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In-situ test methods for thermal site characterization – a comparison

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ABSTRACT

The demand for thermal site characterization has risen noticeably in the past decade, particularly for design of geothermal energy solutions and for design of in-ground power cable networks. The results of thermal characterization of a site are typically incorporated in a ground model based on environmental, geological, geophysical and geotechnical geodata. This paper compares in-situ test methods for thermal site characterization of soil. The comparison considers method applicability, deployment method, maximum test depth, test duration and uncertainty of results. A distinction is made between three categories of in-situ tests: (1) in-situ tests using active heat generation, (2) in-situ tests using passive heat generation and (3) in-situ tests with no specific thermal data acquisition.

Keywords: thermal site characterization; thermal conductivity; volumetric heat capacity; in-situ testing.

1. Introduction

The demand for thermal site characterization has risen noticeably in the past decade, particularly for (1) design of geothermal energy solutions, for example ground heat exchangers (shallow geothermal energy solutions) and (2) in-ground electricity cables and cable-in-pipe systems, both onshore and offshore.

The results of thermal characterization of a site are typically incorporated in a ground model based on environmental, geological, geophysical, and geotechnical geodata.

For accurate thermal site characterisation, it is common to acquire specific source geodata, notably values of thermal conductivity k and volumetric heat capacity C derived from laboratory tests and in-situ tests. Thermal properties can be regarded as a subgroup of geotechnical properties.

A large number of publications provide valuable comparisons of geotechnical laboratory tests versus in-situ tests. The comparisons typically focus on topics such as schedule (early availability of geodata), cost, volume of tested soil, specimen representativeness of in-situ conditions, and representativeness of in-situ test results for future in-situ conditions. Generally, these topics would also apply to thermal testing.

This paper compares in-situ test methods for thermal site characterization of soil. The comparison focuses on commercially available methods. The scope of the methods discussed is limited to methods that are used within a depth of 200 m below ground surface. This depth limit includes most vertical ground heat exchangers. The comparison can serve as input for decisions on thermal site characterization projects.

2. Comparison of test methods

2.1. Overview

Table 1 and Figure 1 present an overview of in-situ test methods for thermal site characterization.

The table applies to thermal data points as input parameter values for thermal site characterization. Table 1 excludes considerations for post-test integration of these values into an appropriate ground model. Post-test integration activities can include application of value enhancement technologies such as geostatistical and Bayesian methods for combining results of multiple thermal test methods and use of prior geodata. These activities are particularly valuable for the common cases of sparse data sets and geodata gaps.

The columns ‘Depth limit’, ‘Test data’ and ‘Test duration’ in Table 1 provide indicators for schedule and cost. Efficient accomplishment of thermal site characterization can require the mobilization and use of more than one of the methods of Table 1.

Further explanatory notes are given in Sections 2.2 to 2.5. Method-specific comments are included in Sections 3 to 5.

2.2. Categories

The columns ‘Test type’ and ‘Category’ (of Table 1) refer to in-situ test methods summarized in Sections 3 to 5 below.

Category 1 refers to in-situ tests using active heat generation, Category 2 to in-situ tests using passive heat generation, and Category 3 to in-situ test correlations, i.e. in-situ tests with no specific thermal data acquisition.

As expected, applicability ratings for Categories 1 and 2 are typically more favourable than those for Category 3.

Table 1. Comparison of in-situ test methods for thermal site characterization. Symbols and abbreviations used are explained in Section 2

Test type	Category	Deployment method	Depth limit	Test data	Test duration	Geodata value	
						(A)	(B)
Heat Flow Needle Probe Test – Single Sensor	1	SD, DD	1.5 – 15 m	1 datapoint per test	~ 20 minutes	** (na)	na (na)
Heat Flow Needle Probe Test – Multi Sensor	1	SD	1.5 - 6 m	0.3 m to 0.45 m between datapoints	~ 2 minutes	** (na)	na (na)
Heat Flow CPT Module Test	1	SD	~50 m	1 datapoint per test	~ 15-20 Minutes	*** (*)	*** (*)
Heat Flow Thermistors Test – Gravity Deployment	1	SD	~5 m	~0.25 m between datapoints	~ 2 minutes	** (**)	na (na)
Heat Flow Thermistors Test - Vibratory Deployment	1	SD	~5 m	~0.25 m between datapoints	~ 2 minutes	** (**)	* (*)
Heat Flow Thermistors Test - Mini Penetrometer Deployment	1	SD	~6 m	~0.45 m between datapoints	~ 3 minutes	*** (***)	*** (***)
Borehole Thermal Response Test	1	DD	200 m	1 average value per borehole	~ 50 hours	*** (***)	*** (***)
Thermal Cone Penetration Test	2	SD, DD	50 – 200 m	1 datapoint per test	~ 15 minutes	* (*)	*** (*)
Cone Penetration Test	3	SD, DD	50 – 200 m	0.02 m between data points	1 second	* (*)	* (*)
Borehole Geophysical Logging	3	DD	200 m	1 datapoint per test	~ 2 minutes	* (*)	* (*)

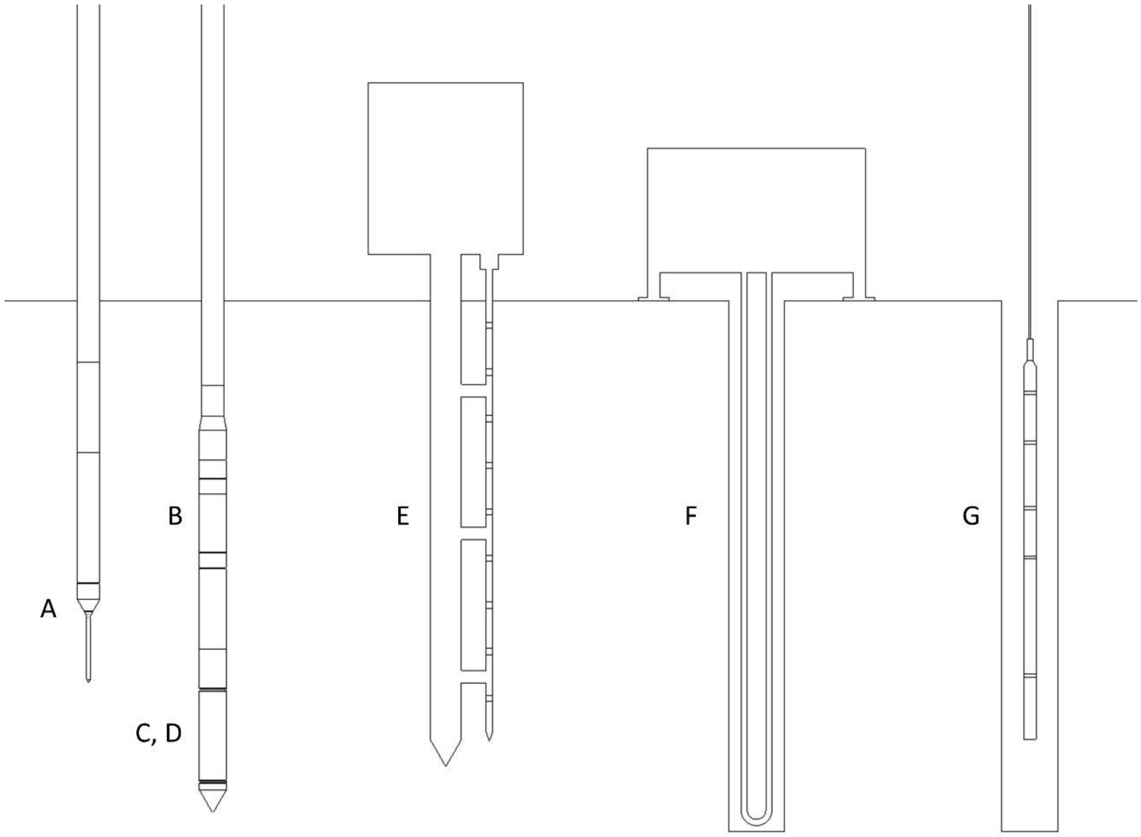

Figure 1. Sketch of in-situ test methods for thermal site characterization (not to scale). A: heat flow needle probe test – single sensor; B: heat flow CPT module test; C: cone penetration test; D: thermal cone penetration test; E: heat flow thermistors test – gravity deployment; F: borehole thermal response test; G: borehole geophysical logging – P and S suspension logging

2.3. Deployment methods

Deployment methods are broadly summarized in the column ‘Deployment Method’, as follows:

SD	Surface Deployment
DD	Drilling Deployment.

SD methods include push systems using a thrust machine (e.g. for cone penetration tests, CPTs), use of gravity (free fall systems and winch-deployed systems) and vibratory (sonic, resonance) driving.

DD methods cover (1) incremental probe deployment below the bottom of a borehole and (2) system deployment in an open borehole.

ISO (2023) includes extensive descriptions of SD and DD methods for in-situ testing in a marine environment. Similar, typically smaller-scale, systems are available for onshore in-situ testing.

2.4. Depth limits

The column ‘Depth limit’ provides typical values for maximum depth below ground surface that can be achieved for a particular in-situ test method for Soil Types (A) and (B), where applicable. These soil types are described in Section 2.6.

Depth limits typically depend on deployment method and probe robustness. Depth limits for SD systems typically range from about 5 m to 50 m. Depth limits for DD methods typically range from 100 m to > 200 m. Probe robustness is covered in Sections 3 to 5, where applicable.

If depth limits for SD systems are acceptable, then they can offer schedule and cost advantages compared to DD systems.

2.5. Test data and duration

The columns ‘Test data’ and ‘Test duration’ should be considered in combination.

It can be noted here that in-situ methods of Categories 1 and 2 require data acquisition at a stationary geospatial position. For a single geospatial of the tool, test data can comprise one or more data points. For example, a heat flow thermistors system with its tip at 5 m below ground surface can typically acquire 20 data points. Test time at this geospatial position would be about 20 minutes. The column ‘Test duration’ shows the time per data point. Test duration excludes the time required for reaching the required geospatial position.

Tests with SD methods of Categories 1 and 2 can include the following stages:

1. Advance probe to required test depth.
2. Record temperature over time to measure thermal dissipation of the heat induced by soil friction during penetration.
3. Apply constant power to the probe’s heater and record temperature over time.
4. Record temperature dissipation of the heat induced by the heating element of the probe.
5. Penetrate the probe to next required test depth or retrieve the probe.

Further details per test method are given in Sections 3 and 4.

In-situ methods of Category 3 can include continuous data acquisition (notably CPTs) and can require data acquisition at a stationary geospatial position (borehole geophysical logging).

Note that the term ‘data point’ is used here, consistent with geotechnical practice. A depth range or the term ‘data zone’ can also be considered, accounting for the volume of soil actually tested.

2.6. Geodata value

Method applicability is rated by 'Geodata value’ (last column of Table 1) for two broad soil types:

(A)	Soil with CPT cone resistance lower than 3 MPa
(B)	Soil with CPT cone resistance between 3 MPa and 80 MPa.

Explanation of the qualitative indicators is as follows

***	Low uncertainty of thermal test results
**	Medium uncertainty of test results
*	High uncertainty of test results
na	Test method not applicable.

Indicators without parentheses refer to values of thermal conductivity. Indicators within parentheses refer to values of volumetric heat capacity.

To the knowledge of the authors, rigorous methods for estimation of uncertainties of in-situ test results have been published only for a few geotechnical parameters, e.g. CPT parameters (Peuchen & Terwindt, 2014) and small-strain shear modulus derived from seismic cone penetration tests (Parasie et al. 2022). No such methods have been published for in-situ thermal test results and, for that matter, laboratory thermal test results.

The geodata value comparison rating considers:

- Conventional soils. Unconventional soils (ISO, 2023) and rock are excluded from the rating;
- Homogenous volume of ground applicable to the test method. Heterogeneity, such a thinly bedded soil, can adversely affect uncertainty of test results;
- $D_{90}/D_p < 0.2$, where D_{90} is a soil particle diameter such that 90 % of the dry mass of soil has a smaller particle diameter and where D_p is the effective diameter of the in-situ test probe. The D_{90}/D_p ratio can be important for soil-probe interface effects on acquired test values;
- Source geodata. This implies using the data from the test method only, with no enhancement by use of other data from the ground model;
- Representativeness of acquired thermal parameter values for in-situ conditions existing immediately before performing the test;

Opportunities for use of the test results for defined (future) conditions other than in-situ conditions existing immediately before performing the test.

3. In-situ tests using active heat generation

3.1. Heat flow needle probe test

The heat flow needle probe represents a large-scale, in-situ adaptation of the widely employed laboratory heat flow needle probe, providing thermal conductivity values.

The probe consists of a cylindrical steel rod which houses a heater and one or multiple temperature sensors (IEEE, 2017). The probe has a high length-to-diameter ratio with the aim that the soil thermal behaviour of the probe can be approximated by an infinite line heat source model.

The probe can have a length of 200 mm to 250 mm, acquiring a single datapoint per test (single sensor probe, Table 1). Probes with a length of > 1 m are also available, acquiring multiple datapoints per test, with a spacing of 300 mm to 450 mm between datapoints (multi sensor probe, Table 1).

Some probe types can be deployed by hand (manual push, SD deployment). Manual push can also be combined with a pre-drilled access/ pilot hole, DD deployment. Some probe types allow deployment with use of Cone Penetration Test (CPT) deployment systems.

A heat flow needle probe test consists of Stages 1, 2, 3 and 5 of Section 2.5. Stages 2 and 3 typically take 5 minutes and 15 minutes to conduct respectively. Stage 4 can additionally be incorporated in the test procedure to minimize errors from small temperature drifts (ASTM, 2022).

The thermal data acquired during Stage 3 of the test procedure are interpreted (for k) in accordance with Carlslaw and Jaeger (1959) utilizing the 1D analytical thermal line source solution of the heat conduction equation. This interpretation method is recommended by e.g. ASTM (2022) and IEEE (2017).

The probe finds optimal application in Soil Type (A), as there is considerable risk of irreversibly damaging the tool in Soil Type (B) due to its relatively delicate geometric structure.

As the diameter of the probe (Dp) can be relatively small, the limit on the D90/Dp ratio, as described in Section 2.6, should be considered.

3.2. Heat flow CPT module test

The heat flow CPT module is add-on instrument integrated with a Cone Penetration Test (CPT). Like the heat flow needle probe, this module incorporates a heating element and temperature sensors (Isaev et al. 2018; Mo et al. 2021; Mo et al. 2022; Vrielink 2022; Vrielink et al. 2023).

The external surface of the probe is flush with the external surface of sections above and below probe. The instrumentation is in an internal recess of the shaft of the cone penetrometer or the push rod. The module has a relatively small length-to-diameter ratio, allowing high probe robustness and precluding interpretation of test data by 1D thermal line source solutions.

A heat flow CPT module test consists of Stages 1, 2, 3 and 5 of Section 2.5. Stages 2 and 3 typically take 10 minutes each to conduct.

For thermal conductivity k, the thermal data (Stages 2 and 3) are interpreted using an interpretation method that includes an inversion of a 2D axisymmetric numerical model of the probe and the surrounding soil (patent pending). This interpretation method accommodates for soil frictional heat during Stage 2 and integrates CPT data, enhancing the overall accuracy of the method (Vrielink, 2022).

Values of volumetric heat capacity C are derived from CPT data (Category 3, Table 1).

3.3. Heat flow thermistors test

3.3.1. General

A heat flow thermistors probe, commonly referred to in literature as a Lister-type heat flow probe (named after Lister, 1963; Hartmann & Villinger, 2002) is a probe containing multiple thermistors and one or more heating wires. The probe typically features a diameter of about 10 mm to 15 mm and a length of about 4 m to 6 m.

A heat flow thermistors probe test typically consists of all 5 stages of Section 2.5. Measuring the thermal dissipation for Stages 2 and 4 typically takes 20 minutes. For Stage 3, the heating wire(s) of the probe are activated for a 20 second period at a power level of 350 W to 400 W, creating a short heat pulse in the probe.

The interpretation of thermal conductivity and volumetric heat capacity per thermistor is carried out using an inversion scheme that incorporates a forward analytical solution based on the heat conduction equation for an infinite cylinder (Hartmann & Villinger, 2002).

The probe can be deployed by various deployment systems, each explained separately.

3.3.2. Gravity deployment

The probe is deployed as an outrigger of a 60 mm diameter solid steel strength rod (winch-deployed penetrometer) or as an outrigger of a gravity core sampler (Hyndman et al., 1979; Hornbach et al., 2021). The thermistor probe is about 50 mm to 100 mm parallel to the penetrometer or sampler. General details of winch-deployed penetrometer and sampler systems are given by ISO (2023).

This method of deployment is typically limited to Soil Type (A).

The use of an outrigger system and, potentially an oversized tip at the end of the thermistor sting, can lead to significant soil disturbance, affecting geodata value. To the knowledge of the authors, no analysis of soil disturbance effects has been published.

3.3.3. Vibratory deployment

A vibratory (sonic, resonance) deployment system includes a vibrocore sampler with an outrigger thermistor probe as for gravity deployment (Müller et al. 2016). General details of vibrocore samplers are covered by ISO (2023).

Significant soil disturbance can be expected because of vibratory driving and the use of an outrigger system. Soil disturbance effects are possibly less pronounced for Soil Type (A) compared to Soil Type (B) where the force and time needed for penetration of the vibrocore sampler is relatively large (Evenset et al., 2016).

3.3.4. Mini Penetrometer Deployment

Here, the heat flow thermistors probe is incorporated into the push rod of a CPT-like mini penetrometer with the same diameter (De Vries & Usbeck, 2018). The combined probe is pushed into the soil by a CPT deployment system.

For this deployment system, soil disturbance is reasonable controlled, as the probe is flush with the end of the penetrometer and as no outrigger system is used.

The relatively small diameter (16 mm) and the space requirements for the thermistor instrumentation imply limited probe robustness. This affects depth limits.

Data acquisition includes both mini penetrometer data and heat flow thermistor data. These data sets can be integrated for geodata value.

3.4. Borehole thermal response test

The borehole thermal response test is standardized by ISO (2015). The test method provides (average) thermal properties of soil surrounding a borehole. This approach is commonly utilized for design of ground heat exchangers.

A borehole thermal response test applies a constant heating or cooling rate to a thermal loop. Parameters such as the flow rate, inlet and outlet temperatures of the carrier fluid are logged over time, along with surface air temperature. The duration of a test is multiple days.

This data are interpreted using a numerical or analytical model of the borehole to derive thermal properties of the soil surrounding the borehole.

4. In-situ tests using passive heat generation

4.1. Thermal cone penetration test

The thermal cone penetration test uses a CPT cone penetrometer equipped with an internal temperature sensor. As the cone penetrometer penetrates the soil, friction forces induce heating (temperature rise of the cone penetrometer), which is logged by the temperature sensor. An interruption in penetration allows performance of a temperature dissipation test (Test stages 1, 2 and 5 of Section 2.5)

Akrouch et al. (2016) proposed a method for interpretation of thermal conductivity k from the temperature dissipation test results. This method was later expanded by utilizing multiple analytical solutions of the 1D axisymmetric heat conduction equation (Vardon et. al, 2019).

Vardon et al. (2019) also proposed a method to derive values of volumetric heat capacity C. In practice, this method was found to show a comparatively high uncertainty of test results (see Table 1).

The inclusion of a temperature sensor in a cone penetrometer is covered by ISO (2022, 2023), with no specific guidance other than references to possibilities of applying corrections to CPT measurements. For thermal cone penetration testing, the precise position of the temperature sensor within a cone penetrometer is important, as indicated by Vardon et al. (2019).

Table 1 indicates that the test method has relatively low applicability for Soil Type (A). This is because of probable inadequate generation of (passive) heat for reliable interpretation of the acquired data.

5. In-situ test correlations

5.1. CPT correlations

Vardon & Peuchen (2019) proposed empirical CPT-based correlations for thermal conductivity k and volumetric heat capacity C of saturated soils. These correlations consider normalized friction ratio and normalized cone resistance, broadly related to soil density and soil behavior type.

Validation of the correlations included laboratory test results and in-situ test results (thermal cone penetration tests). Inevitably, the uncertainty of the results of these validation values also affects the uncertainties of the correlations.

5.2. Borehole geophysical logging correlations

Similar to CPT correlations (Section 5.1), data acquired from borehole geophysical logging (wireline logging) can be used to derive values of k and C for a wide range of soils and rock to depths of > 200 m below ground surface. To the knowledge of the authors, no such correlations have yet been published.

Borehole geophysical logging methods are standardized by e.g. ASTM (2018) and ISO (2023). One example of a common geotechnical method that can be considered for derivation of the thermal conductivity and volumetric heat capacity is P and S suspension logging. Less common borehole geophysical methods that target soil density can also be considered for correlations, e.g. gamma-gamma density logging and downhole magnetic resonance logging.

The presented value for ‘Test duration’ in Table 1 is for downhole magnetic resonance logging.

6. Conclusion

A wide range of in-situ test methods is available for thermal site characterization. The range typically reflects trade-offs in value and applicability. The use of two or more in-situ methods can be considered for efficient thermal site characterization.

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