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Determination of Thermal Conductivity of Soil Using Standard Cone Penetration Test

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Abstract

The thermal cone dissipation test is a newly-developed method for determining thermal conductivity *in situ* based on temperature dissipation over time. The standard cone penetration test with pore pressure measurement (CPTu) is used. The cone heats up as it is pushed through the soil, due to the build-up of friction on the cone and rods. The dissipation of this heat can then be measured when penetration of the cone is stopped at intervals, and the thermal conductivity of the soil over that test interval determined. Three thermal cone dissipation tests (TCT) were conducted, the first test in soft clay with a high moisture content, and the second and third tests in clay containing a stiff sandy clay layer. The stiff sandy clay layer showed the more significant temperature increase on cone penetration. Using a previously developed correlation, the thermal conductivity was then calculated for each TCT. The temperature increase of the cone for the duration of each CPTu test was also recorded. While the TCT is a promising new test, it is suggested that further research is necessary to develop and refine the method.

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Keywords: Standard cone penetration, thermal testing, thermal conductivity

1. Introduction

Demand for clean energy has increased in recent decades, coinciding with raising energy costs, price fluctuations [1], and the need to reduce carbon emissions due to their proven link to global warming [2]. These factors have seen a rise in geothermal applications worldwide, with direct utilisation of geothermal energy seeing an increase of up to

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7.7% annually. Ground-source heat pumps represent the most common method of utilising low temperature geothermal energy [3]. The primary reason for the increasing use of geothermal resources is the increasing efficiency of geothermal energy capture, in addition to the environmental benefits. As the use of energy becomes more prominent, the need for rapid and reliable testing of the thermal parameters and response of the ground increases. Current state-of-the-art methods include the thermal response test (TRT). This test involves circulating a fluid through pipes embedded in the ground for a period of 48 to 72 hours. Under constant flow and power, the measured change in the temperature of the fluid over time enables the thermal parameters of both the vertical borehole and the surrounding ground to be determined [4]. As a result of the need for a borehole, the long duration of the test, and necessity for constant power over the test duration, the costs associated with a TRT can be significant. There has been significant research carried out exploring the TRT method and its different applications [5] to [9]. In addition, the results obtained using the TRT are only considered accurate to within 10% due to numerous uncertainties that cannot be fully accounted for [10]. Advantages of the TRT are that the ground is tested *in situ*, and the properties of the grout or concrete are included in the interpretation of the test, making it reasonably rigorous. An alternative method to the TRT for determining the thermal parameters of soils is by borehole sampling and laboratory measurements. However, a borehole is still required, samples will likely suffer disturbance, laboratory testing can be expensive, and the effect of the borehole, grout or pile cannot be accounted for. Hence both the TRT, and borehole sampling and laboratory testing have their drawbacks.

In this study, a newly-developed test, the thermal cone dissipation test (TCT) was used to measure the thermal parameters and response of the ground [11]. The test involves using the cone penetration test with pre pressure measurement (CPTu), with the addition of a soil moisture probe (SMP). The thermal cone dissipation test overcomes most of the drawbacks associated with the previously mentioned test methods in that it is rapid and less expensive. However, the TCT will not obtain thermal information for the borehole, grout or pile. This paper aims to increase awareness and knowledge of the TCT method for estimating the thermal parameters and response of different soil profiles, and to extend its application to other soil profiles and improve its reliability.

2. Test apparatus and procedure

The CPTu is a common test method used to determine soil profiles and to estimate soil parameters such as shear strength, deformation and permeability, among others. To adapt this test to the estimation of the thermal parameters of soils is straightforward, based on the temperature of the cone during testing and its dissipation when penetration is stopped at intervals. The measured dissipation of heat is then used to determine the thermal parameters of the soil over the test interval. Being a common *in situ* testing procedure, the use of the CPTu for determining thermal parameters may readily be implemented in most soil profiles. The purpose of this research was to evaluate the use of the standard CPTu test, with the addition of a SMP for the purpose of measuring temperature. The SMP used was from Geomil, and was capable of measuring temperature to within 0.04°C. The probe was mounted above a S15 (15 cm^2) piezocone allowing for the conventional CPTu data to be recorded from the same test. It was pushed at the standard rate of 2 cm/s and a number of temperature dissipation tests were undertaken at varying depths and within different soil layers. The piezocone was stopped at the desired locations for a period of 16 to 20 min, during which the temperature was recorded. In addition to recording the temperature decrease, the temperature increase per metre was recorded to allow an estimation of the expected increase resulting from friction on the cone and rods. The location of the SMP was approximately 900 mm behind the tip (see Fig. 1).

3. Field tests

Three CPTu tests were carried out at two different sites. The first two CPTu tests were carried out to a depth of 20 m with temperature dissipation testing at 5 m intervals, and the third test was carried out to a depth of 9 m with the temperature dissipation testing at 3.5 m, 7 m and 9 m depth. The first CPTu test was in soft clay with a high moisture content, while the second and third CPTu tests encountered a layer of stiff sandy clay overlying softer clay. The sites were located in Brisbane, Australia, which has a ground temperature potentially well-suited to low enthalpy geothermal energy for the heating and cooling of buildings. The thermal parameters of the ground would be a requirement for the design of geothermal energy systems, making the locations and test depths selected ideal for implementation of the TCT.

4. Analysis

Conduction is considered the primary mechanism of heat transfer in soils, whereby thermal conductivity is calculated by measuring temperature change over time. From the Fourier expression for heat flux, thermal conductivity is denoted by the parameter λ to give Eq. (1). Another mechanism of heat transfer within soils is convection. Convection occurs when groundwater flow is rapid. However, due to the relatively short duration of the temperature dissipation test it is expected that convection would have minimal to no impact. Previously, TCT testing has yielded the simple Eq. (2) to determine the thermal conductivity of soil [11].

$$\vec{q} = -\lambda \nabla T \tag{1}$$

$$\lambda = \frac{125}{t_{50}} \tag{2}$$

In Eq. (2), t_{50} represents the time it takes for 50% of the heat to dissipate from the maximum temperature reached to the undisturbed temperature. The time necessary to reach the truly undisturbed temperature would be excessive and result in the test being impractical. Therefore, the temperature that remained stable for 2 min was taken as the final temperature. Another crucial value to determine is the temperature increase per metre. When calculating the temperature increase per metre, the change in temperature recorded was divided by the distance between each recording. This value was then compared against the friction on the cone (as represented by the measured sleeve friction) as this most affects the increase in temperature.

5. Results and discussion

5.1 CPTu Results

Fig. 2 clearly shows the temperature profiles from the CPTu tests displaying both heat generation and variation with depth. The temperature is seen to vary by up to 3°C, particularly in the second and third CPTu test. This increase represents the stiff sandy clay layer (5 to 10 m depth) encountered in the second and third tests. However, despite temperature increasing strongly at certain depths, there are intervals in which the temperature does not increase markedly. This is most clearly seen for CPTu-1 below 10 m depth, which shows minimal temperature change, resulting in less than optimal conditions for the TCT test to be performed.

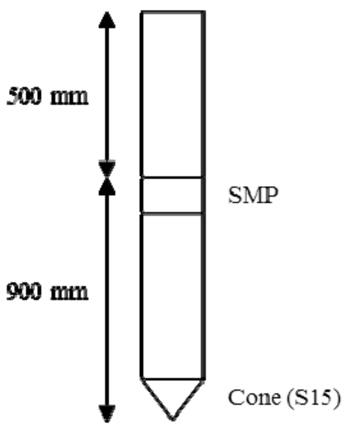

Fig. 1. Piezocone schematic.

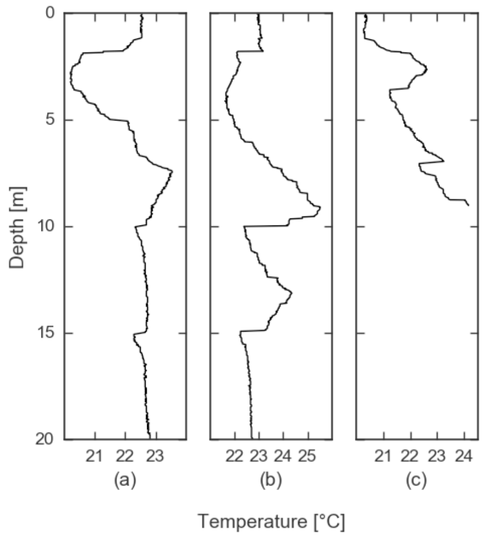

Fig. 2. Temperature profiles for: (a) CPTu-1, (b) CPTu-2, and (c) CPTu-3.

To determine the depth interval of the stiff sandy clay layer, the cone tip resistance was used. The cone tip resistance profiles shown in Fig. 3 shows that for first CPTu test the soil profile was soft for almost the entire depth. For the second and third CPTu tests, stiff sandy clay was encountered from 6 to 13 m depth, with a cone tip resistance of 6 to 10 MPa, underlain by much softer clay with a cone tip resistance from 0.6 to 1.0 MPa. Comparing the temperature in the stiff sandy clay to that in the underlying softer clay, it can be seen in Fig. 2 that the stiff sandy clay generated a much higher temperature increase. The second CPTu test shows the largest variation in temperature, with an increase from 21.61°C at 4.14 m depth to 25.53°C at 9.12 m depth, an increase of 3.92°C, over less than 5 m depth. Fig. 4 shows the volumetric moisture content (VMC) estimated from the CPTu test results. For the first CPTu test, the VMC reaches 100% at about 5 m depth and remains unchanged below that depth. However, for the second CPTu test the VMC reaches 100% at 7 m and reduces to 50% below 15 m depth. It is difficult to interpret and correlate the temperature and VMC data. For the first CPTu test, there is no heat generation when the VMC is steady, while for the second CPTu test there is significant heat generation when the VMC is 100%, and minimal heat generation when the VMC is 50%.

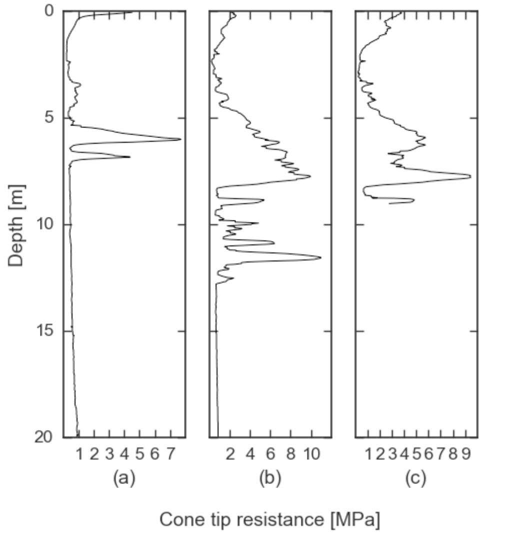

Fig. 3. Cone tip resistance profiles for: (a) CPTu-1, (b) CPTu-2, and (c) CPTu-3.

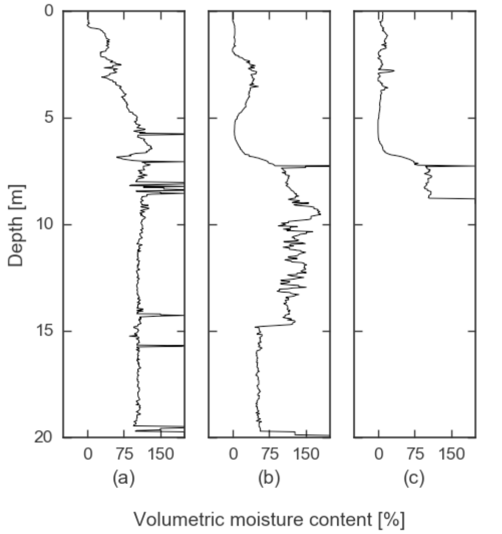

Fig. 4. Estimated volumetric moisture content profiles for: (a) CPTu-1, (b) CPTu-2, and (c) CPTu-3.

The main purpose of the TCT test is to measure heat dissipation at different depth intervals. The initial 5 min of the TCT test is the most important period, since this is when by far the largest dissipation in temperature occurs. For TCT-1 (see Fig. 5) there is only a slight decrease in temperature over time in the lower layers. This is mainly because there was only ever a slight increase in temperature on penetration of the piezocone. The largest temperature dissipation was only 0.16°C, at 15 m depth, since the temperature generated on penetrating the soft clay was limited.

The TCT-1 test at 5 m depth experienced a temperature increase of 0.41°C, similar to the initial increase in temperature by 0.2°C in the TCT-2 test at 5 m depth (see Fig. 6), although the temperature in this test later dropped to within 0.04°C of the original value. The temperature profiles for CPTu-1 and CPTu-2 shown in Fig. 2 show a drop in the heat generated by penetration of the piezocone between 2 m and 6 m depth. This is attributed to the effect of the lower ambient air temperature. The higher temperatures generated in CPTu-2 and CPTu-3 tests (see Fig. 7), due to the stiff sandy clay layer encountered, resulted in greater heat dissipation in TCT-2 (see Fig. 7) and TCT-3 (see Fig. 7). For the TCT-2 test at 10 m depth, a decrease of 1.61°C was observed, while for the TCT-3 test at 9 m depth a decrease of 1.79°C was observed. Using Eq. (3), the thermal conductivities shown in Table 1 were calculated.

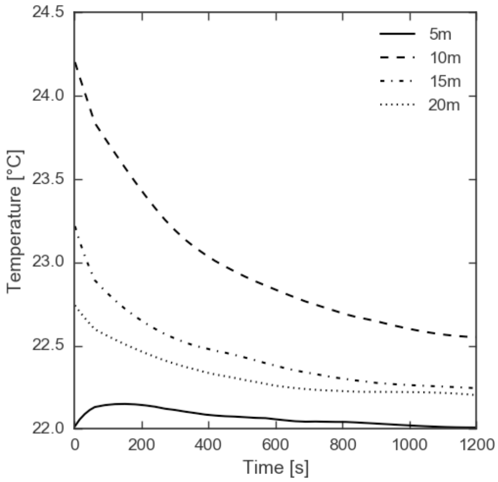

Fig. 5. Heat dissipation over 1,200 s for TCT-1.

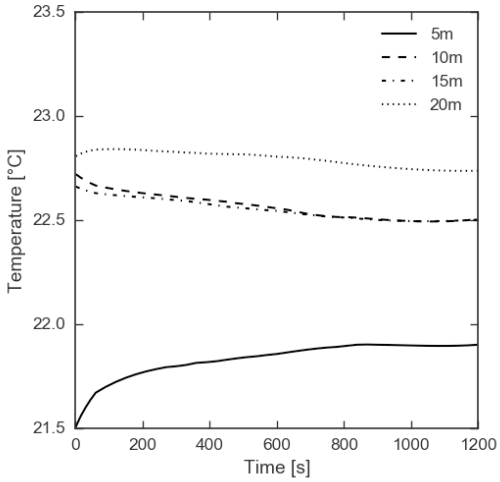

Fig. 6. Heat dissipation over 1,200 s for TCT-2.

The TCT-1 test at 5 m depth experienced a temperature increase of 0.41°C, similar to the initial increase in temperature by 0.2°C in the TCT-2 test at 5 m depth (see Fig. 6), although the temperature in this test later dropped to within 0.04°C of the original value. The temperature profiles for CPTu-1 and CPTu-2 shown in Fig. 2 show a drop in the heat generated by penetration of the piezocone between 2 m and 6 m depth. This is attributed to the effect of the lower ambient air temperature. The higher temperatures generated in CPTu-2 and CPTu-3 tests (see Fig. 7), due to the stiff sandy clay layer encountered, resulted in greater heat dissipation in TCT-2 (see Fig. 7) and TCT-3 (see Fig. 7). For the TCT-2 test at 10 m depth, a decrease of 1.61°C was observed, while for the TCT-3 test at 9 m depth a decrease of 1.79°C was observed. Using Eq. (3), the thermal conductivities shown in Table 1 were calculated.

The lower the generation of heat on penetration of the piezocone, which is evident in soft clay (CPTu-1), the lower the calculated thermal conductivity. This is likely to result in a less precise, and likely lower than expected, calculated value. The TCT-1 tests gave calculated thermal conductivities of only 0.19 to 0.42 W/mK, while the TCT-2 and TCT-3 tests gave calculated values of 0.58 to 0.87 W/mK and 0.60 to 1.39 W/mK, respectively. Thermal conductivity values expected would be from the range of 1 to 2
W/mK [12].

Table 1. In situ TCT Results

Test	Depth (m)	t_{50} (s)	λ (W/mK)
CPT-1	5.0	-	-
CPT-1	10	490	0.26
CPT-1	15	300	0.42
CPT-1	20	660	0.19
CPT-2	5.0	-	-
CPT-2	10.0	214	0.58
CPT-2	15.0	144	0.87
CPT-2	20.0	169	0.74
CPT-3	3.5	90	1.39
CPT-3	7.0	204	0.61
CPT-3	9.0	209	0.60

Fig. 8 shows the cone temperature increase per metre depth for all three piezocone tests. For the majority of the data, the increase was nominal at approximately 1 to 2°C/m. However, there were some data indicating a much faster rate of cone temperature increase. This may be limited by the need to change rods at 1 m intervals.

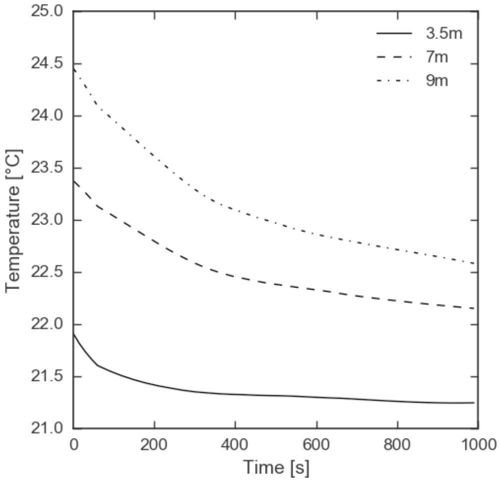

Fig. 7. Heat dissipation over 1,000 s for TCT-3.

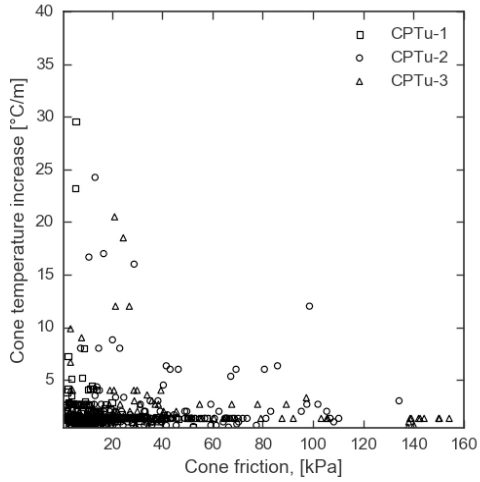

Fig. 8. Cone temperature increase against friction on cone.

6. Conclusions

Three CPTu tests were carried out, each involving three or four TCT tests for the purposes of determining the thermal conductivity of the soil at different depths. The results were analysed using a previously proposed method to determine the applicability of the method in varying soil conditions. The analysis showed that:

1. The previously derived equation produced some unexpected results, with lower thermal conductivities than expected, requiring further research and calibration to improve the reliability of the method. In addition, testing with a more precise sensor may enhance the results obtained.
2. TCT testing may not be suitable for all soil conditions, in particular, if little heat is generated on piezocone penetration, a heat dissipation test may yield little useful data. In such cases, it would be necessary to make the cone a heat source or use an alternate method of testing.
3. The TCT test has the potential to be useful as a quick means of obtaining an approximate estimate of the thermal conductivity of the ground under conditions in which the cone generates significant heat on penetration. As the CPTu is commonly carried out in routine geotechnical investigations, the TCT may represent an economical means of obtaining soil thermal parameters for the initial design stage.

The results of this initial investigation into thermal cone dissipation testing show that there is some promise in the testing method. However, further research and calibration is required to improve its reliability as a method for estimating the thermal conductivity of soil profiles.

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