Interpretation of thermal and pore pressure dissipation tests

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Abstract

This paper discusses recent developments in pore water pressure and temperature dissipation testing of soils, conducted during Cone Penetration testing (CPTu) where the CPTu cone is fitted with a temperature sensor and with the Medusa Automated Flatplate Dilatometer (DMT). Thermal conductivities, derived from temperature dissipation tests are used in design of underground cables for solar and wind projects. An interpreted thermal dissipation test is reported. Dilatory response in pore pressure dissipation tests is relatively common. Data from U1 and U2 CPTu, and DMT, dissipation tests performed adjacent to each other in ground that exhibited a dilatory response are interpreted and found to produce similar estimates for the co-efficient of horizontal consolidation. The DMT test provides the simplest interpretation of behaviour in dilatory ground but CPT interpretations can also be performed successfully.

Keywords: *CPT, DMT, dissipation, thermal*

1. INTRODUCTION

Recent developments in in-situ testing include the CPT thermal dissipation test (Vardon *et al*, 2019; Vardon and Peuchen, 2020), interpretation of dilatory CPT U2 pore pressure dissipation tests (Burns and Mayne, 2002; Mayne, 2013) and the dilatometer (DMT) dissipation test (Totani *et al*, 1998). Case histories where these tests were performed and interpreted are presented in this paper.

Many solar and wind projects are being constructed at the present time. Key information includes the mechanical and thermal properties of the soil. The mechanical properties are used for foundation design and the thermal properties are used for buried cable design. A typical geotechnical investigation includes borehole drilling with standard penetration tests (SPT), test pitting where tube samples are collected for laboratory thermal testing and where needle point thermal dissipation tests are performed in the side wall of the test pit. Typically, CPT tests are not performed as they can refuse on shallow rock and do not collect a sample. However, there are benefits to using CPT tests. One benefit is that the CPT provides higher quality strength information than the SPT. A second potential benefit is that thermal dissipation tests can be performed if the CPT is equipped with temperature sensors to obtain the thermal conductivity and can be interpreted to provide a profile of thermal conductivity with depth. In principle, the CPT could supplement or replace the needle point tests.

Dilatory responses in CPT U2 dissipation tests are commonly observed, particularly in overconsolidated soils. A dilatory response is one where the measured pore pressure increases initially before reducing over time. A dilatory response can occur if the pore filter is not fully saturated but also occurs as a result of shear dilation adjacent to the CPT shaft (Burns and Mayne, 2002). If the analyst can be confident that the pore filter is fully saturated then an interpretation needs to consider the effects of dilation on the test data. DMT dissipation tests can also be performed. The DMT measures changes of pressure against an impermeable membrane and is not affected by de-saturation of a filter element. CPT and DMT tests were performed at the same location; data and interpretation are presented in this paper.

2. THERMAL DISSIPATION TESTS

The temperature of a cone penetrometer increases during installation due to friction between the CPT and the ground. The thermal dissipation test is similar to a pore pressure dissipation test where penetration is stopped and the temperature is recorded with time. A typical thermal dissipation test result performed in a sand tailings deposit is presented in Figure 1.

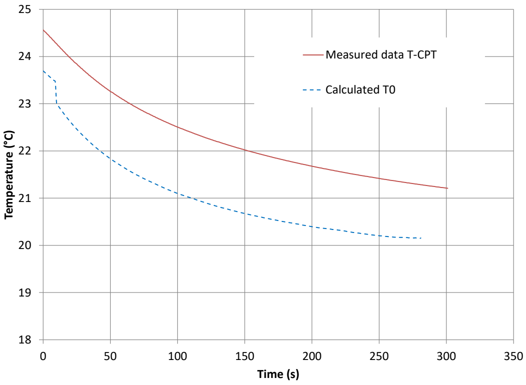


Figure 1 Results of a thermal dissipation test

Vardon *et al* (2019) present an analytical and a graphical method for interpretation of the dissipation tests. The analytical method uses Equation 1a while the graphical method is based on Equation 1b.

$$k = f_{TC}\frac{S(T_{max}-T_0)}{4\pi[t(T-T_0)]} \qquad (1a)$$

$$k = f_{TC}\frac{S(T_{max}-T_0)}{4\pi exp(i_T)} \qquad (1b)$$

In these equations, k is the thermal conductivity, f_{TC} is a calibration factor for thermal conductivity which is a function of the cone cross section where the temperature sensor is located, S is heat content per unit length, T_{max} is the maximum recorded temperature, T_0 is the insitu soil temperature, T is current temperature, t is time and i_T is the y-intercept from a ln(T-T0) versus ln(t) plot.

The parameter T_0 can either be obtained from running the test long enough for the insitu temperature to be measured or estimated using Equation 2. In Equation 2, t_i and T_i are times and respective temperatures at those times. When Equation 2 is used, a running average of several data points helps to average out local fluctuations and the value of T_0 should asymptote as time progresses, as shown in Figure 1.

$$T_0 = \frac{t_1T_1-t_2T_2}{t_1-t_2} \qquad (2)$$

For the purpose of this exercise, the value of f_{TC} was set to 0.66 after Vardon *et al* (2019). The value of this parameter changes with sensor location in the CPT and ideally should be calibrated to results of needle point thermal dissipation tests.

The dissipation test was performed using a low capacity cone which is constructed from aluminium. The parameter $S = c_p\rho A$ where c_p is the specific heat capacity, ρ is the density and A is the cross sectional area of the metal in the T-CPT cone.

The thermal conductivity derived from the analytical method was calculated as 2.85 W/m^2 and is shown in Figure 2. Results of the graphical method are shown in Figure 3 and the i_T value is 5.707. Based on this value, the thermal conductivity is calculated as 2.79W/m^2. Roshankhah *et al* (2021) show this magnitude of thermal conductivity is consistent with a soil unit weight in the order of 15kN/m^3. The minimum unit weight in their laboratory tests was about 14.5kN/m^3 and it is not clear how the thermal conductivity would vary at lower unit weight. The CPT interpretation indicates the actual unit weight was in the order of 12kN/m^3.

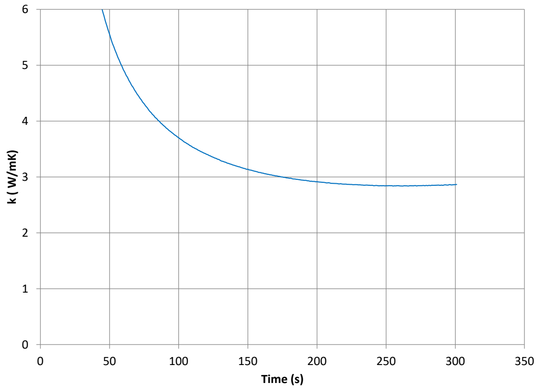


Figure 2 Analytical solution

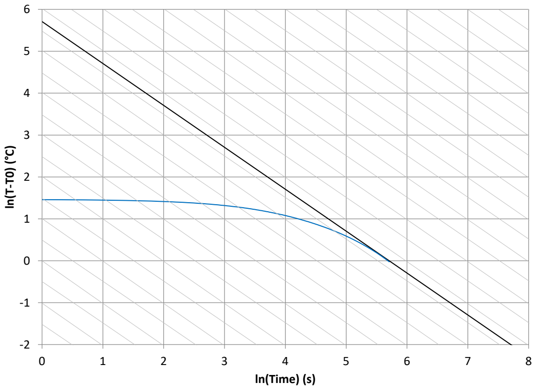


Figure 3 Graphical

Vardon and Peuchen (2020) propose CPT interpretations for thermal conductivity based on first estimating the porosity of the soil and then the thermal conductivity. CPT interpretations with depth are shown in Figure 4 using two different methods for estimating porosity. The interpretations are compared with the result of thermal dissipation tests which show that the CPT underestimates the thermal conductivity of these tests. These thermal dissipation tests were performed in a clay layer, while the CPT interpretations were largely calibrated to data from tests in sand (Vardon and Peuchen, 2020). The CPT interpretation of thermal conductivity in a sand layer between 10m and 20m depth is consistent with values reported by Roshankhah *et al* (2020) from laboratory tests. A preliminary conclusion is that the CPT interpretation for clay materials should be treated with caution.

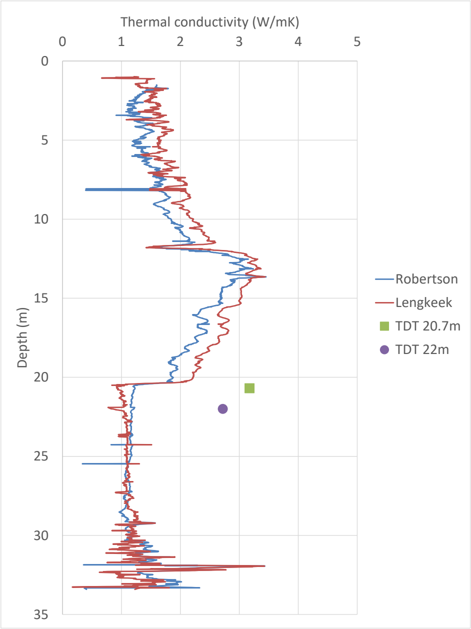


Figure 4 Comparison of CPT and TDT interpretations

3. CPT AND DMT PORE PRESSURE DISSIPATION TESTS

CPT tests with U2 and U1 pore pressure dissipations and a DMT test were performed in close proximity to each other. CPT U2 and DMT dissipation tests were performed at 8.5m depth. The CPT U1 dissipation test was performed at 8.4m depth.

For all CPTu tests, the pore pressure filter rings were rigorously de-aired in a vacuum and saturated with heated high viscosity silicone oil for a minimum of 72 hours in the laboratory. Saturated pore pressure filter rings were transported to site in an airtight container filled with the saturation fluid. Additional de-airing was conducted on board the CPT Rig with a vacuum pump once the cone was assembled in the saturating fluid and prior to commencing the penetration test. Once assembly and additional de-airing was complete, a thin rubber membrane was placed over the cone to eliminate the risk of any desaturation prior to commencing the test.

An interpretation of the CPT test with depth is provided in Figure 5. Results of the CPT dissipations are shown in Figure 6 and results from the DMT dissipation test are shown in Figure 7. A strong dilatory response can be observed in the CPT tests. In contrast, a monotonic pressure decay is observed in the DMT test.

The U1 and U2 tests can be interpreted using approximations reported by Mayne (2013) to the theoretical results derived by Teh and Houlsby (1991). These approximations are shown in Figures 8a and 8b. In these figures c_h is the coefficient of consolidation, a is the cone radius, t is time and I_R is the rigidity index (G/s_u) where G is the shear modulus and s_u is the undrained shear strength. In order to use these procedures, the degree of consolidation needs to be estimated and to do this an estimate of initial pore pressure without the dilatory response is required. The initial pore pressure was estimated by plotting the dissipation test data against the square root of time and then projecting the linear portion of the curve post peak pressure to the y axis. Using this method, initial pore pressure for the U2 test was 540kPa and for the U1 test was 623kPa. Comparisons of data and interpretation are shown in Figures 9a and 9b for the U1 and U2 tests respectively.

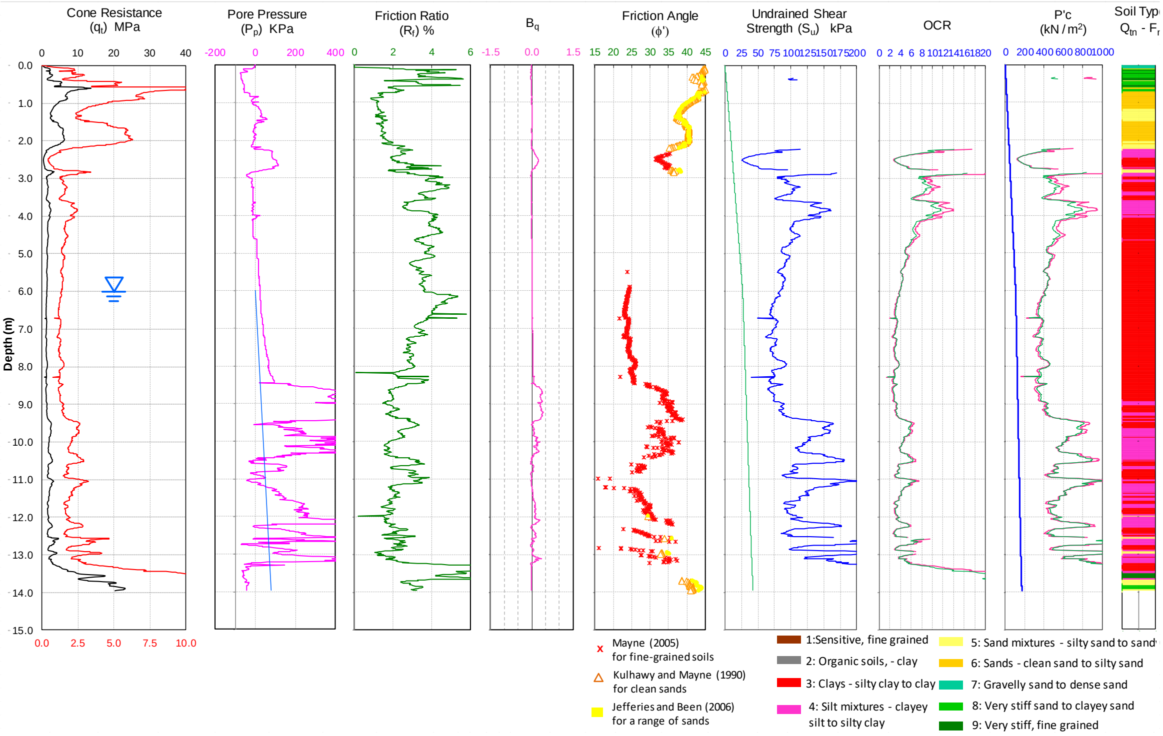
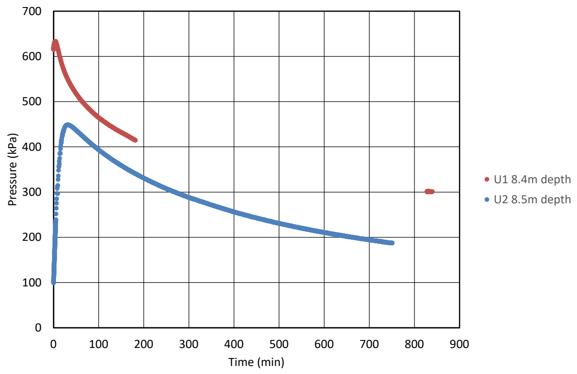


Figure 5 Interpretation of U2 CPT test



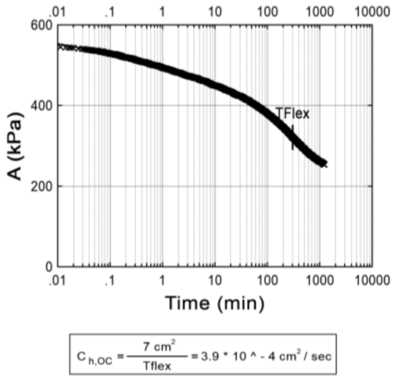
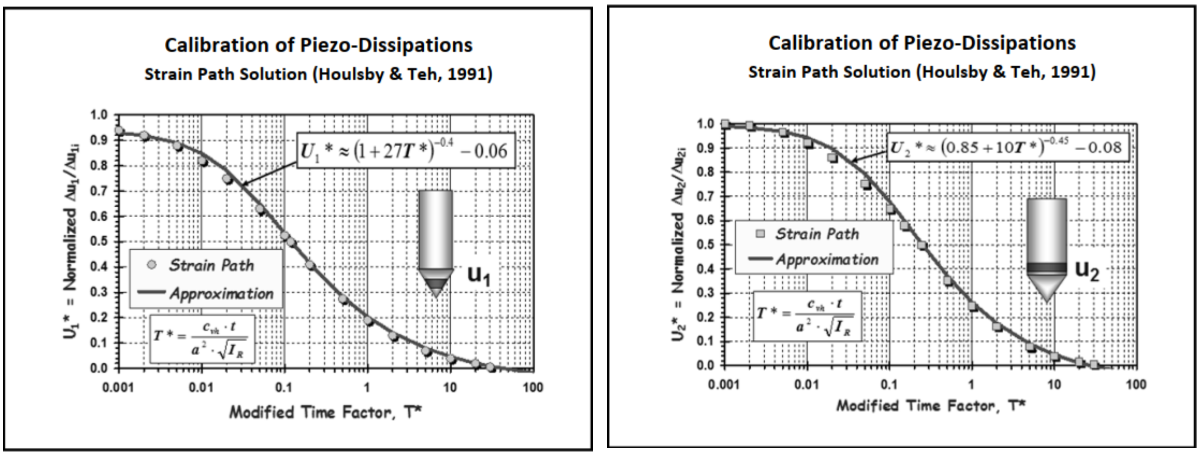


Figure 6 Results of CPT dissipation tests **Figure 7 DMT dissipation test**



Figures 8a and 8b interpretation of U1 and U2 tests (Mayne, 2013)

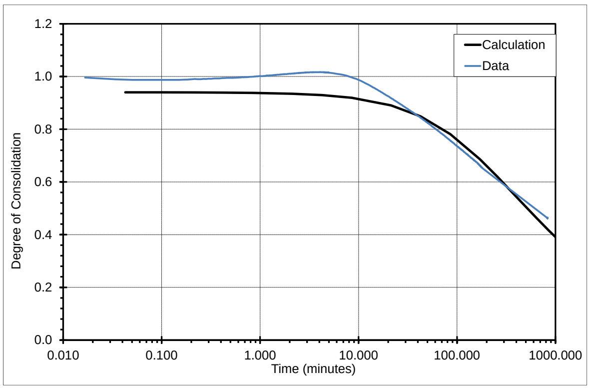


Figure 9a U1 interpretation

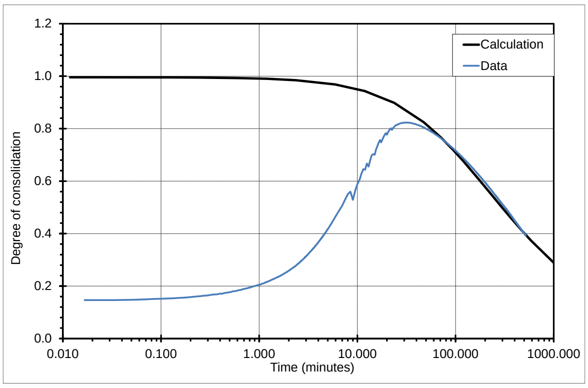


Figure 9b U2 interpretation

The dilatometer dissipation test has been interpreted using Totani *et al* (1998). In this method, the time for the shape of the pore pressure versus logarithm of time to change from convex to concave (*Tflex*) is taken from the curve and input into an empirical equation derived from various field trials in different materials.

The U2 dissipation test data can be interpreted using an approximation by Mayne (2013) to Burns and Mayne (2002). First the initial octahedral and shear pore pressure components are estimated using Equations 3a and 3b, then the total initial pore pressure is calculated by 3c. Time dependent dissipation is then calculated using 4a and 4b.

$$(\Delta u_{oct})_i = \left(\frac{2M}{3}\right)\left(\frac{OCR}{2}\right)^{\Lambda} \ln(I_R)\sigma'_{v0} \qquad 3a$$

$$(\Delta u_{shear})_i = \left[1 - \left(\frac{OCR}{2}\right)^{\Lambda}\right]\sigma'_{v0} \qquad 3b$$

$$\Delta u_i = (\Delta u_{shear})_i + (\Delta u_{oct})_i \qquad 3c$$

$$T' = \frac{c_h t}{a^2 I_R^{0.75}} \qquad 4a$$

$$(\Delta u)_t = \frac{(\Delta u_{oct})_i}{1+50T'} + \frac{(\Delta u_{shear})_i}{1+\left(\frac{1}{s_t}\right)\left(\frac{326}{x}\right)^2 T'} \qquad 4b$$

In these equations, M is the slope of the critical state line in triaxial space, OCR is the over consolidation ratio, Λ is $1 - c_s/c_c$ where c_s is the recompression index and c_c is the compression index, σ'_{v0} is the in-situ effective stress, Δu_{oct} is the octahedral component of pore pressure, Δu_{shear} is the shear component of pore pressure, T' is a modified time factor, s_t is the soil sensitivity and x (mm) is the thickness of the shear zone next to the CPT sleeve. An interpretation of the CPT U2 test using these equations is shown in Figure 10. The parameters used to interpret the data are shown in Table 1. The initial octahedral component of the pore pressure derived from the theoretical equations was 538kPa in order to provide consistency with the previous interpretation.

Interpreted coefficients of horizontal consolidation from all of the tests are summarized in Table 1. The Teh and Houlsby (1991) U2 interpretation is similar to the DMT interpretation while the Teh and Houlsby (1991) U1 interpretation is similar to the Burns and Mayne (2002) dilatory interpretation. Of these methods, the DMT interpretation requires the least data manipulation and use of engineering judgement.

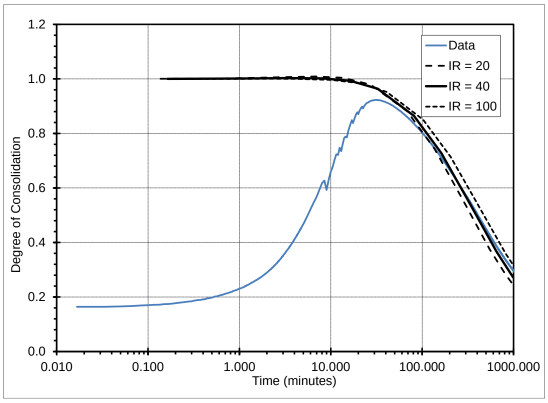


Figure 10 interpretation of CPT U2 test using dilatory equations

Table 1. Interpreted coefficients of horizontal consolidation

Depth	**Test**	**Type***	**IR**	**phi**	**OCR**	**Λ**	**S_t**	**X (mm)**	**c_h (m^2/yr)**
8.5m	CPT U2	T&H	40	-	-	-	-	-	1.34
8.5m	CPT U2	Dilatory	40	31	3	0.9	1.5	10	0.25
8.5m	DMT	Totani et al	-	-	-	-	-	-	1.23
8.4m	CPT U1	T&H	40	-	-	-	-	-	0.37

* T&H = Teh and Houlsby (1991), Dilatory = Burns and Mayne (2002)

4. CONCLUSIONS

Relatively new developments in thermal and pore pressure dissipation testing have the potential to change site investigations for onshore solar and wind projects and enable interpretation of dilatory soil behaviour. Example interpretations of thermal dissipation tests have been provided.

The interpretation of thermal conductivity from cone tip and sleeve friction data assumes saturated soils. This requirement may limit the use of these interpretations in unsaturated soils on shore. The correlations presented by Vardon and Peuchen (2020) appear to be more suited to sands than clays. However, the analytical and graphical interpretations of the thermal dissipation test can be used in these conditions. Calibrations with *in-situ* needle tests and laboratory tests would help provide confidence in the TDT and CPT interpretations.

Four types of pore pressure dissipation test have been used to interpret the results of dilatory CPT dissipation tests. Of these, the DMT test was interpreted without any judgement required to establish parameters but uses an empirical relationship. The CPT tests use analytical solutions with a basis in theory but require some judgement to establish the initial octahedral stress and parameters associated with the shear zone adjacent to the CPT. Therefore, what value of c_h should be adopted remains subject to the judgement of the person interpreting the data. The range of values interpreted for the coefficient of horizontal consolidation is in excess of 5 and therefore selection of a design value could have a profound effect on the time required for pore pressure dissipation.

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