind of pore water pressure is measured until the borehole wall is not moving inwards after the deflation (C data).

Table 1 Approximate t_{50} and t_{90} dissipation times for measurements at different filter positions in clay

Filter position	t_{50} [min]	t_{90} [min]
A	8	200
B	22	250
C	60	300
D	90	>600
E	110	>600

Table 2. Summary of point-symmetric consolidation models.

Model type	ν or ε boundary condition (Model Set or Family)	Origin
1D (Oedometric models)	No (uncoupled)	Terzaghi 1923
	ν - ν (coupled 1)	Imre1997-1999
	ν - ε (coupled 2)	Biot 1941
2D (Cylindrical pile models)	No (uncoupled)	Soderberg 1962
	ν - ν (coupled 1)	Imre & Rózsa 1998
	ν - ε (coupled 2)	Randolph at al 1879
3D (Spherical pile models)	No (uncoupled)	Torstenson 1975
	ν - ν (coupled 1)	Imre & Rózsa 2002
	ν - ε (coupled 2)	Imre & Rózsa 2005

3 MODELLING

3.1 Consolidation model

Generally linear consolidation model is used, since unloading takes place around the shaft after penetration. The consolidation model for the pore water pressure can be two dimensional, uncoupled with numerical solution which is less favourable from the point of view of inverse problem solution (see e.g. Teh and Houlsby, 1988).

Alternatively, the model can be one dimensional with analytical solution which is more favourable from the point of view of inverse problem solution (Table 2, Imre et al., 2010).

The latter form three sets ('families'), the uncoupled, the coupled 1 and the coupled 2 families, consisting of such oedometric, cylindrical and spherical models that have the same set of boundary conditions and assumptions.

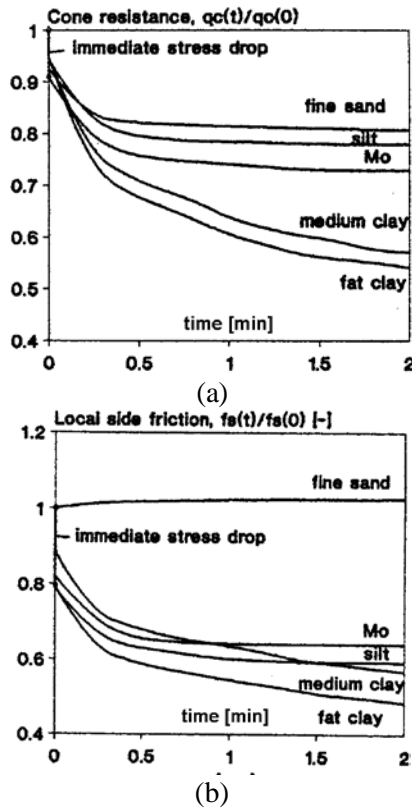


Fig. 3 Simple test, mean data in the function of the time. (a) q_c -time relation. (b) f_s -time relation

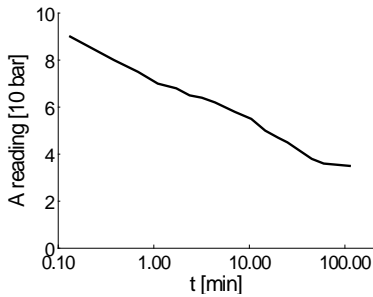


Fig. 4. Measured dilatometer dissipation test data

The two coupled model sets use constant radial displacement boundary condition at the inner boundary r_o (even though unloading takes place around the shaft after penetration with a slight decrease of the shaft radius).

At the outer boundary r_I the coupled 1 models use constant displacement and result in a total stress drop at the shaft-soil interface with time (i.e. by the value of the initial mean pore water pressure). The coupled 2 models use constant volumetric strain at r_I , and result in a constant total stress with time (see e.g. Randolph and Wroth, 1979).

3.2 Modelling pore water pressure dissipation

The pore water pressure dissipation curves are monotonic or non-monotonic, if the initial pore

water pressure distribution is monotonic or non-monotonic, respectively.

The monotonic initial condition is defined in the form of a normalized parametric shape functions (u_0). The mean absolute initial pore water pressure D is a key parameter of the solution of the consolidation model, D is approximately equal to $u_0(r_0)/(n+1)$, depending inversely on the space dimension, n .

In the case of over-consolidated soils the initial pore water pressure distribution u_0 may have a negative component due to dilation in a thin interface shear zone along the shaft.

Within the shear zone ($r_0 < r < r_s$), the initial pore water pressure is negative. For clays, the relative thicknesses $s = t_s/r_0$ are considered for the interface shear zone as $0.05r_0 < t_s < 1.92r_0$, no data are available for sands.

3.3 Modeling total stress dissipation

To model the about 73% total stress drop for clays (see section 2.3), such consolidation model can be used that can describe some total stress drop. The coupled 1 consolidation model results in a total stress drop with value being equal to the initial mean pore water pressure.

The coupled 1 model family can be enlarged into a joined model family. In the suggested joined model an empirical relaxation part-model is added to the coupled consolidation 1 model (due to the constant radial displacement boundary condition at r_o Imre et al., 2010, 2013). These have similar boundary total normal stress and effective normal stress solution for all space dimensions (oedometer, cylindrical and spherical cases).

The total stress drop is the sum of two terms originated from relaxation and from consolidation being influenced by the initial mean pore water pressure distribution. All parameters are dependent on the soil type. The time variation of the effective stress (Fig. 5) is determined by the opposite effect of the coefficient of consolidation (c) and the coefficient of relaxation (s) for a fixed initial condition. It is influenced by the initial mean pore water pressure distribution, also. All parameters are dependent on the soil type.

The effective stress solution hence describes both the local side resistance dissipation test results (qualitatively) and the multistage oedometric relaxation test (MRT), total stress and effective stress results (precisely).

4 APPROXIMATE EVALUATION

An approximate time factor is used for a “one point” model fitting in most approximate methods.

4.1 Evaluating pore water pressure dissipation

At present, the pore water pressure dissipation test data and the total stress dissipation test data are evaluated to determine the coefficient of consolidation (c). The measured and the theoretical dissipation curves are fitted in one point only using a kind of approximate time factor concept. The time factor is heuristic, it is based on the observation that the theoretical dissipation curves can approximately be normalized.

For example, using pore water pressure data, the coefficient of consolidation c is determined by Teh and Houlsby (1991) as follows:

$$c = \frac{T_{50}^{T-H}}{t_{50}} r_0^2 I_r^{1/2} \quad (1)$$

where r_0 is the radius of the rod, T_{50}^{T-H} is a heuristic time factor, and t_{50} is the measured time for 50% dissipation, I_r is the rigidity index. The t_{50} is measured which can be as long as 60 min in clays in filter position immediately above the tip which is commercially used (Lunne et al, 1992).

4.2 Evaluating total stress dissipation

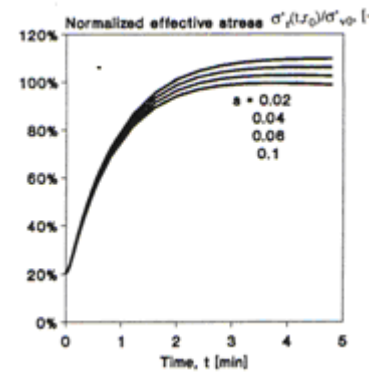
Using total stress data measured in DMT, the coefficient of consolidation c is determined with the following one-point fitting equation:

$$c = \frac{F}{t_{50}} \quad (2)$$

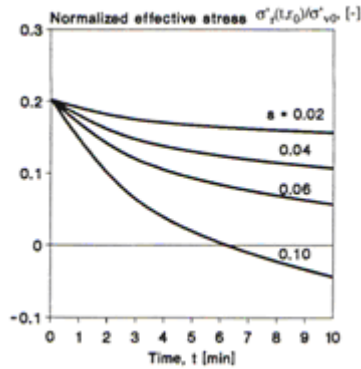
where F is between 7 and 12 cm² (Totani et al, 1998). This method does not work in case of no inflexion point since it is assumed that the t_{50} dissipation time of the pore water pressure and the inflexion point of the total normal stress dissipation curve coincide.

4.3 The problems with approximate evaluation

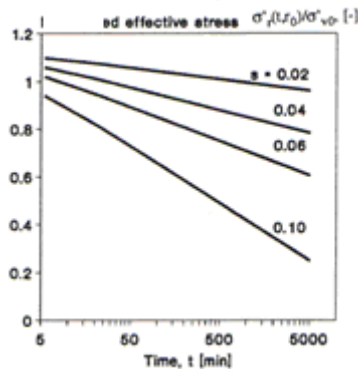
The first problem with the approximate evaluation methods is that some soil physical parameters may be needed a priori since the theoretical dissipation curves are given as the function of those parameters that are used for the calculation of the initial condition. The initial condition is estimated either from cavity expansion theory or from strain path theory using the rigidity index I_r , the OCR and the friction angle.



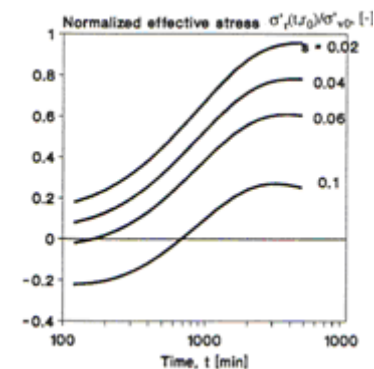
(a)



(b)



(c)



(d)

Fig. 5. Joined model, effective radial stresses on the shaft, for a fixed initial condition, in the function of the coefficient of relaxation s . a. short term behaviour, $c_v = 1e-3$ m²/s, b. short term behaviour, $c_v = 1e-8$ m²/s; c. long term behaviour, $c_v = 1e-8$ m²/s. The term behaviour is opposite for sands and clays.

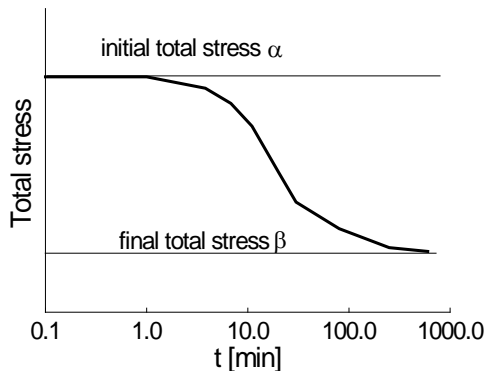


Fig. 6 Total stress parameters $\alpha = \sigma_r(0, r_0)$, $\beta = \sigma_r^s(r_0)$

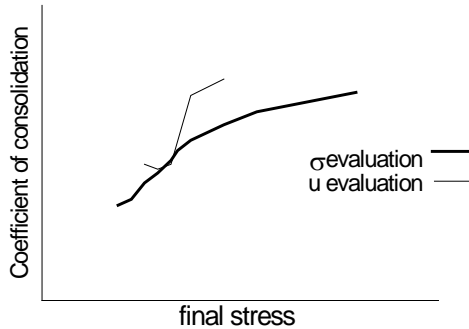


Fig. 7 Matching solutions of the two inverse problem series.

The second problem is that the inverse problem solution is approximate and the potential error of this method is uncertain, possibly as great as one order of magnitude. Since the accuracy improves with increasing duration of the measurement, the measured data are generally related to the 50% dissipation time. However, the 50% dissipation time, even in the case of tip-close filters, can be extremely long as indicated by the data in Table 1.

The third problem is that, in some cases (e.g. non-monotonic data or no inflexion point), the 50% dissipation time can not be assessed precisely.

5 LEAST SQUARES EVALUATION

5.1 Pore water pressure dissipation test data

The measured pore water pressure dissipation data can be monotonic, or dilatatory with time (t) and is dependent on the filter position. In case of a one dimensional theory, the monotonic, or dilatatory nature is determined by the initial condition and, the dependence on the filter position can be taken into account by the boundary condition (i.e. the width of the displacement domain).

The precise evaluation methods are automatic and are worthy to be used if the necessary testing time can be reduced. According to the results of the validation of the one dimensional models on the

basis of the data measured in five filter positions (Lunne et al., 1992), the optimal filter position is well above the tip. In this case very short test (~2 min) is needed. (The identified c is practically independent of the test duration in filter position well above the tip which is certainly not true for any other filter position, where it is a continuous function of the test duration.)

The result is basically the same for the various one dimensional, coupled 1 and 2 models, the only difference is that the identified value of c differs by a constant multiplier (Imre et al., 2010).

5.2 Radial total stress dissipation test data

Piezo-lateral stress cell data

The measured radial total stress dissipation data in Boston Blue Clay show that the radial total stress at the shaft decreases by 73% of its initial value (Baligh et al. 1985). The result is similar in the case of DMT as well (Totani et al., 1998). The suggested joined model may describe about 50 % total stress decrease which is less than the measured 73%.

The possible reason for the difference is the very slight decrease of the penetrometer radius due to the stress release. In other words, the constant radial displacement boundary condition at the shaft-soil interface is non-precise, since a tiny partial unloading may occur (Imre et al., 2010). This assumption was verified by a similar oedometer test.

DMT data

A mathematically precise method was suggested by identifying the additional stress drop during inverse problem solution. Two methods are combined (the foregoing approximate evaluation method used in the DMT technique and, the precise evaluation method for the in the pore water pressure dissipation data). The data can precisely be evaluated even in the lack of inflexion point (Figs 6,7, Imre et al., 2011).

5.3 Multistage relaxation test (MRT) data

The model suggested for the total stress dissipation test was validated using for various soil types in the case of the oedometer (Imre and Singh, 2012; Imre et al., 2013 and 2015). Only a few representative results are shown here in Figs 8, 9.

In the short MRT procedure the load increment was uniform, 0.1 mm and the stages were 10 - 20 minutes long except the last one being longer than the t_{99} dissipation time. The strain rate of the loading was slightly too fast. A typical stage record showed

an immediate stress drop with constant stress rate and a subsequent, time dependent stress variation. The constant stress rate stress drop was caused by the limitations of the control system, a slight partial unloading in terms of the displacement occurred.

By using a mathematically precise inverse problem solver, not only the test duration could have been decreased, but also a model discrimination study could have been made as follows. The fitting error decreased to the half if the viscous effect, the creep/ relaxation was taken into account. The measured and fitted data and, the identified initial condition are shown in Fig. 9.

6 TIME FACTOR

No time factor can be separated from the analytical solution of the point-symmetric coupled consolidation models for dimensions larger than one, only an approximate time factor can be assessed.

The coupled 1 and 2 models allow the derivation of the following two time factors T , respectively:

$$T^1 = \frac{ct}{(r_1 - r_o)^2} \text{ or } T^2 = \frac{ct}{4(r_1 - r_o)^2} \quad (3)$$

where r_o is the radius of the rod, r_1 is the radius of the displacement domain. These are approximate in the cylindrical and spherical cases since no time factor can be separated from the analytical solution of the one dimensional consolidation models for embedding dimensions larger than one. Compiling Equations (1) and (3) for the coupled 1 model:

$$r_1 - r_o = r_o \left(T^{T-H} / T^1 \right)^{1/2} I_r^{1/4} \quad (4)$$

Using the values for the rigidity index I_r , measured in Szeged city (for sandy silts typically 200 to 800, for clays typically 850 to 1000), the value of $r_1 - r_o$ is less for sands and silts than for clays by a factor of about 0.7 to 0.95. Compiling Equations (1) to (2) and (2) to (3) for the coupled 1 model, respectively:

$$\frac{t_{50,CPT}}{t_{50,DMT}} = \frac{T_{50}^{T-H}}{F} r_o^2 I_r^{1/2} \quad (5)$$

$$\frac{t_{50,CPT}}{t_{50,DMT}} = \frac{T_{50}^1}{F} (r_1 - r_o)^2 \quad (6)$$

For Equation (5), using a time factor value of 2,5; F of 17 and 2 cm², I_r of 200, this ratio is about equal to 15 and 9, respectively. For Equation (6), using a time factor value of 0,02 (Imre et al, 2010); $r_1 - r_o$ of 63 cm (Baligh, 1986), 7 and 12 cm² for F , this ratio is about equal to 11 and 7, respectively.

7 CONCLUSIONS

7.1 Immediate stress drop

In the simple rheological test, the cone resistance and the local side resistance dissipation measurement results showed an immediate stress drop at the stop of the steady penetration.

In case of DMT, the measurement is made at discrete values of the time after the stop of the steady penetration, the immediate stress drop is not apparent in the measured data. This fact makes the DMT measurement to be related to quasi-static state.

It can be noted that a similar testing mode can be suggested for the CPTu in parallel to the continuous log, after the continuous penetration, the steady penetration is stopped, the penetrometer rod is clamped and the time variation of some stress variable is measured at the penetrometer - soil interface for about 2 minutes.

7.2 Time dependent stress variation

Using the rheological testing mode, the immediate stress drop can be eliminated from the continuous CPTu data. Some information on the soil type can be collected (see the Appendix) on condition that the measuring elements are proper. For this aim, a local shaft element with a 350 cm² area at least is suggested.

It was shown that not only the effect of the consolidation but also the effect of the viscosity is needed to be taken into account to describe the effective stress variation along the shaft. It follows from the similarity of the solution of the joined model in various space dimension, that the MRT can be used to study the dissipation tests.

The suggested joined model may describe about 50 % total stress decrease around the shaft which is less than the measured 73%. The possible reason for the difference is the slight decrease of the radius of the shaft due to the stress release. Further research is suggested on this and, on the relaxation part-model.

7.3 Pore water pressure dissipation test

In case of pore water pressure dissipation test, the necessary testing time can be reduced if the sensor is situated well above where one-dimensional, linear model can be used due to the slight unloading. It can be noted that very few knowledge is available on the shear zone thickness - where the pore water pressure is negative - for soils with decreasing plasticity. Further research is suggested on this topic.

7.4 Time factors

The two time factor formulae derived for static cone penetrometer (1) and (3) was used to derive some information for displacement domain thickness. The first result indicates that the size of the displacement domain may decrease with decreasing plasticity with respect to the undrained penetration case. By using time factor formulae (1) to (2) and (2) to (3), two formulae were derived indicating that the dissipation is longer for CPTu than DMT. Further research is suggested on this point.

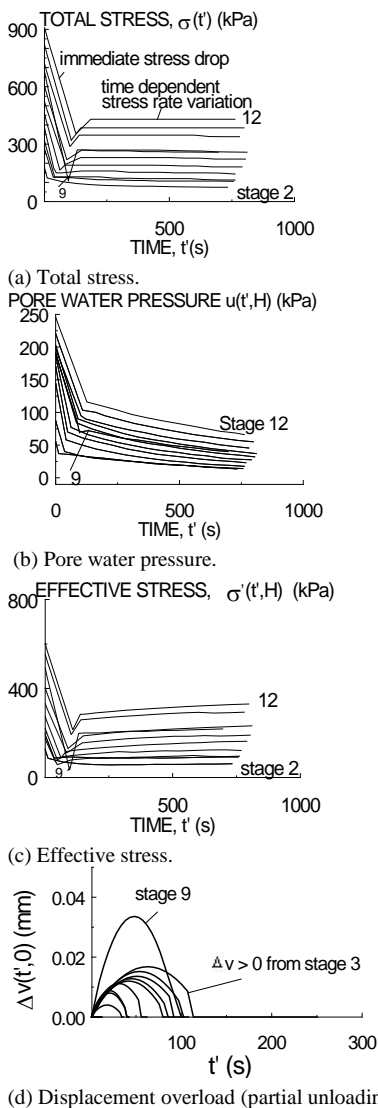
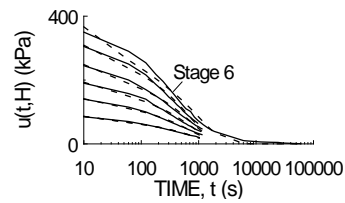
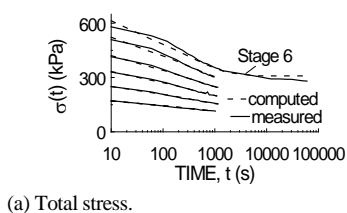
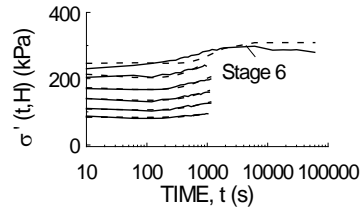


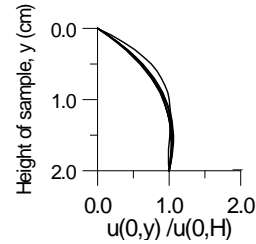
Fig. 8. MRT, data measured on an intact clay soil



(b) Pore water pressure.



(c) Effective stress.



(d) Identified initial condition.

Fig. 9. MRT, simulated and measured stresses

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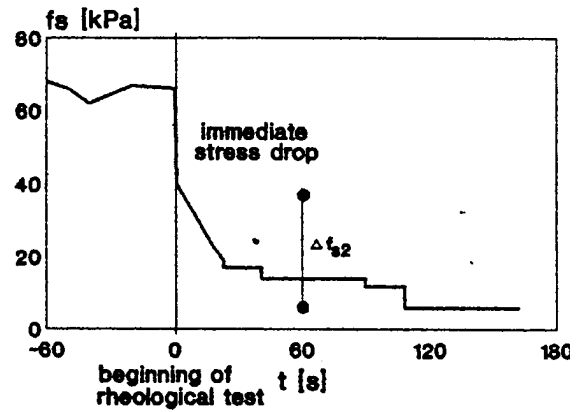


Fig. 10. Shaft parameter Δf_{s2}

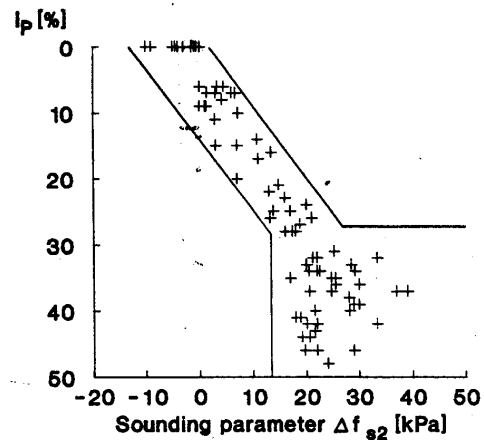


Fig. 11. Δf_{s2} - I_p relation, 'off' points are related to the vicinity of layer boundaries and layers with secondary structure

Appendix: Empirical evaluation of simple tests

Some empirical parameters have been developed for the characterization of the simple rheological-type cone penetration test records (Imre 1995, Figs 10 to 12). One such factor is the local side friction sounding parameter Δf_{s2} is given by:

$$\Delta f_{s2} = f_s(t_i) - f_s(t_i + t_1); \quad (7)$$

where t_i is the time when the immediate stress drop is ended, and t_1 is a reference time of 120 s.

An additional sounding parameter ν is defined by fitting the relaxation equation of the Poynting-Thomson model to the cone resistance data. The equation of the model is:

$$\sigma(t) = \sigma_\infty + (\sigma_0 - \sigma_\infty) e^{-\frac{t}{\nu}} \quad (8)$$

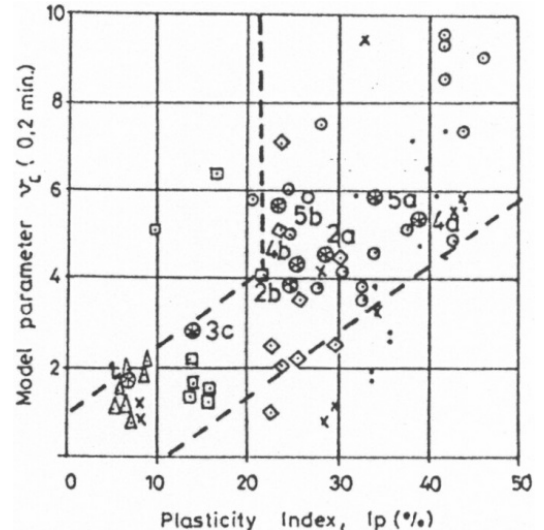


Fig. 12. ν - I_p relation, the 'off' points are related to the vicinity of layer boundaries and layers with secondary structure