



Field and laboratory estimation of thermal conductivity of unsaturated soils using thermal cone penetration test (T-CPT)

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Abstract

Ground source heat pump (GSHP) systems have been widely used to harvest shallow geothermal energy from the ground, providing renewable and low carbon energy sources. A comprehensive investigation of ground thermal properties is critical for effective design of GSHP systems in building heating and cooling applications. This study assesses the effectiveness of Thermal Cone Penetration Test (T-CPT) as a method for determining ground thermal conductivity of unsaturated tropical soils, in which saturation degree can vary seasonally, altering soil thermal properties. This work conducted laboratory model T-CPT tests on sand and clay soils with varying saturation degrees. For field measurements, T-CPT tests were carried out at three different sites of unsaturated tropical soils in South and Southeast regions of Brazil. As a result, measured thermal conductivity values were consistent with data available in literature. Furthermore, laboratory measurements demonstrate that soil thermal conductivity increases with saturation degree and soil density. Results indicate that T-CPT test is an efficient and practical method to capture the impact of saturation degree on thermal conductivity of unsaturated soils. The ease of test performing is a great advantage, because the field test used for this purpose is Thermal Response Test (TRT), which is a much longer test that requires prior installation of heat exchanger tubes in the soil, needs specific equipment for its execution and has a complex interpretation of results.

Keywords Thermal cone penetration test (T-CPT) · Soil thermal conductivity · Unsaturated soils · Tropical soils

Abbreviations

T Temperature
 ΔT Temperature variation

T_{max} Maximum test temperature
 T_0 Initial soil temperature
 t Time
 t_{50} Time to dissipate 50% of the heat
 D_{10}, D_{30}, D_{60} Grain diameter corresponding to 10%, 30% or 60% of passing material
 S_r Saturation degree
 λ Thermal conductivity
 C_g Specific heat capacity
 A, B T-CPT calibration parameters
 S Amount of heat released
 f_{TC} Cone calibration factor
 i_T Y-intercept of the tangent line on a graph
 w Moisture content
 e Void ratio
 γ Density
 γ_D Dry density
 γ_S Density of solid particles
 σ Standard deviation
 CV Coefficient of variation
 CPT Cone penetration test

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<i>TCT ou T-CPT</i>	Thermal cone penetration test
<i>TRT</i>	Thermal response test
<i>LM35</i>	Temperature sensor
<i>CNU</i>	Coefficient of non-uniformity
<i>CC</i>	Coefficient of curvature

Introduction

In the last century, annual per capita energy consumption has exponentially increased. This growing demand must be addressed by enhancing energy supply, expanding existing installed capacity, and exploring previously untapped low greenhouse gas emissions sources (Loveridge et al. 2020). In Brazil, one underexplored source is shallow geothermal energy, which offers an alternative for reducing electricity consumption for climate control and water heating. It is a clean, renewable, and reliable energy source (Lee et al. 2007). The energy harvesting system can be integrated into a building's foundations during its construction stage, taking advantage of the permanent structures to exchange heat with the ground.

To design ground source heat pump (GSHP) systems to harvest shallow geothermal energy from the ground, it is essential to know materials thermal, geotechnical and mechanical properties. Appropriate selection of thermal parameters is critical for designing geothermal systems, with soil thermal conductivity being a crucial parameter for accurate prediction. Like other geotechnical parameters, thermal conductivity can be determined in laboratory. Nevertheless, field tests for determining soil thermal conductivity offer the advantage of assessing large and representative soil volume, minimizing disturbance and providing real-time results (Graham 2006). Loveridge et al. (2020) noted that in most cases, thermal conductivity values obtained from field tests are higher than those obtained in laboratory.

In laboratory thermal conductivity measurements, it is necessary to impose a temperature gradient through the soil sample. This can be achieved either by waiting for the temperature to reach equilibrium during the test (steady state test) or by conducting the test while the temperature varies (transient test). The primary steady state tests are Guarded Hot Plate Test and Thermal Cell Test, while the most common transient test is Thermal Needle Probe Test (Farouki 1981).

Among field tests, the most used is Thermal Response Test (TRT), which can be conducted in a borehole or pile foundations equipped with heat transfer pipes (Sanner et al. 2005). The test involves injecting heat into the borehole at a constant rate and monitoring the temperature change of the circulating fluid. This procedure generally is carried out for approximately 2 to 3 days. The equipment commonly used for the test includes a heater (reservoir), a hydraulic pump,

a flow meter, heat exchange pipes and a data acquisition system.

Recently, Akrouch et al. (2016a) proposed an adaptation of Cone Penetration Test (CPT), which is widely used to determine soil parameters employed in geotechnical engineering, to measure soil thermal conductivity. This adapted test is known as Thermal Cone Penetration Test (T-CPT). The equipment consists of a conical penetrometer equipped with thermocouples located at the cone's tip, which can also accommodate additional sensors for measuring seismic wave velocity, temperature, and electrical resistivity.

The primary objective of this study was to assess the effectiveness of T-CPT for determining thermal conductivity of unsaturated tropical soils. This parameter is essential for the design of shallow geothermal systems and obtaining it in the field can be challenging. This test offers a significant advantage by allowing measurements to be completed in a reduced time, approximately 30 min for each tested depth, using equipment commonly employed in geotechnical in situ investigations without the need for drilling or pile installation. It is worth mentioning that such test has never been used in Brazil and has only a few published studies in other regions worldwide. To evaluate its applicability, several tests were conducted in laboratory under various soil scenarios and saturation degrees. Subsequently, numerical simulations were performed to compare the laboratory results. Finally, field tests were carried out at three distinct unsaturated soil sites located in South and Southeast regions of Brazil to assess thermal conductivities of different Brazilian unsaturated tropical soils.

Thermal cone penetration test (T-CPT)

Thermal Cone Penetration Test (T-CPT) expands the purpose of Cone Penetration Test (CPT) to include thermal measurements. The T-CPT, also known as TCT, is quite simple and relatively fast. It can be conducted in natural soil conditions at any depth that can be reached by the CPT test. According to Akrouch et al. (2016a), it has the advantage of not requiring any heating device, as the heat generated from the soil cone friction during penetration is sufficient to determine soil thermal properties. Another advantage is that it provides not only soil thermal properties but also stratigraphy, hydraulic and mechanical properties. The proposed test is classified as an in situ transient test because temperature varies over time during measurements.

In addition to Akrouch et al. (2016a), other authors have also studied this test, such as Keshavarz et al. (2017), Lines et al. (2019), Vardon et al. (2018, 2019), Mo et al. (2021) and Liu et al. (2022). These latter authors suggest the use of a heater in the cone to overcome difficulties encountered when conducting tests at shallow depths or in soft soils,

where friction generated during cone penetration may not generate sufficient heat for the test.

To perform Thermal Cone Penetration Test (T-CPT), a temperature sensor is connected to the cone to measure temperature at the contact between the rod and the surrounding soil. The proposed procedure consists in penetrate the cone to the desired depth and allowing the stored heat to dissipate while a sensor measures the temperature drop over time. Soil thermal properties can be calculated based on cone temperature as a function of time decay curve obtained from thermocouple readings (Akrouch et al. 2016a).

It is important to emphasize that the cone and the equipment for drilling the soil are the same as used in conventional Cone Penetration Test (CPT). The difference is that a temperature sensor is inserted at the tip of the cone and that the drilling needs to be stopped at specific depths to wait for the heat generated during the drilling process to dissipate for subsequent calculation of thermal conductivity.

According to Akrouch et al. (2016a), the development of Thermal Cone Penetration Test (T-CPT) was based on the idea of pore water pressure (PWP) dissipation test (Janbu and Senneset 1974; Torstensson 1975; Wissa et al. 1975) and the equivalence between thermal and hydraulic flow problems in soils. Both processes are governed by the same type of differential equation (Terzaghi 1943).

Akrouch et al. (2016a) and Vardon et al. (2019) proposed different methods for interpreting Thermal Cone Penetration Test (T-CPT). The first group of researchers suggested an empirical method, while the second group proposed an analytical method.

Method of Akrouch et al. (2016a)

Based on the similarity of physical processes related to water and heat dissipation, Eq. 1 was proposed by Akrouch et al. (2016a) to estimate thermal conductivity (λ) considering the temperature dissipation curve obtained from Thermal Cone Penetration Test (T-CPT).

$$\lambda \approx \frac{1}{(A \cdot t_{50})^B} \tag{1}$$

where A and B are test calibration parameters, and t_{50} is the time in seconds for 50% heat dissipation.

To obtain these calibration parameters, eleven Thermal Cone Penetration Tests were conducted at three different locations in Texas, United States. For each field Thermal Cone Penetration Test, samples were collected for laboratory testing using Thermal Shock Method to determine thermal conductivity. In addition to field and laboratory tests, numerical modeling was performed, varying thermal conductivity and the soils volumetric specific heat to calibrate data and propose parameters.

Equation 2 for thermal conductivity calculation (λ) refers to the adjustment made using the curve obtained from numerical modeling data, while Eq. 3 refers to the adjusted curve considering laboratory tests results, both as a function of time for 50% heat dissipation along the test (t_{50}).

$$\lambda = \frac{77}{(t_{50})^{0.968}} \tag{2}$$

$$\lambda = \frac{125}{t_{50}} \tag{3}$$

Method of Vardon et al. (2019)

Vardon et al. (2019) developed an interpretation model for estimating thermal conductivity (λ) using Thermal Cone Penetration Test (T-CPT). They based their model on the analytical method of the infinite linear source, considering an axisymmetric model and heat conduction as the dominant heat transfer process.

They proposed that thermal conductivity (λ) can be determined by Eq. 4 using heat dissipation data from Thermal Cone Penetration Test (T-CPT). Then, it is calculated for all temperatures recorded in T-CPT and plotted on graph as a function of time. Final thermal conductivity of the test is obtained as the average between time intervals of 500 to 600 s, where it is already stabilized or within a time range where it stabilizes.

$$\lambda = f_{TC} \cdot \frac{S \cdot (T_{max} - T_0)}{4\pi \cdot [t \cdot (T - T_0)]} \tag{4}$$

where f_{TC} is the cone calibration factor that takes into account cone voids and sensors position (0.35); S is the amount of heat released (product of steel gravimetric specific heat, steel density and the cone cross-sectional area); T_{max} is the test maximum temperature; T_0 is the initial soil temperature; T is the temperature at the analyzed time; t is the time in seconds.

The value of T_0 , the initial temperature of the soil, significantly affects thermal conductivity final value and can be assumed as the temperature after complete heat dissipation from the test; or calculated using Eq. 5.

$$T_0 = \frac{t_1 \cdot T_1 - t_2 \cdot T_2}{t_1 - t_2} \tag{5}$$

where t_1 is the time at an earlier moment; t_2 is the time at a later moment; T_1 is the temperature at an earlier moment; T_2 is the temperature at a later moment.

Another way to determine thermal conductivity is by defining Eq. 4 denominator graphically, as shown in Eq. 6.

$$\lambda = f_{TC} \cdot \frac{S \cdot (T_{max} - T_0)}{4\pi \cdot \exp(i_T)} \tag{6}$$

where i_T is the y-intercept of the tangent line on a graph $\ln(T-T_0) \times \ln(t)$.

Vardon et al. (2019) highlight the increase in thermal conductivity with depth in the soil, which is expected due to soil density increase. They also note that, in most cases, thermal conductivity measured in laboratory tends to be lower than in in situ tests, which occurs due to sampling process that disturbs and disrupts the sample. Additionally, the authors observed that when the increase in thermal cone temperature was less than 1 °C, calculated thermal conductivity was not representative. However, this can occur in soft soil conditions, where it is preferable to use Thermal Needle Probe test. Although, it is challenging to perform this test in field at significant depths because it requires a borehole pre-drilling and then inserting the probe, which is easily damaged.

Experimental program

To perform the general objective of this study, evaluate T-CPT use to determine unsaturated tropical soils thermal conductivity, which is the main parameter for shallow geothermal systems design, research was divided in three main stages: laboratory tests, numerical simulations and, finally, field tests at three different locations.

Figure 1 presents a photo and a sketch of the cone used in tests, where is possible to observe the temperature sensor positioning and its dimensions. A Celeron sleeve – a technical laminated material with cotton fabric reinforcements and phenolic resin – was added between the cone tip and the rod. The purpose of this sleeve is to isolate the heat at the cone tip so that dissipation during test occurs only radially and not through the rod. Temperature sensor located at the cone tip is an LM35 sensor.

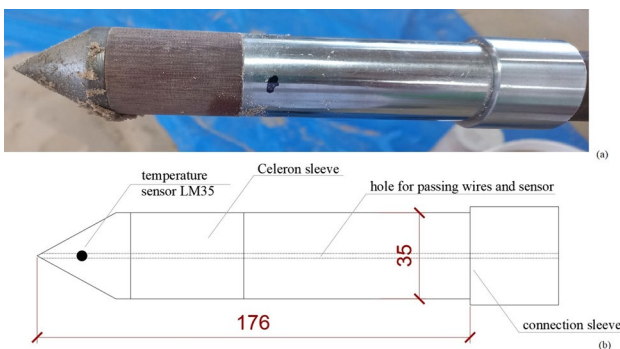


Fig. 1 (a) Thermal cone used; (b) Cone sketch, millimeters dimensions

LM35 sensor is a semiconductor temperature sensor, consisting in an integrated circuit based on PTAT (proportional to absolute temperature) and providing temperature measurements as a function of circuit electrical voltage, where 10 mV is equivalent to 1 °C. This sensor contains three pins: VCC, GND and OUT. VCC is the power supply pin that can be connected to 4 V or 30 V of the supply, GND is the ground pin and it should be connected to the supply ground and OUT is the temperature sensor analog output pin.

It is important to mention that the cone used in this study only includes temperature sensor and does not have instrumentation for soil resistance and pore pressure measuring, but it is possible and recommended to use cones with complete instrumentation.

Laboratory tests

Laboratory Thermal Cone Penetration Tests (T-CPT) were conducted in a tank with both diameter and height of 0.30 m filled with two types of sand sample, as illustrated in Fig. 2. To build the model, sand was compacted in 6 layers of 0.05 m thick, with the amount of water and sand necessary to reach saturation degree and relative density in each case.

The natural sand used in tests was obtained from Tibagi River, located in Ponta Grossa region. Two types of sand were used: fine and medium sand, as shown in particle size distributions in Fig. 3. Table 1 presents sand samples properties.

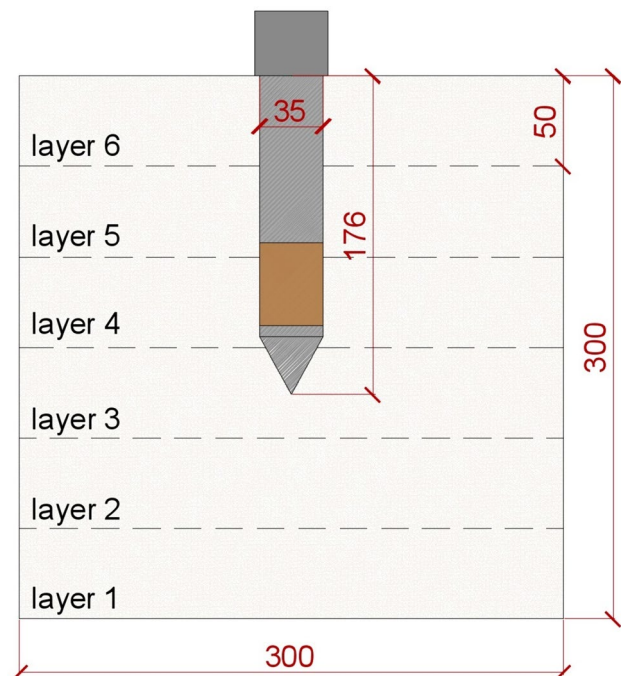


Fig. 2 Schematic section of thermal tests performed in the laboratory (millimeter dimensions)

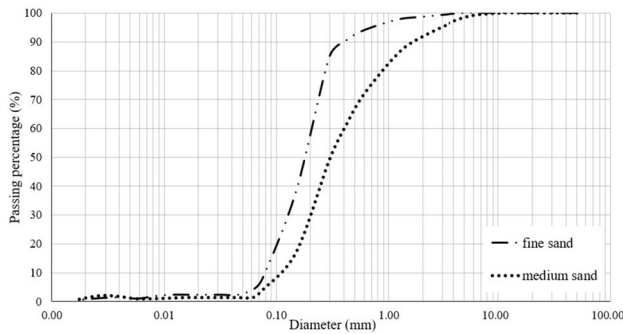


Fig. 3 Sands particle size distribution

Table 1 Sand samples properties

Parameter	Fine sand	Medium sand
γ_s (g/cm ³)	2.654	2.655
e_{MAX}	0.80	0.70
e_{MIN}	0.59	0.43
D_{10}	0.08	0.12
D_{30}	0.14	0.20
D_{60}	0.21	0.40
CNU	2.63	3.33
CC	1.17	0.83

Before each test, the cone was heated in hot water to approximately 70 °C and manually inserted into the soil, where it remained for 30 min to record the temperature dissipation over time. As the cone was inserted manually, the relative density adopted for compacting the sand was low, around 5%, so as not to make insertion difficult. Tests were carried out in an air-conditioned room with a constant temperature of 20 °C, which is equivalent to the initial temperature of each test. At the end of each test, two undisturbed samples were taken to check density and saturation degree.

The tank used was made of plastic material and its diameter was chosen based on other models made in Tonus (2022). In this study models were built with a diameter of 0.55 m and temperature sensors were placed around the cone to check radially how far the temperature increased, where it was noted that a sensor positioned 0.15 m from the axis of the cone did not show significant warming during the study period. Therefore, tank edges did not have a significant influence on heat dissipation. That way, six tests were conducted for each type of sand, with variations in moisture content (w) and saturation degree (Sr), as shown in Table 2.

Subsequently, a verification on the influence of initial cone heating temperature on obtained results was proceeded. For this purpose, some tests were repeated by applying an additional temperature increase of 5 °C, 10 °C, 20 °C and 35 °C to the cone, regarding to ambient temperature (20°).

Table 2 Laboratory thermal cone penetration tests (T-CPT) on sand samples

Sand	Test	w (%)	Sr (%)
Fine	FS1	0	2
	FS2	5	16
	FS3	10	34
	FS4	15	49
	FS5	22	72
	FS6	24	81
Medium	MS7	0	0
	MS8	5	19
	MS9	10	40
	MS10	14	54
	MS11	17	67
	MS12	18	70

These new tests were conducted on three different moisture contents for each type of sand, resulting in an additional 24 laboratory thermal tests.

After conducting laboratory Thermal Cone Penetration Tests (T-CPT) on sand samples, tests were also performed at a clayey soil obtained from Geotechnical Experimental Site located at Ponta Grossa, Parana State, Brazil. The particle size distribution of this soil is shown in Fig. 4. These tests aimed to compare results with field tests carried out at this location and explained in Sect. 3.3. Therefore, soil was collected in disturbed samples, disaggregated and recompacted to reproduce the field soil condition through its dry density, which was obtained from undisturbed samples, resulting in a dry density of 1.27 g/cm³, void ratio of 1.126, moisture content of 34%, and saturation degree of 81%. Samples were prepared with soil in a dry state, with natural field moisture content and with saturated soil, as shown in Table 3. For each saturation degree, the test was repeated three times.

Values of thermal conductivity were estimated using methods of Akrouch et al. (2016a) and Vardon et al. (2019) (Eqs. 1–6).

Numerical tests

Thermal Cone Penetration Tests (T-CPT) conducted in laboratory were numerically simulated using the heat transfer module of the Comsol software, in order to evaluate temperature contour behavior under different thermal conductivity conditions. Figure 5a displays the two-dimensional square section (0.30 m × 0.30 m), discretized by an unstructured free triangular mesh composed of 3,423 vertices and 6,644 elements with sizes up to 0.006 m. Each model was simulated considering 30 minutes of heat exchange between the cone tip and surrounding soil, promoted by the differential temperature of 50 °C defined at the start of simulation. As

Fig. 4 Clayey soil particle size distribution

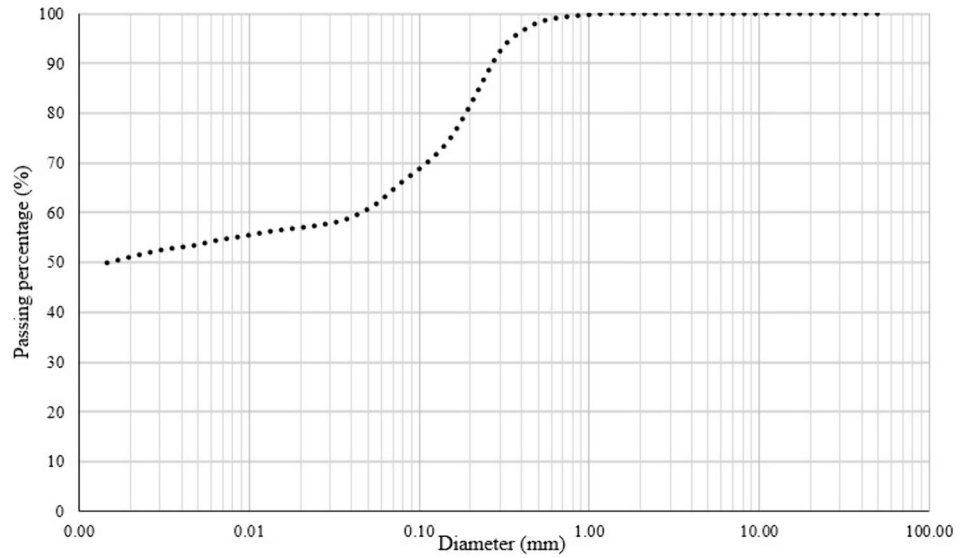


Table 3 Laboratory thermal cone penetration tests (T-CPT) on clayey soil samples

State Sample	w (%)	Sr (%)
Dry	0	0
Natural	34	81
Saturated	42	100

the evaluated behavior is time dependent, simulation was initially divided into 60 timesteps, 30 seconds each. Regarding boundary conditions during simulation, temperature in the

side and down boundaries of the model was kept constant. Initial temperature conditions can be seen in Fig. 5b.

Tables 4 and 5 presents constant and variable parameters used in simulations. It is noted that the specific soils heat capacity (C_g) and thermal conductivity (λ) were varied, to verify their influence on heat dissipation time. The extreme values for thermal conductivity and specific heat capacity were based on suggested values by Laloui and Loria (2020) for dry and saturated sand. Specifically for thermal conductivity, the range of values was adjusted in function of the

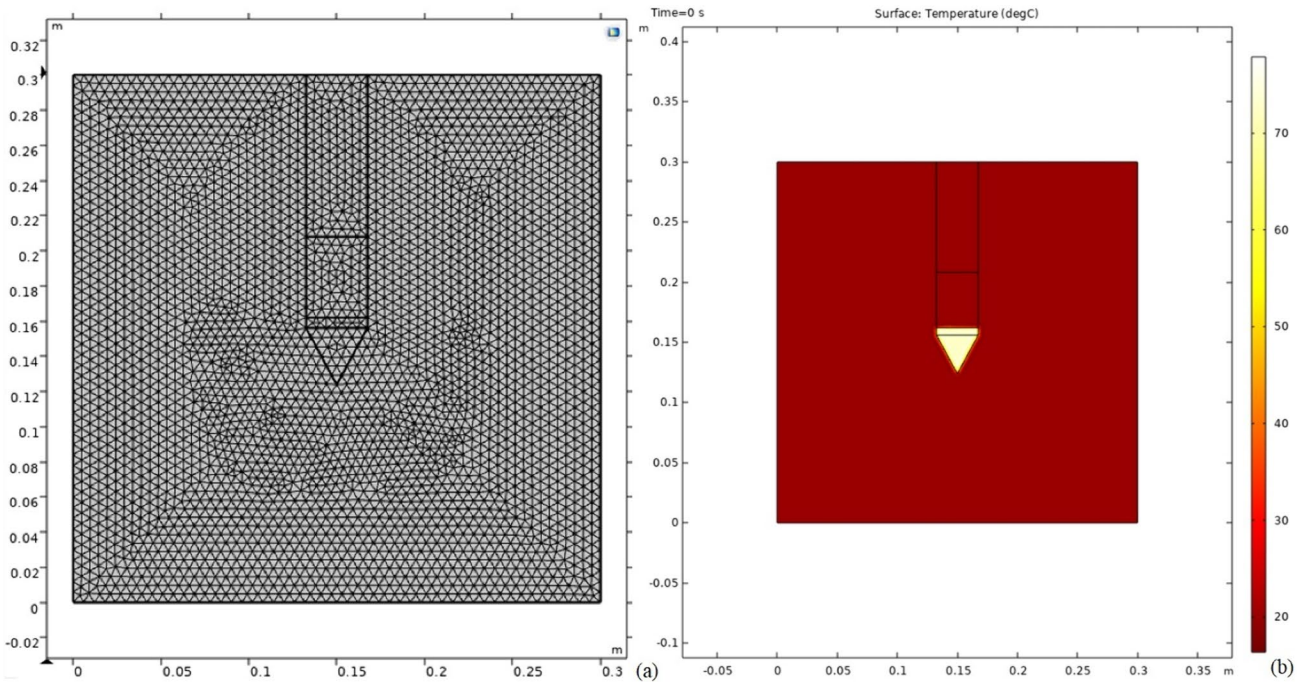


Fig. 5 (a) Section used in numerical modeling (Niedvieski et al. 2023); (b) Model initial conditions (Tonus et al. 2022)

Table 4 Constant parameters used in numerical simulations

Parameter	Value
Cone radius	0.0175 m
Initial soil temperature	20.0 °C
Initial cone temperature	70.0 °C
Specific heat capacity of dry sand	900 J/kg.°C
Specific heat capacity of moist sand	1,250 J/kg.°C
Specific heat capacity of the cone (steel)	475 J/kg.°C
Specific heat capacity of the insulating sleeve (Celeron)	1,465 J/kg.°C
Density of the cone (steel)	7,850 kg/m ³
Density of the insulating sleeve (Celeron)	1,350 kg/m ³
Thermal conductivity of the cone (steel)	44.5 W/m.°C
Thermal conductivity of the insulating sleeve (Celeron)	0.35 W/m.°C

Table 5 Variable parameters used in numerical simulations

Thermal conductivity (W/m.°C)	Specific heat capacity (J/kg.°C)		
	600	700	800
0.5	600	700	800
0.8	600	700	800
1.1	900	1150	1400
1.8	900	1150	1400
2.1	1500	1750	2000
2.8	1500	1750 </td <td>2000</td>	2000

results obtained in laboratory tests with sand. Soil density was considered constant and equal to 1700 kg/m³.

Field tests

Thermal Cone Penetration Tests (T-CPT) were conducted in three different locations: at the Geotechnical Experimental Site of Ponta Grossa, along with the Geotechnical Experimental Site of Maringá, both cities located in Paraná state, Southern region of Brazil; and at the Foundations Experimental Site, located in São Carlos city, São Paulo state, Southeastern region of Brazil. These tests carried out in different locations made it possible to measure thermal conductivity in different types of unsaturated tropical soils.

At the Geotechnical Experimental Site of Ponta Grossa, subsurface consists of a thick superficial layer, approximately 12 m deep, of residual sandy clay of shale, which is porous, collapsible and exhibits lateritic behavior. Below this layer lies a layer of residual silty sand. Average water level was found to be approximately 11 m below the surface. A schematic soil profile is presented in the Fig. 6a. At this location, 18 Thermal Cone Penetration Tests (T-CPT) were conducted at depths ranging from 0.5 m to 7.0 m. Further

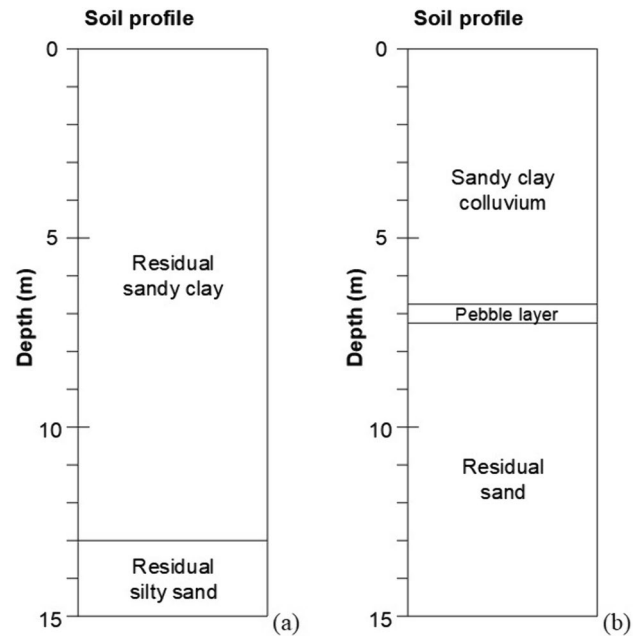


Fig. 6 (a) Geotechnical Experimental Site of Ponta Grossa soil profile; (b) Foundation Experimental Site of São Carlos soil profile

details regarding the site characterization can be obtained in Tonus et al. (2022) and Tonus (2023).

At the Foundation Experimental Site of São Carlos, subsurface consists of two distinct layers. Superficial layer is composed of porous, collapsible, lateritic sandy clay colluvium, extending to approximately 7.0 m in depth. Below this layer, up to a depth of about 23.5 m, there is a layer of fine sandy residual soil derived from sandstone with variable clay content. Between these two soil layers, there is a pebble line composed of quartz and limonite, which separates the upper colluvium layer from the residual soil layer. Water level at the time of the tests was at a depth of 9.5 m from the surface. A schematic soil profile is presented in the Fig. 6b. At this location, 7 Thermal Cone Penetration Tests (T-CPT) were conducted at depths ranging from 3.0 m to 7.0 m. Previously, Thermal Response Tests (TRT) and Thermal Needle Probe Tests were conducted to estimate thermal conductivity. More details about these tests and the site characterization can be obtained in Morais et al. (2020).

Thermal Needle Probe Tests were previously conducted on disturbed samples taken at three different depths (3 m, 6 m, and 12 m) and resulted in thermal conductivity values ranging from 1.08 to 1.66 W/m.°C. Otherwise, Thermal Response Tests (TRT) were previously conducted on a 12 m long, 0.25 m diameter drilled pile with U-shaped heat exchange tubes. These tests were performed on different dates, considering different water and saturation levels along the pile and durations, resulting in thermal conductivity values ranging from 2.34 to 3.43 W/m.°C. The authors noted

that differences between the results of these tests may be attributed to the fact that TRT is a large-scale field test that considers various soil characteristics such as groundwater flow, distinct layers and variation of moisture and density with depth. Furthermore, saturation degree and water level variation over time significantly affects the obtained results.

At the Geotechnical Experimental Site of Maringá, sub-surface consists of residual clayey soil derived from basalt, but at this location only superficial characterization tests were carried out, therefore soil profile is not known. Five Thermal Cone Penetration Tests (T-CPT) were conducted at depths ranging from 0.5 m to 1.5 m. Tests did not reach greater depths at this location because their objective was to install heat exchange tubes in trenches with a depth of 1.5 m.

Results

Laboratory tests

Thermal Cone Penetration Tests (T-CPT) in laboratory were conducted for different combinations presented in Table 2. Figures 7 and 8 shows cone heat dissipation curves over time for each scenario considered for fine and medium sands, respectively. It can be observed that, for both sands, there is a slower temperature decay for the case of dry sand (FS1 and MS7), which is expected to result in a lower thermal conductivity. It is also noticeable

Fig. 7 Cone heat dissipation for fine sand

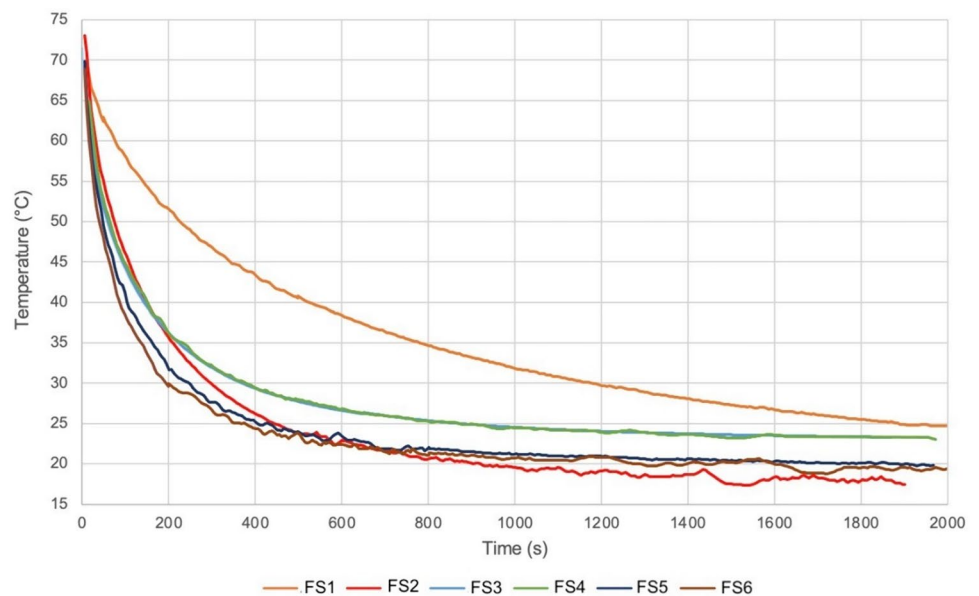


Fig. 8 Cone heat dissipation for medium sand

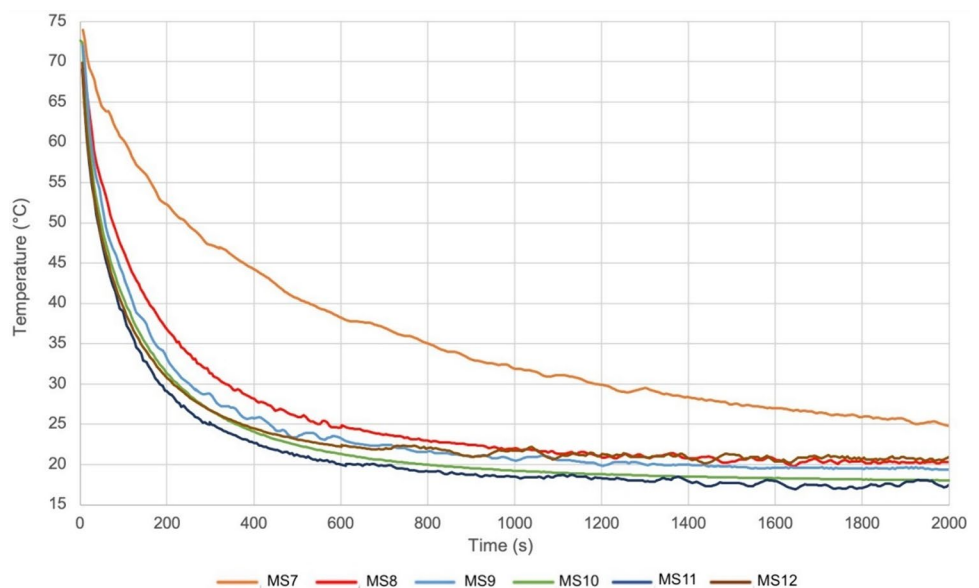


Table 6 Laboratory thermal cone penetration tests (T-CPT) results for fine sand

	w (%)	γ (g/cm ³)	Sr (%)	t_{50} (s)	λ (W/m.°C)	
					Akrouch et al. (2016)	Vardon et al. (2019)
FS1	0.48	1.48	2	243	0.51	0.37
FS2	4.84	1.56	16	97	1.29	1.31
FS3	9.98	1.63	34	80	1.56	1.46
FS4	14.65	1.71	49	76	1.64	1.64
FS5	21.54	1.78	72	65	1.92	2.02
FS6	24.12	1.85	81	54	2.31	2.20

Table 7 Laboratory thermal cone penetration tests (T-CPT) results for medium sand

	w (%)	γ (g/cm ³)	Sr (%)	t_{50} (s)	λ (W/m.°C)	
					Akrouch et al. (2016)	Vardon et al. (2019)
MS7	0.12	1.57	0	239	0.52	0.47
MS8	5.03	1.65	19	92	1.36	1.36
MS9	10.27	1.73	40	82	1.52	1.83
MS10	13.98	1.81	54	70	1.79	1.80
MS11	17.29	1.84	67	60	2.08	2.03
MS12	18.17	1.90	70	54	2.31	2.13

that heat dissipation occurred more quickly as saturation degree increased in each scenario, for both sands.

With temperature decay curves for each scenario, it was possible to determine thermal conductivity through the procedures proposed by Akrouch et al. (2016a) and Vardon et al. (2019). Table 6 shows results obtained for fine sand, where values for moisture content (w) of each model are presented, together with density (γ), saturation degree (Sr) and time for 50% dissipation of cone temperature (t_{50}). The void ratio was kept constant and equal to 0.79, which indicates a low relative sand compactness of the sand and ease of manual cone penetration. Table 7 presents the same results for tests conducted with medium sand. The void ratio was kept constant and equal to 0.69.

It is noted that FS6 and MS12 models were made with a significantly high amount of water to represent the sand saturated behavior. However, maximum saturation degree achieved was 81% for fine sand and 70% for medium sand. When plotting thermal conductivity values for both sands and both calculation methods as a function of the saturation degree in Fig. 9, it is possible to observe an increase in thermal conductivity with saturation and extrapolate the curve to theoretical saturation of 100%. It is also noticeable that the sand grain size did not strongly influence thermal conductivity values, as a polynomial adjustment with a high determination coefficient (R^2) could be achieved considering both sands and calculation methods. Therefore, it can be

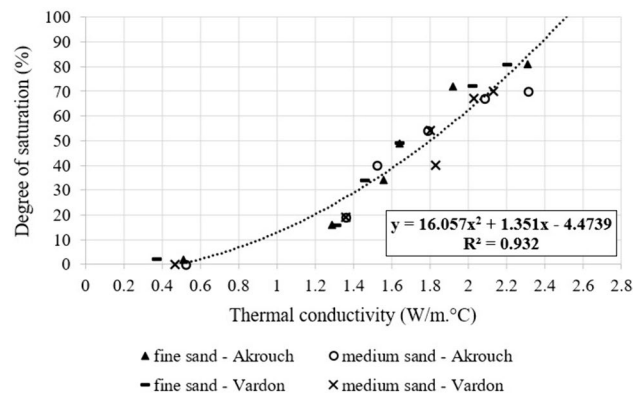


Fig. 9 Thermal conductivity variation with saturation degree

stated that thermal conductivity for dry sand is around 0.5 W/m.°C, while for saturated sand, it is around 2.5 W/m.°C.

These thermal conductivity values obtained for the studied sands showed consistency with reference values proposed in literature by various authors, such as Laloui and Loria (2020), Brandl (2006) and Akrouch et al. (2016b). That indicates suitability and representativeness of Thermal Cone Penetration Test (T-CPT) for obtaining soil thermal conductivity.

To check if cone initial heating temperature affected obtained thermal conductivity values, additional Thermal

Cone Penetration Tests (T-CPT) were conducted with lower heating temperatures below 70 °C. For this purpose, tests were repeated for both dry sands and for fine sand with saturation degrees of 49% and 72% and for medium sand with saturation degrees of 40% and 54%. Each test was performed with temperature increments of 5 °C, 10 °C, 20 °C and 35 °C. For tests conducted with a heating temperature of 70 °C, temperature increment was 50 °C, because ambient temperature was controlled at 20 °C.

Tables 8 and 9 presents obtained results for fine and medium sands, respectively, including previously obtained results for 50 °C temperature increment to facilitate comparison. It should be noted that, for simplicity, results are presented only for the Akrouch et al. (2016a) method, with standard deviation values (σ) and coefficient of variation values (CV) been provided for each tested scenario.

It is noted that, even with the cone's heating temperature variation from 5 °C to 50 °C, thermal conductivity obtained results for fine sand were very similar, resulting in low standard deviation and low coefficient of variation for the average value. In the case of a saturation degree of 72%, there was a higher standard deviation due to thermal conductivity value obtained when heating the cone by 5 °C (1.44 W/m.°C). If this value is disregarded, standard deviation decreases to 0.08 W/m.°C and coefficient of variation decreases to 4%.

When analyzing values obtained for medium sand, it is also noted that thermal conductivity results were alike, resulting in low standard deviation and low coefficient of variation. For the case of a saturation degree equal to 40%, there was a higher standard deviation due to thermal conductivity value obtained when heating the cone by 5 °C

Table 8 Thermal conductivity with variation of cone heating temperature for fine sand

Sr (%)	ΔT (°C)	λ (W/m.°C)	λ_{avg} (W/m.°C)	Σ (W/m.°C)	CV (%)
2	5	0.47	0.47	0.03	6.02
	10	0.46			
	20	0.44			
	35	0.49			
	50	0.51			
49	5	1.54	1.56	0.08	5.21
	10	1.45			
	20	1.64			
	35	1.52			
	50	1.64			
72	5	1.44	1.86	0.25	13.20
	10	1.92			
	20	1.92			
	35	2.08			
	50	1.92			

Table 9 Thermal conductivity with variation of cone heating temperature for medium sand

Sr (%)	ΔT (°C)	λ (W/m.°C)	λ médio (W/m.°C)	σ (W/m.°C)	CV (%)
0	5	0.45	0.51	0.03	6.62
	10	0.52			
	20	0.54			
	35	0.54			
	50	0.52			
40	5	1.10	1.43	0.19	13.33
	10	1.54			
	20	1.44			
	35	1.54			
	50	1.52			
54	5	1.64	1.68	0.10	5.85
	10	1.54			
	20	1.67			
	35	1.76			
	50	1.79			

(1.10 W/m.°C). If this value is disregarded, standard deviation decreases to 0.05 W/m.°C and coefficient of variation decreases to 3%.

It is concluded, therefore, that in two cases with a heating temperature of 5 °C, the obtained value of thermal conductivity deviated more from the mean value, making it more desirable to heat the cone to at least 10 °C. It is also important to highlight that the heating temperature does not need to be the same to obtain representative results, which is crucial for conducting field tests where controlling initial temperature is more challenging.

As presented in Sect. 3.1, Thermal Cone Penetration Tests (T-CPT) were conducted in laboratory for surface soil of the Geotechnical Experimental Site of Ponta Grossa too, which consists of sandy clay. The objective was to obtain thermal conductivity values for dry soil, for soil at natural moisture content and for saturated soil. Table 10 contains thermal conductivity results obtained by using procedures proposed by Akrouch et al. (2016a) and Vardon et al. (2019). Additionally, moisture content values for each sample (w), along with dry density (γ_d), saturation degree (Sr) and time for 50% dissipation of cone temperature (t_{50}) are provided. In all tests, the cone was heated up to a temperature of 70 °C.

Three tests conducted with a hygroscopic moisture content of 2.33% represents the dry soil condition. Tests with a moisture content ranging from 34.84% to 37.40% represents the soil condition at its natural moisture content in the field. And finally, tests with a moisture content of 43.80% represent the saturated soil condition. It is observed that, for the three different moisture conditions, thermal conductivity obtained values increased with

Table 10 Results of laboratory Thermal Cone Penetration Tests (T-CPT) with sandy clay soil

w (%)	γ_d (g/cm ³)	Sr (%)	t_{50} (s)	λ (W/m.°C)	
				Akrouch et al. (2016)	Vardon et al. (2019)
2.33	1.08	4	265	0.47	0.50
2.33	1.08	4	271	0.46	0.42
2.33	1.08	4	255	0.49	0.42
34.84	1.13	68	114	1.10	1.16
37.40	1.12	72	125	1.00	1.16
37.40	1.12	72	125	1.00	1.16
43.80	1.10	81	92	1.36	1.26
43.80	1.15	88	86	1.45	1.21
43.80	1.13	85	97	1.29	1.23

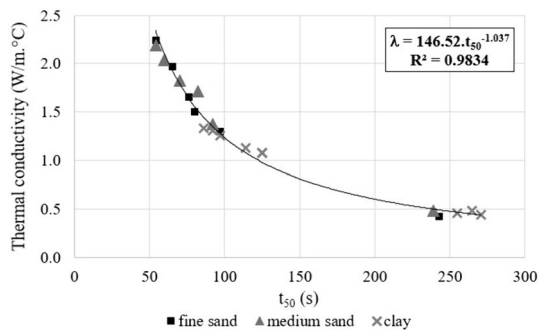


Fig. 10 Average thermal conductivity variation with t_{50} considering sand and clay soils

saturation degrees and showed minimal variation among them, which indicates good representativeness about the results. However, it was not possible to achieve a dry density of 1.27 g/cm³, highlighting the challenge of reproducing soil structure from the field in laboratory.

Nonetheless, values obtained for clayey soil thermal conductivity are consistent with typical data available in Laloui and Loria (2020). Average thermal conductivity for dry clay resulted in 0,5 W/m.°C, while for saturated clay it was 1,3W/m.°C. It is also noteworthy that, as expected, thermal conductivity value for clay was lower than that of sand, which can be particularly observed in moist soil conditions.

With the aim of visualizing the influence of time for 50% heat dissipation (t_{50}) on reached thermal conductivity results, Figure 10 shows these variables for laboratory tests conducted on both sands and clayey soil. For thermal conductivity, values plotted on graph represents the average between values obtained through those two considered methods. It is remarkable that it was possible to fit a curve with a high R² value, even considering tests on different soils.

Numerical tests

Regarding numerical modeling of Thermal Cone Penetration Tests (T-CPT), thermal conductivity was varied from 0.5 to 2.8 W/m.°C to compare it with experimentally obtained heat dissipation curves. Figure 11 presents the heat bulb formed after 30 minutes of testing for lower and upper limits of thermal conductivity, 0.5 and 2.8W/m.°C, respectively. It can be observed that when considering lower thermal conductivity, there is still heat to be dissipated after 30 minutes, with the region around the cone at approximately 35°C. However, for a thermal conductivity of 2.8 W/m.°C, considering the same time, the excess heat near the cone has already been dissipated.

To evaluate heat dissipation over time, the time for 50% heat dissipation (t_{50}) obtained from numerical simulations was plotted against adopted thermal conductivities, resulting in the curve shown in Fig. 12.

It can be observed that the curve’s shape is similar to the curve obtained from experimental results in laboratory. Therefore, in Fig. 13, experimental results are also plotted for comparison, showing agreement between the curves even when considering the difference between experimental and numerical domains. As a result, in Fig. 14, a curve encompassing both experimental and numerical results is plotted, and an adjustment is proposed to obtain thermal conductivity as a function of t_{50} .

Field tests

Thermal cone penetration tests (T-CPT) at the geotechnical experimental site of Ponta Grossa—Paraná, Brazil

Thermal Cone Penetration Tests (T-CPT) were conducted at the Geotechnical Experimental Field Site of Ponta Grossa in two stages. First, shallow tests were performed using manual excavation, followed by deep tests with mechanized excavation.

For the execution of shallow Thermal Cone Penetration Tests (T-CPT), T-CPT-01 to T-CPT-09, a preliminary excavation was performed using a manual auger, ranging from 0.5 m to 1.5 m in depth. The cone was preheated in water to at least 35 °C and manually inserted into the soil. Table 11 presents the results of these tests, where it is possible to verify soil moisture content at the time of the test (w), saturation degree (Sr) and initial temperature (T_{max}) at which the cone was heated. Thermal conductivity was calculated using methods of Akrouch et al. (2016a) and Vardon et al. (2019).

It is observed that an average thermal conductivity value of 1.39 W/m.°C was obtained, considering all tests performed and both calculation methods. For this average value, there was a standard deviation of 0.18 W/m.°C and a coefficient of variation of 13%, which can be considered

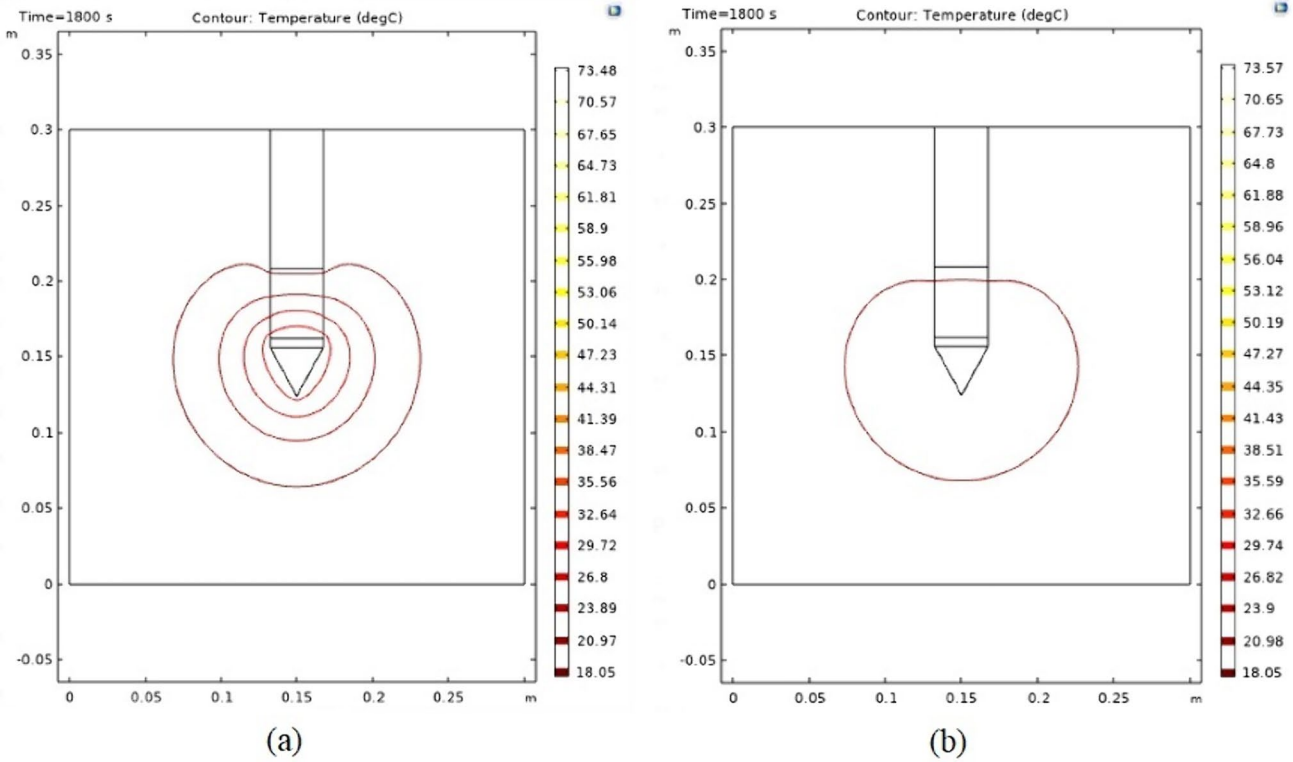


Fig. 11 Heat bulb after 30 min for thermal conductivity of (a) 0.5 W/m.°C and (b) 2.8 W/m.°C

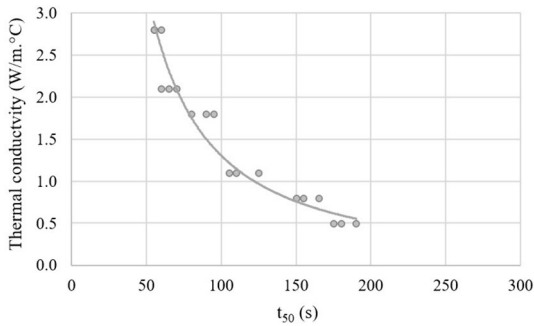


Fig. 12 Variation of average thermal conductivity with t_{50} in numerical simulations

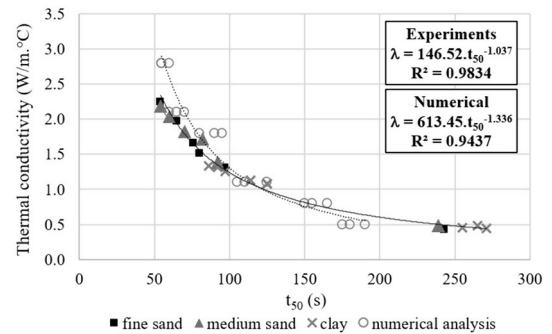


Fig. 13 Average thermal conductivity variation with t_{50} considering experimental and numerical results

low due to common heterogeneity in field tests, especially at shallow depths.

For the execution of deep Thermal Cone Penetration Tests (T-CPT), T-CPT-10 to T-CPT-18, prior excavation was performed using a mechanized auger, with depths ranging from 3.0 m to 7.0 m. The cone was preheated in water to at least 50 °C before being inserted into the soil, which was done with assistance of a Munck truck. It is worth noting that an attempt was made to drive the cone directly using the Munck truck to observe if there would be sufficient heat generation for the test. However, heat generated was quite small, likely

due to low-consistency clayey soil, so the cone heating continued to be performed with hot water.

Table 12 exposes the results of deep Thermal Cone Penetration Tests (T-CPT), where it is possible to verify soil moisture content at the time of the test (w) and initial temperature (T_{max}) to which the cone was heated. Additionally, thermal conductivity values obtained for three tested depths (3.0 m, 5.0 m, 7.0 m) are presented. For deep tests, it was not possible to calculate soil saturation degree, since undisturbed samples were not taken at depth.

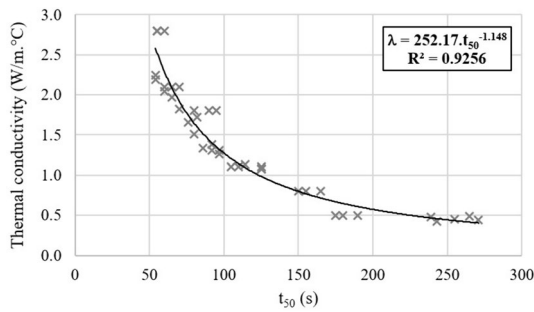


Fig. 14 Proposed curve to estimate thermal conductivity as a function of t_{50}

It is noted that for tests conducted at a depth of 3.0 m, average thermal conductivity value of 1.69 W/m.°C was obtained, with standard deviation of 0.16 W/m.°C and coefficient of variation of 9%. For tests at a depth of 5.0 m, average thermal conductivity value of 2.45 W/m.°C was obtained, with standard deviation of 0.37 W/m.°C and coefficient of variation of 15%. Finally, for tests at a depth of 7.0 m, average thermal conductivity value of 2.27 W/m.°C was obtained, with standard deviation of 0.21 W/m.°C and

coefficient of variation of 9%. It can be concluded that considering common heterogeneity in field tests, relatively low values of standard deviation and coefficient of variation were obtained when analyzing thermal conductivity results for tests conducted at 3.0 m and 7.0 m depth. However, for tests conducted at 5.0 m depth, these values were higher, and it may be advisable to disregard the result of test T-CPT-14 to obtain the average thermal conductivity value. With this it is concluded that is important to carry out at least three field tests for each depth of interest so that variation in data can be analyzed and a more representative value of thermal conductivity can be adopted.

It should be emphasized that all these tests were conducted on the same type of clayey soil and above water level, which justifies the proximity of obtained thermal conductivity values. However, it is noticeable that even with a small variation in soil moisture content, it influences results obtained, leading to higher thermal conductivity values for higher soil moisture content. This influence can be better observed in the graph in Fig. 15, where the increase in thermal conductivity with moisture content is evident and a suitable linear fit is achieved by disregarding two outlier points. Such behavior was also observed in laboratory tests

Table 11 Shallow Thermal Cone Penetration Tests (T-CPT) results in Ponta Grossa

Test	Depth (m)	w (%)	Sr (%)	T_{max} (°C)	λ (W/m.°C)		
					Akrouch et al. (2016)	Vardon et al. (2019)	Average
T-CPT-01	0.5	34.09	81%	55.21	1.54	1.35	1.39
T-CPT-02	0.5	34.30	82%	55.06	1.64	1.42	
T-CPT-03	0.5	33.59	81%	57.35	1.54	1.36	
T-CPT-04	0.5	33.81	81%	45.02	1.44	1.21	
T-CPT-05	1.0	35.50	83%	42.97	1.44	1.19	
T-CPT-06	1.5	39.04	87%	43.43	1.54	1.32	
T-CPT-07	0.5	32.08	79%	61.39	1.76	1.46	
T-CPT-08	0.5	32.06	79%	43.26	1.28	1.30	
T-CPT-09	0.5	34.44	82%	34.91	1.10	1.10	

Table 12 Deep Thermal Cone Penetration Tests (T-CPT) results in Ponta Grossa

Test	Depth (m)	w (%)	T_{max} (°C)	λ (W/m.°C)		
				Akrouch et al. (2016)	Vardon et al. (2019)	Average
T-CPT-10	7	38.34	52.32	2.55	2.38	2.27
T-CPT-11	7	37.30	59.12	2.31	2.16	
T-CPT-12	7	37.57	62.95	2.27	1.92	
T-CPT-13	5	40.06	72.81	2.78	2.70	2.45
T-CPT-14	5	39.08	64.32	1.92	2.04	
T-CPT-15	5	39.63	63.57	2.66	2.58	
T-CPT-16	3	35.33	51.39	1.64	1.53	1.69
T-CPT-17	3	38.42	55.96	1.79	1.52	
T-CPT-18	3	37.03	58.53	1.92	1.72	

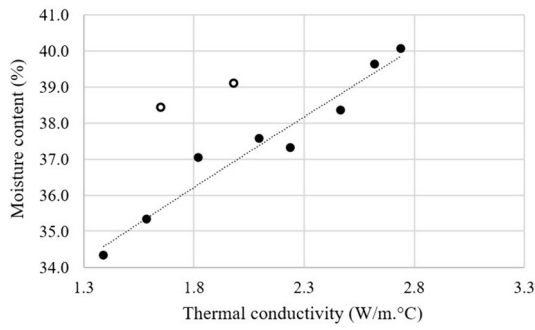


Fig. 15 Thermal conductivity variation with moisture content

when varying the moisture content of the used sand. In the graph, the point with the lowest moisture content and thermal conductivity corresponds to the average value of superficial tests, while other points represent deep tests. This graph was made with moisture content instead of saturation degree because, as already mentioned, undisturbed samples were not extracted at a depth that would allow its calculation.

Regarding obtained thermal conductivity values, it is evident that there is a lower average value for tests conducted at a depth of 3.0 m, which is 1.69 W/m.°C, while tests conducted at depths of 5.0 m and 7.0 m yielded similar values of 2.45 W/m.°C and 2.27 W/m.°C, respectively. It can be observed that higher moisture content values observed at greater depths reflected in an increase in thermal conductivity. Furthermore, for shallow Thermal Cone Penetration Tests, average thermal conductivity value of 1.39 W/m.°C was obtained with average moisture content of 34.3%, which confirms the consistency of obtained results and their variation with soil moisture.

Thermal cone penetration tests (T-CPT) at the geotechnical experimental site of Maringá–Paraná, Brazil

Thermal Cone Penetration Tests (T-CPT) were conducted at the Geotechnical Experimental Site in Maringá within two excavated trenches with a depth of 1.50 m for the installation of geothermal systems. Two T-CPT tests were performed in each trench, with T-CPT-01 and T-CPT-02 in the first

trench (TR-01) and T-CPT-03 and T-CPT-04 in the second trench (TR-02). Test T-CPT-05 was conducted on the ground surface. The cone was preheated in water to at least 35 °C before its insertion into the soil.

Table 13 presents the results of Thermal Cone Penetration Tests (T-CPT) conducted, where it is possible to verify the soil moisture content at the time of the test (*w*), saturation degree (*Sr*) and initial temperature (*T_{max}*) to which the cone was heated. Additionally, thermal conductivity values obtained for two calculation methods under study are presented. For calculation of saturation degree, average natural specific weight of 1.67 g/cm³ was considered, that is available in Visintin (2023).

It is noticeable that despite trenches being excavated in close proximity there was a significant variation in thermal conductivity values between them, resulting in average value of 0.78 W/m.°C, with standard deviation of 0.20 W/m.°C and coefficient of variation of 25%. Although moisture content values are very close, it was observed in the field that the second trench was in a drier condition. Conductivity differences are not insignificant but may have been influenced by common heterogeneity in upper layers or by disturbance of test region during the excavation process.

It is also worth noting that despite both being clayey soils, thermal conductivity values obtained in Maringá were lower than those obtained in Ponta Grossa. This emphasizes the importance of other variables such as mineralogical composition at each location and in situ stress condition.

Thermal cone penetration tests (T-CPT) at the foundation experimental site of São Carlos–São Paulo, Brazil

Thermal Cone Penetration Tests (T-CPT) were also conducted at the Foundation Experimental Site of São Carlos near a 0.25 m diameter heat exchanger pile, in which Thermal Response Tests (TRT) were previously performed. Five tests were done, distributed across two boreholes. In borehole 1, tests T-CPT-01 to T-CPT-03 were performed, while in borehole 2, tests T-CPT-04 and T-CPT-05 were conducted. A conventional Cone Penetration Test (CPT) machine was used to drive the cone and before each test, the cone was heated in boiling water. However, only tests up to

Table 13 Thermal cone penetration tests (T-CPT) results in Maringá

Test	Depth (m)	<i>w</i> (%)	<i>Sr</i> (%)	<i>T_{max}</i> (°C)	<i>λ</i> (W/m.°C)		
					Akrouch et al. (2016)	Vardon et al. (2019)	Average
T-CPT-01	1.5	33.73	71	51.85	1.05	0.92	0.78
T-CPT-02	1.5	31.94	69	40.40	1.04	0.88	
T-CPT-03	1.5	30.90	68	34.53	0.61	0.54	
T-CPT-04	1.5	31.93	69	56.42	0.62	0.53	
T-CPT-05	0.5	25.82	61	60.52	0.80	0.78	

a depth of 7.0 m could be performed successfully. Beyond this limit, the cone cooled down during driving and did not generate sufficient heat.

Table 14 presents the results of Thermal Cone Penetration Tests (T-CPT) conducted, where it is possible to verify soil moisture content at the time of the test (*w*), approximate saturation degree (*Sr*) and initial temperature (*T_{max}*) to which the cone was heated. Soil moisture content was obtained through disturbed samples taken from a pre-drilled hole prior to the test, and saturation was obtained from monitoring data available in Morais et al. (2020).

It is noticeable that thermal conductivity values obtained ranged from 1.42 to 2.31 W/m.°C, with only T-CPT-03 test being conducted in residual soil layer, while other tests focused on shallow colluvial layer. It is noted that there was a small variation in soil moisture content in collected samples since the tests did not reach groundwater, which was located 9.5 m below the surface on the day of the tests.

According to monitoring data available in Morais et al. (2020), soil moisture content does indeed remain relatively constant up to the studied depth, although its magnitude may vary over months. However, saturation degree of soil increases with depth, leading to an increase in thermal conductivity in depth. Additionally, the increase in soil density in depth, with consequent reduction of voids, also raises the soil thermal conductivity.

Regarding previously conducted thermal tests, it is observed that thermal conductivity values obtained by Thermal Cone Penetration Test (T-CPT) were higher than those obtained by Thermal Needle Probe Test. Low et al. (2015) had already observed that laboratory methods give significantly lower values of thermal conductivity than Thermal Response Tests (TRT). According to the authors, TRT thermal conductivity value is about twice the Needle Probe value, and one possible reason is that after soil samples are taken, the soil no longer experiences the same stresses as when it was in the ground, the laboratory tests were undertaken without any confining pressure. Furthermore, Thermal Needle Probe Tests were performed with disturbed samples, where the structure of the cemented lateritic soil is not preserved, which further reduces representativeness

of laboratory results. Thus, Thermal Needle Probe Tests at 3 m and 6 m depth resulted in thermal conductivity of 1.16W/m.°C and 1.08W/m.°C, respectively. While T-CPT between 3 and 7 m depth resulted in values between 1.42W/m.°C and 2.31W/m.°C. Therefore, the behavior already observed by the authors cited previously of lower thermal conductivity values for laboratory tests in relation to field tests is confirmed with T-CPT too.

Regarding results of Thermal Response Tests (TRT), it is emphasized that directly comparing results obtained through Thermal Cone Penetration Test (T-CPT) with those from Thermal Response Tests (TRT) is not appropriate. TRT is not conducted at specific depths but rather along the entire length of the pile (12 m). Consequently, obtained results are influenced by the portion of the pile located below groundwater, along with the time of the year when the test was conducted due to variations in soil saturation and also penetration into denser soils. In any case, the average thermal conductivity obtained by TRT tests was 2.94 W/m.°C, this value being higher than T-CPT thermal conductivity because TRT test reached a denser and saturated soil layer.

Even though, with data obtained in this study, it is possible to conclude about the potential of Thermal Cone Penetration Test (T-CPT) in estimating thermal conductivity. T-CPT is a much faster test compared to TRT and can be conducted with standard geotechnical investigation equipment without the need for prior installation of pipes in the soil. Furthermore, TRT provides an average conductivity value along the depth and T-CPT allows knowing thermal conductivity at each point of interest along the depth, similar to a subsoil thermal stratigraphy. By incorporating a heating system into the cone, the test becomes even quicker, because different depths can be tested within the same borehole without the need to remove the cone for heating in water.

After completing all Thermal Cone Penetration Tests (T-CPT) in the field, their thermal conductivity values, and time for 50% heat dissipation (*t₅₀*) were plotted alongside the curve adjusted with laboratory tests and numerical simulations, as shown in Fig. 16.

It is noted that field results showed the same behavior trend, validating the previously adjusted curve. This shows

Table 14 Thermal cone penetration tests (T-CPT) results in São Carlos

Hole	Test	Depth (m)	<i>w</i> (%)	<i>Sr</i> (%)	<i>T_{max}</i> (°C)	<i>λ</i> (W/m.°C)	
						Akrouch et al. (2016)	Vardon et al. (2019)
1	T-CPT-01	3.0	17.80	50	37.95	1.67	1.51
	T-CPT-02	5.0	18.50	57	27.16	1.79	1.76
	T-CPT-03	7.0	18.90	64	28.52	1.93	1.78
2	T-CPT-04	3.0	17.80	50	49.98	1.44	1.42
	T-CPT-05	5.0	18.50	57	30.21	2.31	2.28

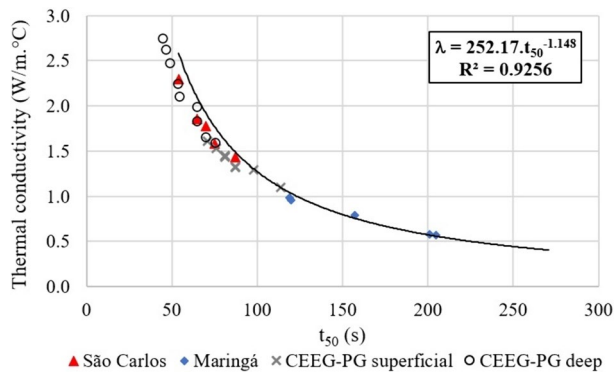


Fig. 16 Thermal conductivity variation with time for 50% heat dissipation (t_{50})

the test suitability for unsaturated tropical soils. Additionally, there is greater similarity between thermal conductivity values obtained in Ponta Grossa and São Carlos, whereas values obtained in Maringá were lower. This difference may be attributed to the fact that Maringá's soil is a residual clayey soil derived from basalt, likely containing a smaller quantity of quartz in its composition.

Finally, it is emphasized that field tests were limited to three locations in Brazil, and it is great important that this research be extended to other regions to consolidate Thermal Cone Penetration Tests (T-CPT) as a suitable tool for obtaining thermal conductivity. In any case, unsaturated tropical lateritic soils are very common in Brazil and can also be found in other regions of the world, such as South America, Africa and Southeast Asia (Sun et al. 2022).

Final remarks

The present research was developed with the aim of analyzing the feasibility of using Thermal Cone Penetration Test (T-CPT) to determine soil thermal properties, considering this test as an available tool with a simple procedure for design and implementation of shallow geothermal systems. Following topics are the main conclusions obtained from the development of this study.

- In Cone Penetration Tests (T-CPT) carried out in laboratory, the magnitude of thermal conductivity values obtained for studied soils showed consistency with reference values proposed in literature by several authors, such as Laloui and Loria (2020), Brandl (2006) and Akrouch et al. (2016b), indicating the appropriate representativeness of Thermal Cone Penetration Tests (T-CPT) for obtaining soil thermal conductivity under tested laboratory conditions. Furthermore, as expected,

an increase in value of thermal conductivity obtained with an increase in soil saturation degree was noted.

- Regarding calculation methods used to obtain thermal conductivity, it was noted that results were very close between the proposals of Akrouch et al. (2016a) and Vardon et al. (2019). However, Akrouch et al. (2016a) method presented values around 10% higher than the Vardon et al. (2019) method for most cases.
- It was possible to adjust a curve of relation between thermal conductivity and time for 50% heat dissipation (t_{50}) with results obtained through laboratory and numerical tests. Thermal conductivity values for sand and clay soils showed the same trend in the curve. The same fitted curve was also fed with results obtained from numerical modeling, leading to the proposal of an equation to obtain thermal conductivity as a function of time for 50% heat dissipation (t_{50}). Even considering tests on different soils and the difference between experimental and numerical domains, the curve presented a high R^2 value.
- With all field tests results, it was noticed the growth of thermal conductivity with the saturation degree and the increase in subsoil density. It was noticed too that the adjusted curve using laboratory and numerical tests adequately represents variation of thermal conductivity with time for 50% heat dissipation (t_{50}). Thermal conductivities between 0.53 and 2.78 W/m.°C were obtained considering the three different locations tested, all being from unsaturated tropical soils. In these soils, saturation degree can vary seasonally, modifying the soil thermal properties; by carrying out Thermal Cone Penetration Test (T-CPT) at different times of the year, it would be possible to establish the thermal conductivity variation.
- Finally, it is concluded that Thermal Cone Penetration Test (T-CPT) is a technically and economically viable tool for obtaining thermal conductivity in the field, since, with many tests conducted, values obtained have always been consistent with data available in literature. Currently, the field test used for this purpose is Thermal Response Test (TRT), which is a much longer test that requires prior installation of heat exchanger tubes in the soil, along with the need for specific equipment for its execution and complex interpretation of results. Furthermore, TRT provides a medium value of thermal conductivity along the depth. On the other hand, Thermal Cone Penetration Test (T-CPT) is performed using conventional Cone Penetration Test (CPT) equipment, which is commonly used in geotechnical investigations and allows multiple tests to be conducted on the same day without the need for specific equipment or prior installations. This allows different results along depth to know the soil stratigraphy in terms of thermal conductivity and not just an average value. It should also be noted that methods for obtaining thermal conductivity in labora-

tory normally underestimate its value, therefore it is more appropriate to carry out field tests to obtain it, and T-CPT is a suitable alternative. However, even though this might not be an issue in soils with higher lateral friction, it is recommended to insert a heater in the cone to facilitate the testing procedure in field for all conditions, because in clay soils tested, not enough heat was generated. Furthermore, with the use of the heater, tests can also be more easily carried out at reduced depths, maintaining the minimum temperature difference between the cone and the ambient of 10 °C as observed in laboratory tests.

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Author contribution B.P.A.T. and C.E.R.L. wrote the main manuscript text. L.B.N. prepared all figures and do the numerical simulations. C.H.T. and V.P.F. reviewed the manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

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