Monotonic and dilatory excess pore water dissipations in silt following CPTU at variable penetration rate

P. Paniagua, R. Carroll, J.-S. L'Heureux
Norwegian Geotechnical Institute, Trondheim & Oslo, Norway

S. Nordal
Norwegian University of Science and Technology, Trondheim, Norway

ABSTRACT: The relationship between cone penetration rate and pore pressure decay is investigated through dissipation tests following penetration at different rates. Field tests and model scale tests in the laboratory are performed. The rates of penetration in situ were 2, 20 (standard) and 250 mm/s while the model scale tests had rates of 0.06, 6 and 50 mm/s. The in situ tests were carried out in a silt with clay content of 11.8 % and the model scale tests were conducted in a silt with 2.5 % clay. Both materials are natural Norwegian silts. The fast penetration rate tests show high pore pressure gradients as soon as the penetration stops and a dilatory response during dissipation. The tests conducted at the slowest penetration rate show monotonic decay. The standard and medium rates show smaller gradients and a dilatory response during dissipation. The results are compared with representative solutions for monotonic and dilatory dissipation responses for determination of t_{50}.

1 INTRODUCTION

Cone penetration tests (CPTU) in saturated intermediate materials such as silty soils typically occur under partial drainage at the standard rate of penetration. Undrained and drained soil responses can be induced by changing the penetration rate (v). High v are typically associated to undrained behavior and slow v are typically associated to drained behavior. The undrained or drained response can be contractive or dilative. A contractive response shows an increase in pore pressure (u_2) and a decrease in cone resistance (q_t) with an increase in v. Recent studies have focused on investigation of effect of increase and decrease of rate in contractive silty intermediate soils (DeJong & Randolph, 2012, DeJong et al. 2012, Schneider et al. 2008, Randolph & Hope, 2004). Opposite trends have been observed by Silva (2005), Schneider et al. (2007) and Paniagua (2014) which are typical of a dilative response. The contractive or dilative responses can either generate large, zero or negative excess pore water pressures (Δu). Regardless of rate, once cone penetration stops for a dissipation test, Δu will vary with time and eventually reach equilibrium conditions towards in situ u_o values. This variation with time can be either monotonic (i.e. the initial pore water pressure u_i is greater than u_o and u_i is the maximum pore water pressure measured) or dilatory (i.e. u_i rises with time, reaches a peak value u_{max}, and then decreases with time towards u_o). Such variations are generally affected by the permeability (k) and coefficient of consolidation (c_h).

The work presented in this study shows results of pore pressure dissipation tests following cone penetration at different rates (i.e. slow, medium/standard and fast) carried out in the field and in the laboratory. Two Norwegian silts with contrasting percentages of clay, 2.5 % and 11.8 % have been tested. Monotonic and dilatory dissipation responses have been recorded. The scope of work is to compare the monotonic and dilatory responses from in situ and laboratory dissipation tests, and assess the influence of the penetration rate on the time for 50% dissipation (t_{50}) for further interpretation of c_h.

2 ANALYSIS OF CPTU DISSIPATIONS TESTS

Evaluation of c_h is based on the change in Δu with time (t), see Equation 1, where u_t is the measured pore pressure (in this case at the u_2 position) at the time t:

$$\Delta u = u_t - u_0 \tag{1}$$

The initial pore pressure (u_i) has a major influence on the dissipation process and its definition is used to select the time for 50% dissipation which is used to calculate c_h. Lunne et al. (1997) highlighted complications encountered for analysis of c_h which include; estimation of u_i, disturbance effects, anisotropy and preferential flow. Carroll & Long (2015) discussed that the estimation of u_i is critical for further analysis of dissipation tests results. The normalized excess pore pressure ratio (U) is used to plot dissipation test results (Equation 2).

$$U = \frac{u_t - u_o}{u_i - u_o} \quad (2)$$

Interpretation of a dissipation tests can be made by taking the time to 50% dissipation from shoulder pore water (u_2) decay if one is certain that u_o has been reached at the end of the dissipation. A theoretical solution to a monotonic response of Δu with time has been proposed by Teh & Houlsby (1991) based on the strain path method. This method requires the use of a time factor T* (Equation 3), where a is the cone radius and I_r is the rigidity index. The theoretical solution plots T* for different degrees of consolidation (1-U) and a value of $T_{50}^* = 0.245$ for u_2 is defined for a 50% consolidation.

$$T^* = \frac{c_h t}{a^2 \sqrt{I_r}} \quad (3)$$

A dilatory response may be due to high vertically oriented pore pressure gradients of different magnitudes at various distances from the u_2 filter (Davidson, 1985, Burns and Mayne, 1998) or pore pressure redistribution that may be associated with partial drainage and pore pressures in gaps between the cone and sleeve. In the case of silts, changes in the soil fabric caused by grain reorientation around the cone create contractive and dilative zones that modify the drainage pattern that at the same time can be modified by the penetration rate (Paniagua et al. 2015). Such behavior complicates interpretation of dissipation tests. Different approaches, for example Burns & Mayne (1998), Sully et al. (1999), Mantaras et al. (2014) and Chai et al. (2012), have been proposed to account for non-standard dissipation behavior. These approaches are applied to results in this study.

2.1.1 *Burns & Mayne (1998)*

This mathematical solution is based on the cavity expansion-critical state. The excess pore water pressure is generated due to changes in the mean octahedral normal stress (u_{oct}, Equation 4) and in the octahedral shear stress (u_{shear}, Equation 5). The excess pore water pressures, Δu_t, at any time (t) can be compared with the initial values during penetration, $\Delta u_i = (\Delta u_{oct})_i + (\Delta u_{shear})_i$, and are represented by Equation 6 where T' is a modified time factor defined in Equation 7. OCR is the overconsolidation ratio, σ'_{vo} is the effective stress in situ, Λ is the plastic volumetric strain ratio and φ' is the friction angle. The procedure requires curve fitting to provide the best overall value of c_h.

$$\Delta u_{oct} = \sigma'_{vo} \frac{2}{3}\left(\frac{6\sin\varphi'}{3-\sin\varphi'}\right)\left(\frac{OCR}{2}\right)^{\Lambda} \ln(I_R) \quad (4)$$

$$\Delta u_{shear} = \sigma'_{vo}\left(1 - \left(\frac{OCR}{2}\right)^{\Lambda}\right) \quad (5)$$

$$\Delta u_t = \frac{(\Delta u_{oct})_i}{1+50T'} + \frac{(\Delta u_{shear})_i}{1+5000T'} \quad (6)$$

$$T' = \frac{c_h t}{a^2 I_R^{0,75}} \quad (7)$$

2.1.2 *Sully et al. (1999)*

A dilatory response is transferred to a monotonic dissipation case by correcting the dissipation curve. One method is the logarithm of time plot correction and the other method is square root of time plot correction. In the square root of time plot, the dissipation after the peak is back extrapolated to t = 0 in order to obtain the modified maximum initial value of pore pressure. This value is then used to calculate the normalized dissipation curve. These methods were noted to only show a significant difference in time for short dissipation periods (Sully et al., 1999). One should notice that these methods do not account for the initial part of the dissipation curve since the shift in time does not account for effect of redistribution of Δu before u_{max} resulting in a possible overestimation of t_{50} thus underestimation of c_h (Chai et al., 2004).

2.1.3 *Chai et al. (2012)*

This method (Equation 8) uses time to u_{max} and t_{50} interpreted using u_{max} and u_o to establish an empirical correction to give a time for 50% dissipation of a non-standard curve. The empirically corrected value for 50% dissipation is referred to as t_{50c}. Chai et al. (2004) noted that the magnitude of the correction was dependent on the ratio $t_{u\text{-}max}/t_{50}$, where $t_{u\text{-}max}$ is time to u_{max}.

$$t_{50c} = \frac{t_{50}}{1+18{,}5\left(\frac{t_{u,max}}{t_{50}}\right)^{0{,}67}\left(\frac{I_r}{200}\right)^{0{,}3}} \quad (8)$$

2.1.4 *Mantaras et al. (2014)*

This procedure determines t_{50} by finding the best fit expression for the measured data and using the first and second derivate without any consideration regarding u_o. The approach lacks of a physical basis. The minimum point of the first derivate and the point when the second derivate is zero correspond to t_{50}. The accuracy of the proposed solution depends mainly on how well the theoretical idealization such as Teh & Houlsby (1991) or Burns & Mayne (1998) describes the pore pressure distribution around the cone.

3 SOIL DESCRIPTION

Two natural silt materials were tested in this study: Vassfjellet silt in the laboratory and Halden silt in the field. Vassfjellet silt is a non-plastic uniform silt. Its grain size distribution is shown in Figure 1a. The clay, silt and sand contents are 2.5%, 90% and ~7%, respectively. High dilatant behavior is observed in samples tested in undrained triaxial tests at maximum density. Electron probe micro analysis (EPMA, Figure 1b) shows two main grain classes: bulky (AR >

0.5) and flaky grains (AR < 0.5). AR or aspect ratio is the ratio between the minor and the major axis lengths, (e.g., $AR_{sphere} = 1$). High quartz (27%) and low feldspar (15%) are found in this material.

Halden silt is a low plasticity silt. The water table is 2.5 m below ground level. It has an average I_P of 10.8% between 6.3 m and 6.8 m .The clay, silt and sand content are 12%, 67% and 20% respectively, see Figure 1a. Under anisotropic consolidation, a piston sample from 5.3 m had a dilatant response with and 'S' shaped stress path, indicating some contraction before dilation. A scanning electron microscope (SEM) image of material from 6.4 m shows a majority of bulky grains (Figure 1c). There is high quartz (41%) and feldspar (42%) in the Halden sample and the feldspar grains of are considered to be angular and of various shapes.

Table 1 presents a summary of the index properties for Vassfjellet and Halden where it is possible to compare the two silts. For example, Vassfjellet silt had high muscovite (35%) compared to Halden silt (8%). The muscovite flaky shapes will infer a stronger anisotropy in the deposit.

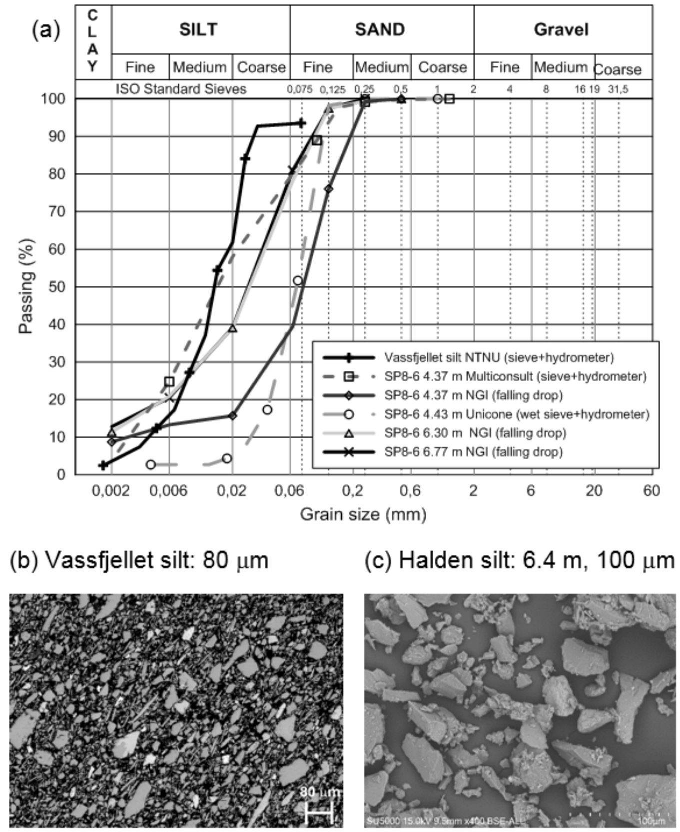

Figure 1: (a) Grain size distribution, (b) backscattered EPMA scan and (c) SEM

4 CPTU DISSIPATION TESTS

4.1 *CPTU dissipation tests in model scale*

Vassfjellet silt specimens were built inside a Plexiglas cylinder of 100 mm inner diameter internally padded with a 6 mm layer of neoprene selected to compensate for the effect of boundary closeness and to simulate a compressible surrounding soil. Saturated specimens of 180 mm height were consolidated from slurry deposition. An overburden pressure of 80 kPa was applied during testing. During sample preparation and cone penetration, pore pressure is monitored in the sample specimens. Laboratory CPTU tests were performed with an F0.5CKEW2 Fugro miniature cone, 11.28 mm diameter, owned by University of Colorado. The rates of v were selected according to the ranges of non-dimensional velocity, V, observed by DeJong & Randolph (2012) corresponding to V = 0.15, 15 and 126, for drained, partially drained and undrained conditions, respectively. The cone stopped at 100-110 mm depth and dissipations of u_2 were immediately recorded.

Table 1: Comparison of soil parameters

Parameter	Vassfjellet silt	Halden silt at 6.5 m or 6-7 m
Water content, w (%)	21-23	27-33
Total unit weight, γ (kN/m³)	19-19.3	18.9-19.0
Density of soilds, γ_s (kN/m³)	24.6	26.3-26.5
Organic content,	< 2%	< 0.5%
Friction angle, φ (o)	32	35
c_v* cm²/s	0.063	0.055
k* at 0% strain m/s	---	1.5×10^{-8}
CPTU	6 mm/s	20 mm/s
q_t (MPa)	0.75-1.75	0.8-1.0
B_q	-0.01-0.04	0.1-0.14

*Measured in CRS tests, k at 0% axial strain, c_v at in situ effective vertical stress.

4.2 *CPTU dissipation tests in the field*

In situ penetration tests at Halden were carried out using NGI's standard rig setup. The penetration rate was constant for 1.2 - 1.5 m before the target depth of the dissipation tests. The penetration occurred at three different rates: 2 mm/s (slow), 20 mm/s (standard) and 320 mm/s (fast). The mechanical operation for a test comprised of stopping penetration at the target depth (i.e. 6,5 m for the slow, 6,51 m for the standard and 6,62 m fast tests) and start logging by manual trigger by the operator. The base clamps are then engaged and the top hydraulic clamps are disengaged to avoid possible movement of the hydraulic system with time and applying pressure on the cone. In essence there can be a short time laps of a couple of seconds between end of penetration and start of logging and some change in stress conditions due to movement of the clamps engaging and disengaging. However care and attention to these processes was made during testing to minimize possible effects on measurements.

5 TEST RESULTS

Results of model scale dissipation tests in Vassfjellet silt are shown in Figure 2. A monotonic decay is observed after the slow tests where low u_2 values, u_{max} ~ 5 kPa, are reached. A dilatory response during dissipation is observed for the tests conducted at medium and fast v. This dilatory response is more accentuated

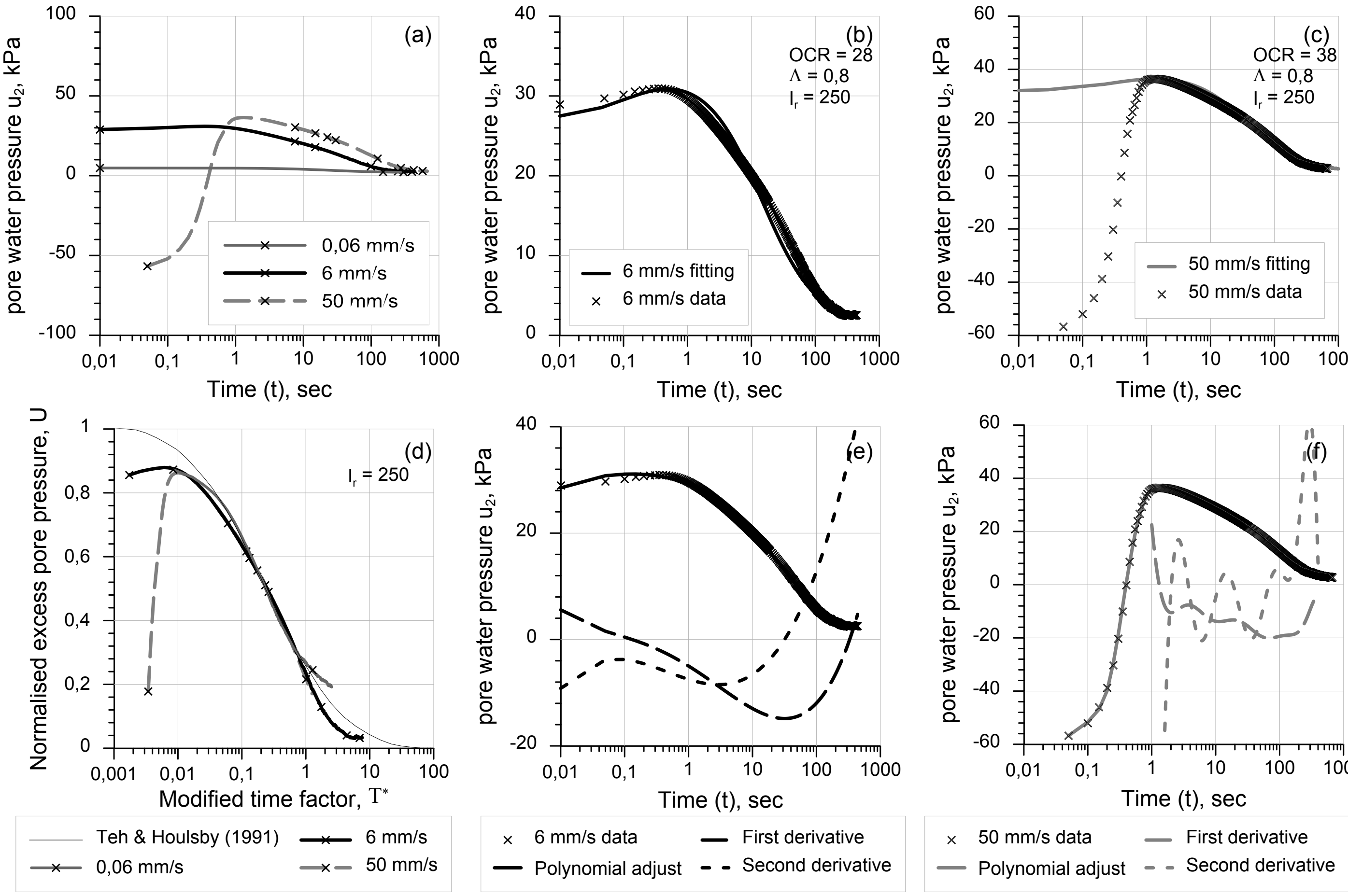

Figure 2. Vassfjellet silt: (a) measured u_2 with time. Burns & Mayne (1998) solution (b) medium v (c) fast v. (d) U with Teh & Houlsby (1991) using square root time method. Mantaras et al. (2014) (e) medium v and (f) fast v.

for the fast test where the dissipation starts at negative pore pressures (due to suction and the dilatant behavior of the soil) and increases to positive values. The fastest test has the highest u_2 value, 36 kPa, compared to the medium v, 31 kPa. Data was continuously recorded between penetration and start of dissipation hence final u_2 penetration is equal to the u_i.

The Halden dissipation test results are presented in Figure 3a. A monotonic decay is observed in the slow test despite the sharp reduction in u_2 after 3 s. This may be due to the clamping arrangement. Values recover to the previous state within 5 s. The medium and fast tests both show a dilatory response. There is an increase in u_2 after 4 s for the standard test while the fastest v shows a steady rapid build up to u_{max}. A sudden small reduction in u_2 post u_{max} is recorded in the fast test. Overall the sharp reductions in u_2 are likely to be linked to rig operation while the increases in u_2 are thought to be linked to natural soil behavior around the cone tip and shoulder. In these tests measured u_i agrees well with the final u_2 measurements before stopping penetration (Figure 3a). This is a simple check which provides reliable background information on conditions just before the dissipation starts. The fastest test generated the highest u_2 value, 193 kPa, compared to the standard and slow v, ~158 kPa. A degree of consolidation higher than 50% was reached in the laboratory (values between 81-97%) and in the field (values between 69-77%).

6 DISCUSSION

The dissipation results in Vassfjellet silt have been interpreted following the procedures described in the analysis section to estimate t_{50}. The u_2 decay method assumed that $u_i = u_{max}$ and therefore there is some account of the time for pore pressure redistribution at the start of the test. The square root method (Sully et al. 1999) was applied in order to further analyze the data with Teh & Houlsby (1991) solution. Figure 2d shows that for short dissipation times, all dissipation tests are about 15% below the theoretical Teh & Houlsby (1991) solution while at 80 % dissipation the measured data for slow v is above the solution and the medium and fast test are below the solution.

The curve fitting proposed by Burns & Mayne (1998) appears to give satisfactory results for the dissipation data after slow and medium tests (Figure 2b). It was not possible to fully fit the fast test results due to the negative pore pressures which are not captured by the analysis (Figure 2c). In order to fit these transition from negative to positive values, Δu_{shear} must be much larger than Δu_{oct}. Burns & Mayne (1998) theory assumed that Δu_{oct} is due to an increase in pore pressure for changes in the octahedral stress. However, investigation of the zone around the cone in Vassfjellet silt tests identified compaction and dilation (Paniagua et al. 2015). Hence a dilation (i.e. suction) zone might reduce the expected Δu_{oct}.

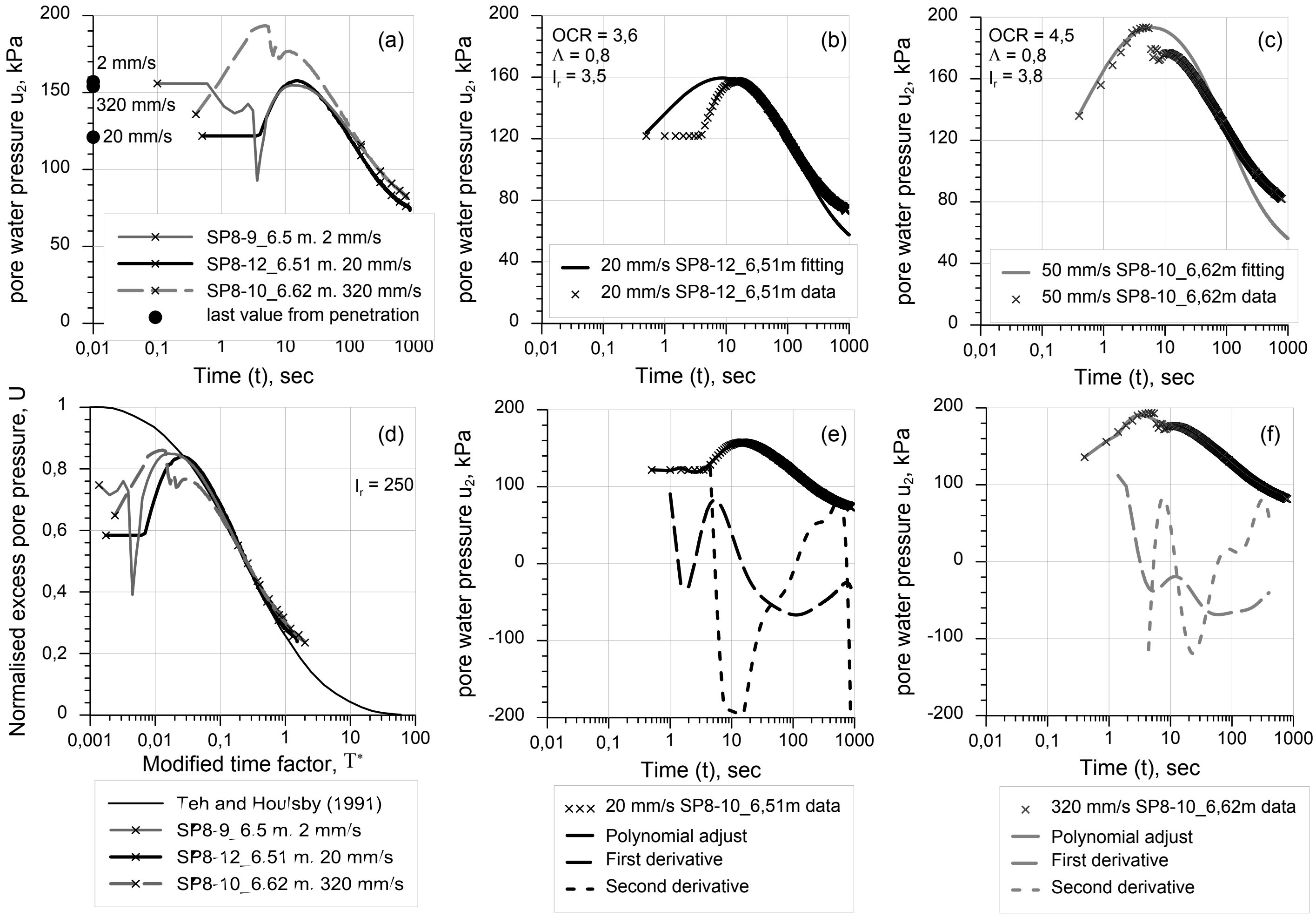

Figure 3. Halden silt: (a) measured u_2 with time. Burns & Mayne (1998) solution (b) standard v (c) fast v. (d) U with Teh & Houlsby (1991) using square root time method. Mantaras et al. (2014) (e) standard v and (f) fast v.

Mantaras et al. (2014) (Figure 2e, 2f) and Chai et al. (2012) procedures were relatively simple to apply. The estimated t_{50} values obtained with these methods show high contrast with each other (Figure 4).

The interpretation for t_{50} from Halden silt was similar to that for Vassfjellet silt. The dissipation data is 15-20% below Teh & Houlsby (1991) solution at the beginning of the test while at 80% dissipation the measured data are above the solution (Figure 3d). Hence suggesting that dissipation is slower than estimated based on the u_i and u_o conditions applied in the analysis. The trend of agreement is opposite to Vassfjellet silt for the medium and fast test. Application of Burns & Mayne (1998) procedure was challenging for all tests due to reductions in u_2 and the sudden increase in u_2 for the standard test (Figure 3b, 3c). The fitting process could not capture these features. Some unrealistic parameters have to be used for fitting. Hence it is challenging to apply this theory to the Halden data set. It is also noted that the fitting vas sensitive to small changes in the parameters. As experienced with Vassfjellet silt data, Mantaras et al. (2014) (Figure 2e, 2f) and Chai et al. (2012) analyses are simpler to apply. Results from Chai et al. (2012) method estimated the shortest t_{50} times at standard and fast v while there is scatter in the trend for the slowest v, see Figure 4. This was also the case for results from Vassfjellet silt tests with this method.

Conditions of testing are under greater control for the model scale tests compared to field tests, in terms of soil uniformity and cone set up. In situ tests are reliant on consistent controlled operation of the CPTU rig, stress conditions at start of dissipation, similar soil conditions between tests at the required depths and correct u_o estimation. The challenges in applying the theories have been greatest for the field data set, which is likely due to a combination of the conditions discussed above and the material dilatory response.

6.1 *Rate effects on t_{50} times*

The t_{50} values obtained from the different theories are shown in Figure 4 for Vassfjellet and Halden silt. For the model scale tests, the range of scatter at the slow and medium v is relatively low while at fast v (associated with $u_2 < 0$s and pore pressure migration from adjacent soil) there is greater scatter. There is a similar trend of reducing t_{50} with increased v for the two data sets if the fastest v with negative u_2 is omitted. In both data sets, the shoulder u_2 decay and Burns and Mayne (1998) estimated high t_{50} times compared to the Sully et al. (1999) square root time method with Teh and Houlsby (1991). However, Mantaras et al. (2014) show the highest t_{50} values in Vassfjellet silt and the lowest t_{50} values for Halden silt, see Figure 4.

7 CONCLUSION

Our results show that model scale dissipation tests give short t_{50} values due to the smaller cone size and therefore a smaller cone influence area. The negative pore pressures in Vassfjellet silt may be due to the low clay (2.5%) content and proportion of flaky grains which have a tendency to create dilatancy during penetration at high penetration rates. Once penetration stops, pore pressure redistribution occurs between zones further away from the cone and the zone adjacent to the cone shoulder as also observed by Silva (2005). Halden silt has a coarser silt and sand content compared to Vassfjellet silt however the 12% clay content may be a controlling factor on the extent to which u_i and u_{max} vary for these tests. However, no negative u_2 values are recorded at the fastest rate.

The range of scatter for the in situ data reflects the challenges in interpreting dilatory in situ tests with the selected theories. This leads to uncertainty as to which method is most appropriate to evaluate a dilatory test. It is noted that irrespective of v, the scatter in t_{50} does not reduce for in situ tests while the model scale tests show greater agreement at the slowest v. Both silts have a monotonic response at slowest v. The Burns and Mayne (1998) method proved unrealistic parameters for fitting that did not reflect expected material parameters, particularly in situ.

It must be noted that, with the exception of the fastest v (expected to be undrained), these tests are carried out under partially drained conditions. The theories used are designed for fully undrained conditions tests. This leads to challenges for interpretation. Future testing to investigate the usefulness and practical conditions required to obtain fully undrained penetration should be carried out, as proposed by DeJong & Randolph (2012). Corrections for partial drainage proposed by DeJong et al. (2012) may also be considered in analysis since t_{50} value increases with the increase in the degree of partial consolidation during penetration. However, the correction applies to contractive materials and monotonic dissipation curves.

The measurement of u_i during a dissipation test, good quality data recording and holding the CPTU-rods fixed are factors of critical importance for subsequent analysis with theoretical solutions.

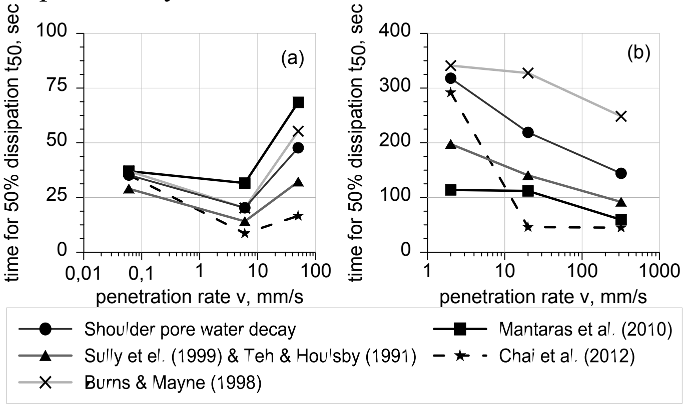

Figure 4: t_{50} and v for (a) Vassfjellet silt and (b) Halden silt

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