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Variable rate of penetration and dissipation test results in a natural silty soil

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ABSTRACT: Variable rate of penetration over 1.2 to 1.5 m intervals were carried out in a natural clayey silt followed by dissipation tests. The tests are grouped into two main sets: an upper set from 5 to 6.5 m and a deeper set from 8.5 to 10.2 m. Index, strength and consolidation parameters are presented for reference to soil behavior and classification. This paper investigates the effect of rate on u_2, q_t and B_q using penetration rates of 2, 20, 100 and 320 mm/s. Similarly the effect of rate was investigated for assessment of dissipation tests and estimation of the time for 50% dissipation (t_{50}). Dissipation tests were predominantly dilatory at all rates and depths. Drainage conditions were evaluated at the different rates using the normalised rate of penetration (V) calculated using one method to estimate the horizontal coefficient of consolidation (c_h). Reference to B_q as a guide of drainage conditions is discussed together with V. A total of six methods to estimate t_{50} and subsequently c_h were used in this study, calculated t_{50} values are presented for all methods. One method is used for presentation of trends and consideration of which methods may yield the most representative c_h values is discussed in relation to laboratory c_v.

1 INTRODUCTION

Cone penetration tests (CPTU) in saturated intermediate materials such as silty soils typically occur under partial drainage at the standard penetration rate of 20 mm/s. Undrained penetration has been referenced in literature to be associated with normalised velocity (V) for V > 30 (Finne & Randolph 1994), V > 10 (Kim et al. 2008) and V > 20–40 (Holmsgaard et al. 2015). These values are representative of a selected number of examples from centrifuge and in situ tests. V less than the above suggested ranges are associated with partially drained to fully drained penetration depending on the V value and boundary used. Fully drained penetration is typically associated with V < 0.01. Carroll (2013) presented a detailed summary of drainage conditions and V values with reference to test type, i.e. centrifuge, in situ or calibration chamber. The summary showed that V values varied based on test type and c_h used in the normalisation.

Senneset et al. (1989) noted that the point of cut off for correlation of undrained shear strength from CPTU was at a pore pressure ratio $B_q < 0.4$ due to association with partially drained penetration. The use of B_q as a parameter associated with delineation of drainage conditions in combination with V has not been widely reported in literature.

A change in soil responses to drained, partially drained or undrained can be induced by changing the penetration rate (v) where equipment can practically reach required rates. Typically fast v are associated with undrained behavior and slow v with drained behavior. The undrained response in a soil can be contractive or dilative. This is assessed by introduction of a varied rate relative to the standard rate to assess the change in pore pressure (u_2) and cone resistance (q_t). With increased rate of penetration (v): (1) a contractive response shows an increase in u_2 and a decrease in q_t and (2) a dilative response shows a decrease in u_2 and increase in q_t. Negative u_2 (i.e. suction) may occur in some cases.

Investigation of the effect of increase and decrease of penetration rate in intermediate soils showing contractive response has been documented by DeJong & Randolph (2012), DeJong et al. (2013), Schneider et al. (2008) and Randolph & Hope (2004). While a dilative response was observed by Silva (2005), Schneider et al. (2007) and Paniagua (2014).

Regardless of penetration rate, once penetration stops Δu will vary with time and eventually reach equilibrium conditions at in situ pore water pressure (u_o). 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 rises with time at the start of the test, reaches a peak value u_{max}, and then decreases with time towards u_o). The rate of recovery to u_0 is a function on permeability (k) and c_h.

This paper presents data from CPTU tests at the standard penetration rate together with faster and slower rates. The tests were conducted at the silt research site, Halden; that is part of the Norwegian GeoTest Sites (NGTS) project. The NGTS project has 5 sites in total: sand, soft clay, quick clay, permafrost and silt. The sites have been characterized and are suitable for use by researchers, industry and developers of geotechnical equipment. They will be maintained for 20 years and interest to test at any of them should be expressed to the NGTS Project Manager. The Halden silt site has been characterized by Blaker et al. (2016) and Paniagua et al. (2016) presented the analysis of some dissipation tests at the site.

The present study evaluates the soil response, dilative or contractive, using a variable rate of penetration prior to dissipation tests. An assessment of the drainage condition at the various penetration rates used, and the corresponding influence of v on dissipation and c_h is discussed. Dissipation test results are presented and several interpretation methods for monotonic and dilatory decay of excess pore pressure to estimate the time for 50% dissipation (t_{50}) have been implemented and discussed. Analysis of results are presented in terms of a single method selected by the authors. The estimated c_h values are compared to laboratory derived c_v.

2 SOIL DESCRIPTION

Halden site is a natural fjord marine deposit which has a low plasticity silt. The water table is approximately 2.5 m below ground level. The silt deposit is relatively uniform between 4.5 m and 15 m, varying from a SILT, sandy clayey around 5 m depth to a SILT, clayey from 6.5 m, see Figure 1. Under anisotropic consolidation, a piston sample from 5.3 m had a dilatant response with an ‘S’ shaped stress path, indicating some contraction before dilation. Table 1 presents typical soil parameters for Halden silt.

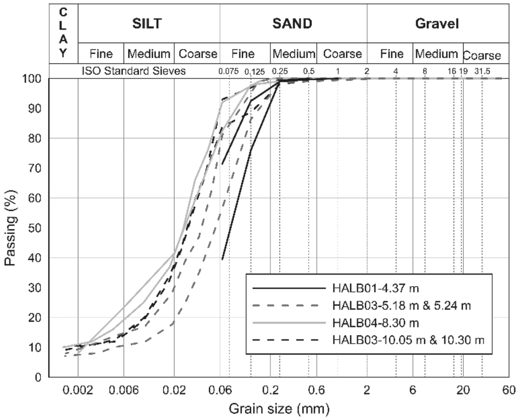

Figure 1. Grain size distribution at Halden.

Table 1. Soil parameters at Halden.

Parameter	Between 5–6.5 m	Between 8.5–10 m
Water content, w (%)	21–23	27–33
Total unit weight, γ (kN/m³)	19–19.3	18.9–19.0
Density of solids, γ_s (kN/m³)	24.6	26.3–26.5
Organic content,	<2%	<0.5%
Friction angle, φ (°)	36	35.5
Rigidity index $I_r = G_{50}/s_u$	147	126
c_v* m²/s	$0.8 \cdot 10^{-5}$	$0.7–1.0 \cdot 10^{-5}$
k* at 0% strain m/s	$1.8 \cdot 10^{-8}$	$1.3 \cdot 10^{-8}$

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

2.1 *I_r determination*

The rigidity index I_r is a critical parameter for estimating c_h using cone data. Research (Teh & Houlsby 1991) has shown that I_r influences the plastic failure zone that develops during cone penetration and therefore the stresses and pore pressures associated with this process. In this paper, I_r was estimated from advanced laboratory testing and conservative undrained shear strength analysis. Comparison is made to the correlations proposed by Krage et al. (2014) based on actual laboratory measured data (Method A) and seismic in situ data (Method B). The values obtained from advanced laboratory testing are shown in Table 1. Values obtained by Method A, in the range of $205 \leq I_r \leq 217$, are higher than the ones presented in Table 1. Method B gives values ($139 \leq I_r \leq 157$) that show good agreement with the values presented in Table 1.

3 CPTU & DISSIPATION TESTS

CPTU tests at Halden were carried out using NGI’s standard rig setup and an Envi cone. The penetration rate was constant for 1.0–1.5 m before the target depth of the dissipation tests. The penetration rate was in the order: 2 mm/s, 20 mm/s (standard rate), 100 mm/s and 320 mm/s. The mechanical operation for a test comprised of stopping penetration at the target depth 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. All pore pressure measurements are at the shoulder (u_2 position).

The target depths for the dissipation tests were 5 m, 6.5 m, 8.5 m and 10 m. Preceding penetration rates for each respective target depth are listed in Table 2. A total of 11 dissipation tests were carried out. The results in Table 3 show a range of u_2 values which are described under the table. Assessment of $u_2^{\times}$ suggests a contractive response, as with increased v there is an increase in u_2, for intervals at 5, 8.5 and 10 m using $u_{2\text{-avg}}$ as base line for standard rate. However the response of q_t does not match the associated behavior for contractive as q_t tends to increase with increased v. At the 5 and 6.5 m intervals the q_t response is not consistent with the clearer trends from deeper intervals that suggest a dilative response.

Table 2. Penetration rate before target depth for dissipation tests.

Target depth m	u_0 kPa	Slow rate mm/s	Standard rate mm/s	Fast rate mm/s
5.0	34	2	20*	
6.5	48	2	20	320
8.5	65		20*	100
10.0	81			100 & 320

*2 tests at 20 mm/s were carried out at this depth

Table 3. Average CPTU values over 1.2–1.5 m before target depth.

Depth m	Rate mm/s	$q_{t\text{-avg}}$ MPa	$u_{2\text{-avg}}$ kPa	$u_2^{\times}$ kPa	$u_{t=0}$ kPa	u_{max} kPa	B_q -	V†	F_r %
5.00	2	1.65	106	94	94	121	0.07	29	1.33
4.96	20	1.26	101	85	92	134	0.09	111	1.17
5.01	20	1.51	104	110	95	102	0.09	178	0.98
6.50-mono	2	0.83	123	157	156	156	0.12	13	0.35
6.51	20	0.76	134	121	122	158	0.15	95	1.11
6.62	320	0.88	150	154	136	193	0.15	1200	1.26
8.50-mono	20	0.90	189	181	176	173	0.18	273	1.23
8.53	20	0.87	192	209	210	232	0.19	139	0.96
8.51	100	0.99	230	226	220	243	0.21	543	0.94
10.20	20*	0.97	222	–	–	–	0.19	180	1.11
10.20	20*	0.96	243	–	–	–	0.23	180	1.19
10.24	100	1.09	288	305	236	265	0.24	959	0.88
10.13	320	1.14	296	308	307	318	0.24	2969	NA

*Reference CPTU data, $u_{2\text{-avg}}$ and $q_{t\text{-avg}}$ values averaged over 1.5 –1.2 m before dissipation interval, × last u_2 measured before stop penetration of CPTU. $u_{t=0}$ is the measured u at start of dissipation test. u_{max} is the maximum u during dissipation.† using square root method. Mono: monotonic dissipation.

Table 3 shows the change in B_q with v and results suggest that there is little effect in this parameter from the range of rates achievable with the CPTU rig. The order of magnitude in change, where a change occurs, is 0.01–0.03. Overall B_q values are in the order of 0.1 to 0.15 at 5 to 6.5 m and 0.2 to 0.24 in the interval of 8.5 to 10.2 m. This response in CPTU is associated with partial drainage and should not be used for undrained shear strength analysis (Senneset et al. 1989).

Table 3 shows a clear increase in V with increased rate as expected. With a reduced rate, to 2 mm/s, V values move closer towards the undrained-partially drained boundary in the upper layer, with V values in the region of 14–27. For the standard rates, V is approximate 100 in the upper interval and 140–280 in the lower interval. Both intervals fit well in the undrained range based on the V values presented previously in the paper. However both cases do not agree with the reasoning suggested by Senneset et al. (1989) on partial drainage and associated B_q range. The drainage condition at the time of a dissipation test is an important consideration as theories used to evaluate the c_h are based on a fully undrained starting point.

4 EVALUATION OF RESULTS

The dissipation test results are presented in Figure 2 and Figure 3 for the upper and lower depth intervals of 5 to 6.5 m and 8.5 to 10.2 m,

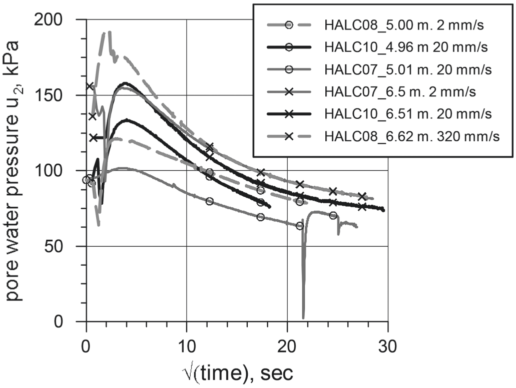

Figure 2. Measured u_2 vs. square root of time, at 5 m & 6.5 m.

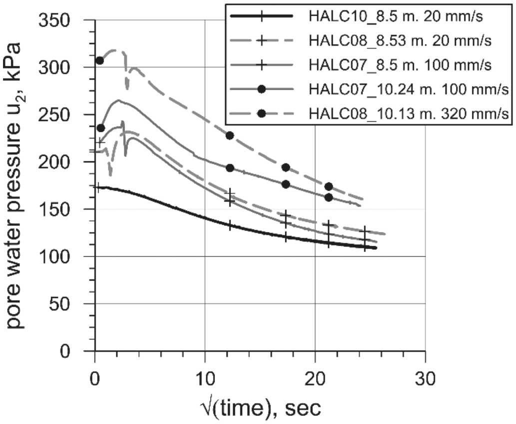

Figure 3. Measured u_2 vs. square root of time, at 8.5 m & 10 m.

respectively. A monotonic response is evident in two of the dissipation tests: HALC07–6.5 m at 2 mm/s and HALC10–8.5 m at 20 mm/s. All other tests show dilatory response. Some tests show a sudden drop in u_2 after the test has begun (about 2 to 5 s). This is particularly evident in the upper test interval while in the lower test interval this drop occurs after $u_{2\text{-max}}$ in two of the tests. The sharp reductions in u_2 are likely to be linked to rig operation with cone unloading while the increases in u_2 are thought to be linked to natural soil behavior (i.e. pore pressures redistribution) around the cone tip and shoulder.

The match between the final u measured ($u_2^{\times}$) (i.e. last point recorded before start of dissipation test) and the initial u ($u_{t=0}$) (i.e. the first u measured at the start of the dissipation test) is shown in Table 3. Results show good agreement in most cases with exception of tests at 5.01 and 6.62 m (with a difference of approximate 15 kPa) and 10.24 m (with a difference of approximate 90 kPa), the latter case shows $u_2^{\times}$ considerably greater than $u_{t=0}$. In these particular tests, undrained conditions are thought to be present based on analysis of V and results suggest that pore pressure redistribution occurs quickly. These tests show a dilatory response along with tests where there is good agreement between $u_{t=0}$ and $u_2^{\times}$. Overall the data is of good quality and shows that conditions prior to the dissipation test are in line with those of the data collected at the start of the dissipation test.

The u_{max} in dilatory test results at 5–6.5 m are approximate 30–45% greater than $u_{t=0}$, with the test at 5.01 m showing a difference of 7%. At 8.5–10.2 m, u_{max} is approx. 3–12% greater than $u_{t=0}$. This suggests that the dilatory response is amplified in the upper depth interval where soil is likely more permeable. The time to reach u_{max} is approx. 5 to 16 s in the upper interval and 3 to 10 s in the lower interval. With increased rate of penetration, the time to u_{max} reduces for dilatory response results. Overall, the dilatory response is rapid in these tests, occurring over several seconds. This highlights the need for good data collection at the start of a test, required to selection or inference of u_i used for later c_h estimation.

4.1 *Interpretation of t_{50} times by different methods*

Estimation of t_{50} was carried out using the following six procedures: (1) shoulder pore water decay (shoulder method), (2) square root method (Sully et al. 1999), (3) logarithm of time method (Sully et al. 1999), (4) Burns & Mayne (1998) method (only tests at 6.5 m target depth as fitting of parameters was considered unrealistic), (5) Mantaras et al. (2010) method and (6) Chai et al. (2012) method. Description of the methods used is summarized in Paniagua et al. (2016). The t_{50} results from each individual method are presented in Table 4.

Normalised excess pore pressure U is plotted with the modified time factor, see Figure 4 and Figure 5, which used for estimation of c_h when t_{50} or t_{50c} is estimated from U with time. Comparison of U versus T^* for the dissipation tests with the Teh & Houlsby (1991) solution shows that in Figure 4 at 20% dissipation tests are in the dilatory phase and below the theoretical curve, with the except of 6.51 m test. After 60 to 70% dissipation the results are above the theoretical solution, again with the exception of 6.51 m test which follows the theoretical solution. As to be expected there is a perfect fit at 50% dissipation for all tests.

For the depth interval 8.5 to 10 m shown in Figure 5 most tests are below theoretical Teh & Houlsby (1991) solution in the initial 20% of dissipation. However test at 8.5 m fits the trend as it is not dilating. After 60% dissipation many tests are above the solution. The lack of fit after 60% dissipation with curves generally above the theoretical line for both depths intervals suggest that the dissipation in Halden silt is slower than the estimated based on the u_i and u_o conditions applied in the analysis, i.e. the t_{50} times may be longer. There is also a lack of fit at the initial 20% dissipation leading to challenges in getting a good fit overall.

In general Mantaras et al. (2010) and Chai et al. (2012) methods show lower t_{50} times compared to the classic shoulder, square root and logarithm (log) time methods. However in the two cases at 2 mm/s, one of which is monotonic, and the monotonic test at 8.50 m, Chai et al. (2010) shows higher t_{50c} times compared to the t_{50} from tests with

Table 4. Estimated t_{50} times using different methods.

Depth m	Rate mm/s	Shouldert† s	Sq. root† s	log time† s	Burns & Mayne (1998) s	Mantaras et al. (2010) s	Chai et al. (2012) t_{50c} s	St. dev. s
5.00	2	484	391	476		286	229	102
4.96	20	258	147	242		90	67	78
5.01	20	337	237	327		143	125	89
6.50*	2	264	264	264	283	114	244	58
6.51	20	188	126	173	308	112	42	83
6.62	320	126	99	122	248	89	43	64
8.50*	20	334	335	334		147	313	75
8.53	20	253	171	244		95	92	69
8.51	100	172	133	166		145	62	39
10.24	100	329	235	324		51	171	104
10.13	320	271	228	268		340	151	63

*Monotonic dissipation. †Sully et al. (1999).

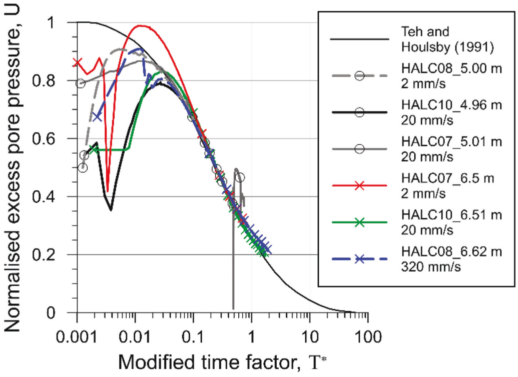

Figure 4. Normalised excess pore pressure vs. modified time factor T*, at 5 m & 6.5 m target depths.

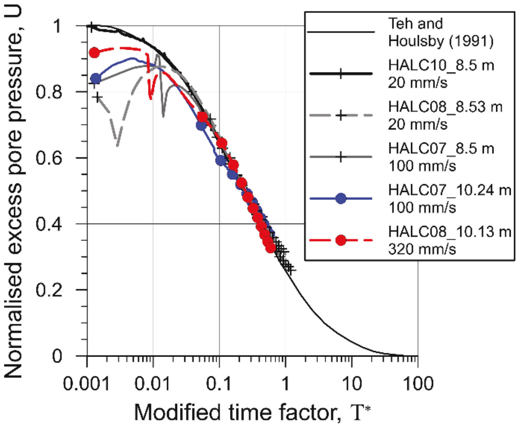

Figure 5. Normalised excess pore pressure vs. modified time factor T*, at 8.5 m & 10 m.

the standard and faster penetration rates at similar depths.

The t_{50} from the log time method is typically slightly lower than t_{50} from the shoulder method as t_0 is taken at time corresponding to u_{max} and not t_0 at the start of the test, as is used for the shoulder method. Hence the difference in t_{50} for these two is the time to u_{max} in a test. The log time method is based on a back extrapolation for u_i which estimates shorter t_{50} times compared to the shoulder and log time method. For the three results for Burns and Mayne (1998) results tend to be greater than the classic methods. Details on the methodology of the above methods is presented in Paniagua et al. (2016). The standard deviation of t_{50} based on the methods used is presented in Table 4 with values between approx. 40 and 100 s.

Overall there is a trend of increasing t_{50} with depth (without the results from 5 m as they are uncharacteristic of expected behavior due to higher sand contents and presence of the upper sand silty layer ending at 4.5 m (Blaker et al., 2016). It is possible that the monotonic test at 8.50 m at 20 mm/s shows a longer t_{50} due to missing data at the start of the test. This test was one of the two tests to show a monotonic response in the data set. The long t_{50} time is not in agreement with its neighboring test at 8.53 m which is also at 20 mm/s; which leads to likely grounds for exclusion of the monotonic tests for further analysis.

Results in Figure 6 are plotted using the square root method. This method was chosen for simplicity of visualization, it is widely known in practice as it is long established. Mean t_{50} values, based on all methods, show values reasonably close to the square root t_{50} values. Hence it is reasonable to use this method for discussion of results in the paper to assess trends with rate and depth.

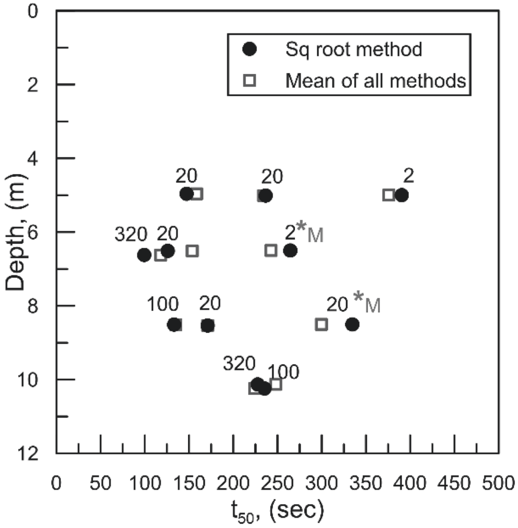

Figure 6. Estimated t_{50} using square root method with depth. Labels show the rate of penetration in mm/s. *M: monotonic tests.

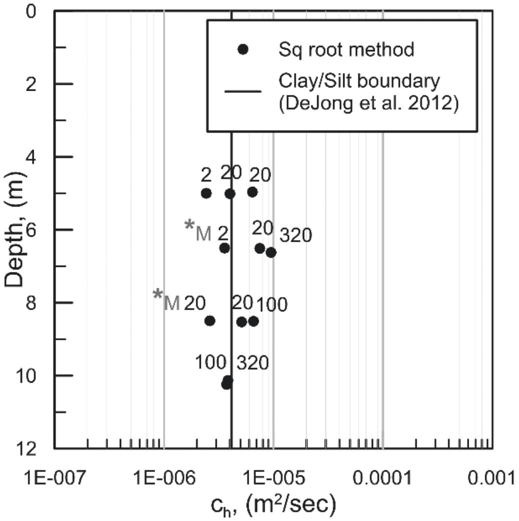

Figure 7. c_h based on estimated t_{50} using square root method with depth. Labels show the rate of penetration in mm/s. *M: monotonic tests.

4.2 *Rate effect on t_{50} times and c_h*

Table 4 shows that for rates of 320 mm/s, the standard deviation of t_{50} is lower than t_{50} at standard or slower rates. Figure 6 shows that with increased rate, t_{50} is lower. Table 3 shows that with increased rate, u_2 increased. These trends suggest that the high excess pore pressure generated during penetration at high rates dissipates faster than slower rate tests.

With decreased rate, there is increased scatter in the t_{50} values, with the values being typically longer. However based on the range of rates achievable, the order of magnitude may not have been enough to fully investigate the effect of faster or slower than standard rates.

The assessment if some tests are truly undrained using V was introduced earlier in the paper and values suggest some tests are truly undrained. For example results from 6.5 to 10.2 m that are dilatory suggest undrained soil behavior as V high. For these tests an increase in the penetration rate from 20 or 100 to 320 mm/s does not affect the interpreted t_{50} value considerably. These tests are in a uniform layer with high silt content and increasing fines and clay content with depth which contrasts to the shallower tests at 5 m with higher sand content and presence of a coarser layer directly above.

Trends for c_h will follow the behavior of t_{50} and the variation of results with depth are shown in Figure 7, based on estimated t_{50} using square root method. There is a trend of higher c_h with increasing v at 6.5 m and 8.5 m while at 10.2 m there is no change in c_h. The c_h values for the 5 m layer do not match the soil type and this confirms the assumption that these test are influenced by partial drainage and theories for use in fully undrained conditions do not apply to these tests, despite the V values shown in Table 3. In this case the B_q criteria from Senneset et al. (1989) is a good indicator. The monotonic tests suggest a c_h representative of a clay which contrasts with the c_h for tests at the same depth which are in the silty zone. Results from 10.2 m suggest low c_h values on the boundary between silt and clay. Overall for tests that are thought to be undrained, there is relatively little difference in c_h based on the rates achieved in the tests (excluding the monotonic tests).

5 CONCLUSIONS

A total of six methods were used to estimate c_h from dilatory dissipation tests following various penetration rates. The methods require input of I_r and t_{50} for estimation using the modified time factor T^* or other theoretical equations. Laboratory estimated I_r from advanced tests at this site agreed well with Krage et al. (2014) correlation which uses seismic in situ data (Method B) while the correlation using laboratory results (Method A) suggested slightly higher I_r values.

For monotonic dissipation tests the shoulder, log time, Burns and Mayne (1998) or Mantaras et al. (2010) methods may be used. Monotonic test in this paper were considered unreliable as longer uncharacteristic t_{50} times were found. It is suggested to carry out more than one test to confirm results in silty soil. Other unreliable tests were considered to be from the upper 5 m depth interval where tests were likely influenced by partial drainage and the presence of a coarser layer above. These tests were mostly dilatory.

Analysis of dilatory tests was carried out using all methods. Burns and Mayne (1998) method was limited to 3 test evaluations as unrealistic parameters were required for fitting. For cases with dilation effects, Chai et al. (2010) method estimate a short t_{50c} in comparison to alternative methods. Mantaras et al. (2010) method showed some scatter for the deeper set of test, as t_{50} from fastest test differed from t_{50} at slower rate both at similar depths. Suggesting that the monotonic tests may be unreliable. Overall the t_{50} values were somewhat greater than those estimated from Chai et al. (2010) method. These two methods gave t_{50} and subsequent c_h values that showed a reasonable match with laboratory c_v, ($0.7.10^{-5}$ to $1.0.10^{-5}$ m^2/s) compared to the lower c_h values estimated using the square root method. This suggests that these methods may capture the behavior in dilation better than the three classical empirical methods noted in the paper.

Based on the range of change in v, the response in u_2 and q_t show contrasting results for behavior of the soil from contractive to dilative respectively, as a result it is not possible to define the soil behavior.

V and B_q suggested change points from undrained to partially drained are not in agreement. If the tests at 10 m are in fact truly undrained, this would suggest that B_q in range of 0.2 to 0.24 at 20 mm/s (V = 180) is representative of an undrained response. Hence a lower threshold for use of undrained analysis in dissipation may be valid based on B_q as a guide. However further investigation of this is required for validation.

Dissipation results show that it is difficult to get a good fit for the full curve with the theoretical Teh and Houlsby (1991) solution, initial phase is conservative while later phase non conservative, e.g. after 60% dissipation curves are generally above the theoretical line. This suggests dissipation is in fact slower than what the classical methods suggest based on u_i conditions. However this is contrary to the suggestion based on c_v and comparison to the c_h estimated form Chai et al. (2010) and Mantaras et al. (2010), as noted previously.

At rates of 100 to 320 mm/s the standard deviation of t_{50} is lower than at standard or slower rates. This suggests that faster penetration rates in this silty site, with increases in u_2 as rate increases, reduces the scatter in t_{50} across the various methods investigated.

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