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OFFSHORE WIND ACCELERATOR (OWA)

Soil Thermal Properties (STP) for subsea cable design

Cables technical working group

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1. Background

1.1 Introduction

The dissipation of thermal energy from subsea HV cables is a key consideration for:

(i) the design and manufacture of subsea cables;

(ii) dynamic rating of the cable during the lifetime of operation;

(iii) the interpretation of distributed temperature sensor (DTS) data for monitoring cable performance, depth of burial, transgression of the "2K criteria" of temperature rise to protect benthic life, and finally, in extreme circumstances, fault location.

This study demonstrates that a proper consideration of the thermal environment, using geotechnical best practices, could save tens of millions of pounds of capital expenditure, whilst also helping to reduce operational costs. For instance, offshore cables represent 30% of offshore wind farm insurance claims incurred and 50% of the total value of claims between 2010 and 2020 (GCube, 2021).

The environmental factors that control heat dissipation from subsea HV cables are the thermal conductivity, volumetric heat capacity and permeability of the seabed soils as well as the lifetime changes in the depth of cover over the cable. The rate and magnitude of heat dissipation, conductor temperature and ultimately the maximum power transfer possible can be determined by the IEC standards or derived from the fundamental physical laws solved analytically or using numerical methods. The factor that has the greatest influence on heat dissipation is the thermal conductivity in most submarine cable environments. Hughes et al (2015) have demonstrated that the permeability of soils can also impact the heat dissipation by enabling convective heat transfer. However, this only becomes an issue for the higher permeabilities found in unimodal medium to coarse sands and gravels and is therefore not considered in detail within these guidance notes.

With this background, the key objective of this *Best Practice Guide* is to:

- Provide an understanding of the impact of thermal conductivity on cable design and identify the influence of the accuracy and precision of these measurements on the cable design and operating condition;
- Present appropriate engineering practices to support measurement of the thermal conductivity of marine soils, highlighting the different levels of accuracy and precision that can be achieved by different methods;
- Provide an understanding of the potential changes of these thermal properties in response to installation effects – from trenching or ploughing and cable burial – and the implications of these changes in soil properties for cable design and operation.

These guidelines are relevant at all of the phases of the OWF including design, installation and operation. The guidelines are a deliverable from the Carbon Trust project "Soil Thermal Properties for Subsea Cable Design". They have been developed from three detailed reports produced earlier in the project which covered "Cost Implications of Thermal Conductivity Values" (WP1), a "Testing Methodology Review" (WP2) and "Trenching Effects on the Design Parameter Framework" (WP3). Selected sections from those reports are provided in Appendix A in this guideline and are referenced within the main text.

Thermal conductivity, in W/mK, is the key parameter measured or reported during geotechnical testing. However, its reciprocal, thermal resistivity (Km/W), is the form used in all electrical cable design and post installation monitoring software and so both will be referred to within this document. These guidance notes are also solely focused on soils in marine conditions, which results in them being fully and permanently saturated. Landfall sites, which experience spatially and temporally varying saturation states, create a significantly more complex thermal environment and therefore require a different thermal assessment approach. This guidance is not appropriate for unsaturated soils.

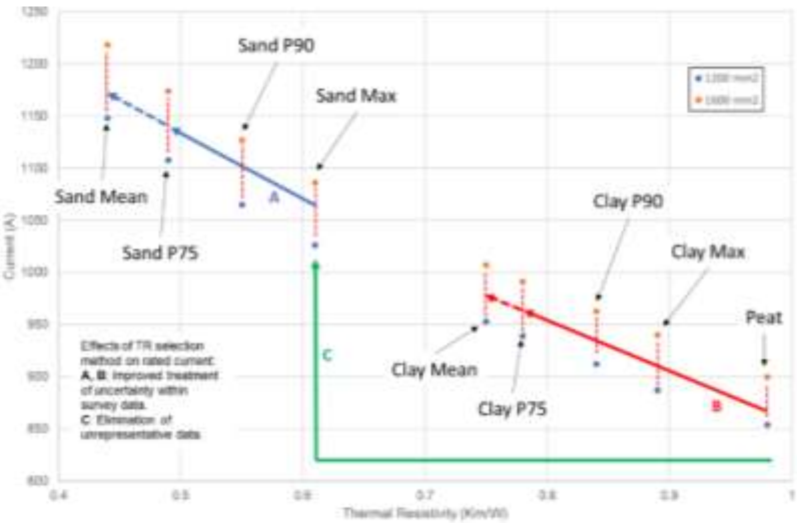
1.2 Impacts of the thermal environment on cable rating and cable cost

WP1 of this project provided a series of Case Studies designed to illustrate the implications of soil thermal properties on subsea cable design, with specific emphasis on the cable cross sectional areas (CSA's) required to achieve a set rating (i.e. maximum current) and the subsequent cost implications of these choices. Each study is compared against a base case of a generic three phase, AC, 1400mm^2 CSA, export cable buried at 1 m depth within a seabed with a fixed thermal resistivity of 0.7 Km/W (which is the standard value quoted in the international standards, IEC-60287 and 60853, and previously used extensively across the sector). The base case has a rating of 1000A. These Case Studies demonstrate the impacts of the following variables on cable design:

- Soil type;
- Uncertainty of thermal measurements;
- Choice of statistical parameter (i.e. fractile within scattered data) for unitised thermal resistivities;
- Impact of trenching on the thermal environment.

Figure 1-1 demonstrates that for two different sizes of cable (1200 and 1600mm^2 respectively) the cable rating can vary by between 300-350A (~35%) depending on both the thermal properties of the soil and which thermal resistivity value (Maximum, P90, P75 and Mean) is used to represent the environmental conditions (WP1). Such a variation is financially and operationally important and is comparable to similar ratings improvements in terrestrial environments that have been considered significant in other studies (e.g. Pilgrim et al, 2012).

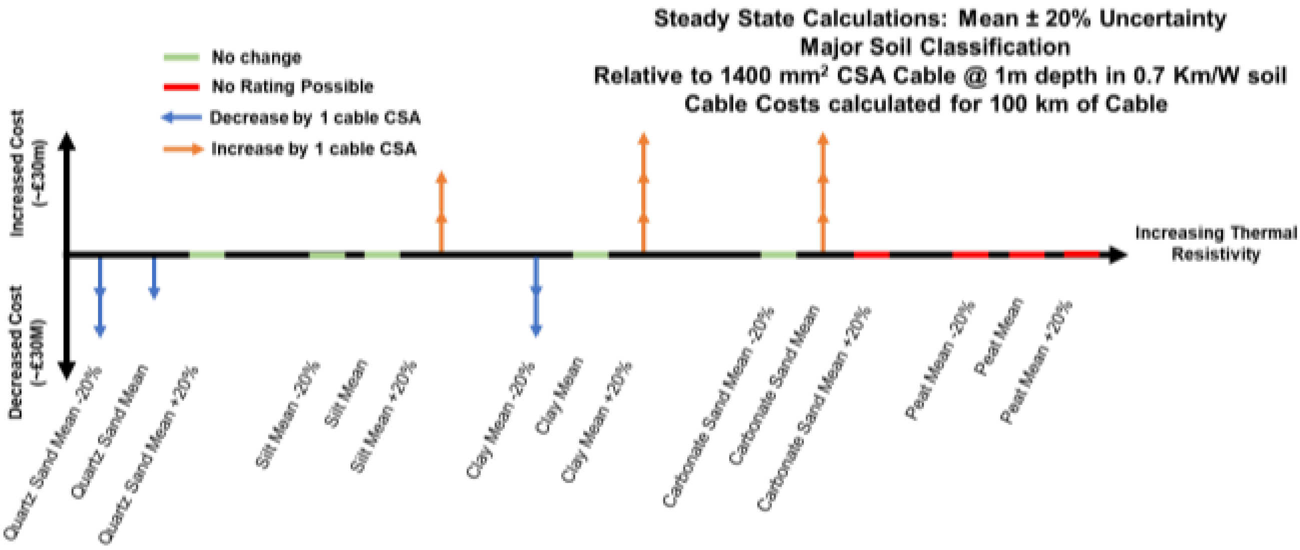
Figure 1-1: Steady state current vs thermal resistivity – 1200 & 1600mm² cables



Note: Plotted are the values for mean, P75, P90 and Max TR values for each soil type

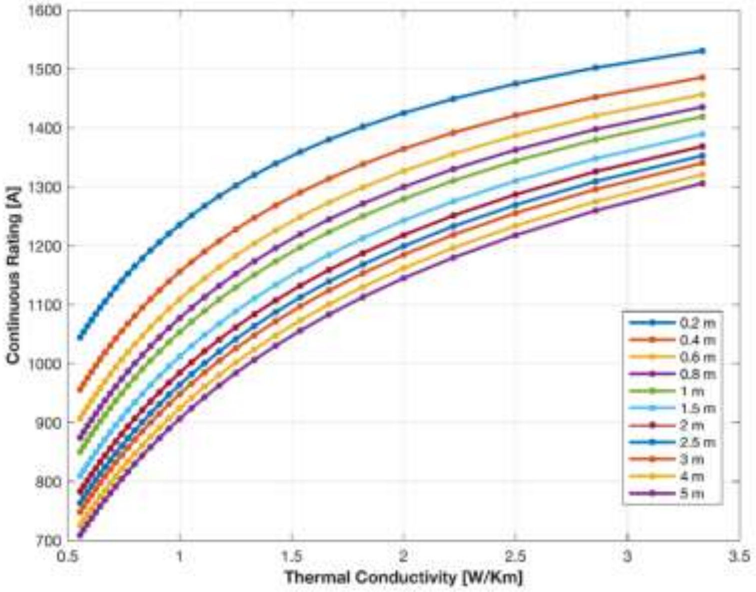
Similarly, Figure 1-2 demonstrates that a 20% uncertainty in the thermal conductivity measurement can lead to a cost differential of up to £48.5 million for a 100km cable when compared against the base case scenario (based on October 2021 materials costs – WP1). Even for a 10% uncertainty in the thermal conductivity, the maximum rating for a single cable can vary between approximately ±1.5% (high thermal conductivities more than ~2W/mK) and ~±5% (low thermal conductivities [less than ~1W/mK]). These impacts increase with increasing burial depth (Figure 1-3). It is therefore essential to adopt the most precise measurement methods possible, for both laboratory based and in situ thermal conductivity measurements and understand the uncertainty budget of all methods used.

Figure 1-2 Schematic representation of cable CSA (vs base case scenario) - steady state



Note: including ±20% uncertainty error in thermal resistivity for a range soil types

Figure 1-3: Continuous static cable rating for a generic AC cable



Notes: Rating satisfying the maximum permissible conductor temperature of 90°C, for a range of varying thermal conductivities and burial depths

These observations are based on using thermal conductivity measurements of the pre trenched, ambient soil condition, which is the condition in which soil is tested in the laboratory and in situ. However, it is important to consider how the key thermal properties may change during and after the installation process. There are no publicly available direct measurements of thermal conductivity of trenched soils. As an alternative, WP3 modelled the potential impact of trenching on thermal conductivity by estimating the change in thermal properties via extant relationships between relative density [for which pre- and post-trenching data is available] => void ratio / porosity => thermal conductivity. These suggest that:

- Jetting and ploughing of sands result in an increase in void ratio and therefore in conductor temperature with 75% of the modelled scenarios resulting in an increase of more than 5°C. However, these relate to the largest inferred changes in relative densities that occur immediately after installation. It is probable that trench conditions will undergo at least some post installation densification and therefore thermal conductivities will trend back towards the pre installation conditions and hence a smaller increase in conductor temperature;
- Jetting and ploughing in soft clays also results in a relative increase in conductor temperature relative to the non-trenched condition but at a level (less than 3°C) that is not significant for cable design as it is within the uncertainties of the cable component of all IEC models;
- Jetting in stiff clays, which frequently results in a blocky backfill within the trench, led to significant decreases (between 5°C and 33°C) or increases (between 1°C and 7°C) in temperature depending on a combination of factors: (i) the block to matrix volume ratio, (ii) the block distribution or packing arrangements, and most importantly (iii) the nature of the fluid or consolidated soil material within the matrix;
- A cut trench in stiff clay that naturally backfills with marine sand has contrasting thermal conductivities between the in situ clay material and the backfill. In addition, the fill has higher

permeability. Together these factors result in a significant temperature drop of between ~7°C and 11°C. This is due to the enhanced conduction and convection through the sand backfill.

The idealised nature of the models examined means the relevant results should not be used as quantitative values of change in conductor temperature (and therefore cable rating) for any specific project site. Instead, the aim is to highlight the need to accurately characterise soil thermal properties to avoid over- or under-estimating the heat diffusion from the cable, and therefore potentially overheating the cable and soil or overdesigning the cable.

In addition, where these case studies involve assumptions about the final state of the ground after trenching, e.g. the form of any backfill blocks and matrix infill, they highlight the potential value of in situ testing in and around installed cables or analysis of DTS data to help resolve these gaps in knowledge.

The financial gains of optimised cable design through an accurate knowledge of the seabed thermal environment could be further enhanced through understanding the full financial impacts of:

- Micro routing to optimise the thermal environment;
- Including thermal considerations in the choice of trenching technique and potentially proactively pre conditioning soils and cable attachments to enhance the thermal diffusion;
- Enhancing operational condition monitoring through the confident use of Real Time Thermal Rating (RTTR) and “Depth of Burial” software thus optimising power transmission and allowing a reduction in the number of post installation geophysical and visual monitoring surveys.

1.3 Characterising the seabed thermal environment for cable design

To support optimised cable thermal design, through accurate characterisation of the seabed thermal properties, a sequence of idealised “data scenarios” is illustrated in Figure 1-4 and summarised in Table 1-1. These staged scenarios broadly represent the evolution of data availability during a project. They represent the available information about the soil conditions and the soil thermal environment and illustrate the progression of this knowledge during the different phases of site investigation.

Figure 1-4: Illustration of data scenarios

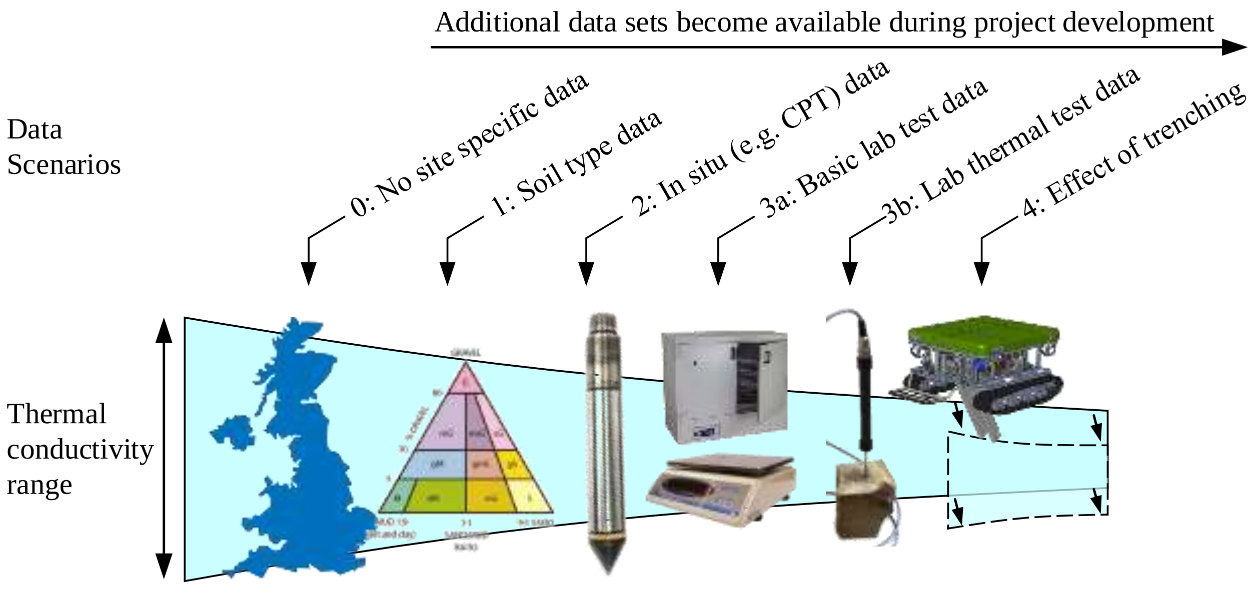


Table 1-1: Data scenarios for Thermal Conductivity estimation

Data scenario / survey stage	Data type	Key data	Basis for estimating Thermal Conductivity	Section
0	No site specific data	None	Full thermal database scaled for region	Section 3.3.1
1	Geological setting	Soil type	Soil type database subset	Section 3.3.2
2	*In situ* testing	T-CPT measurement or CPT profile	Direct Thermal Conductivity measurement or Correlated porosity & database	Sections 2.5 and 3.4.1
3a	Basic lab testing	Moisture content, specific gravity	Correlated soil type, porosity & database	Section 2.3 and 3.4.2
3b	Thermal Conductivity lab test	Measurement of Thermal Conductivity	Measured soil type, porosity & database	Section 2.3 and 3.5
4	Modelled Effect of trench on Thermal Conductivity	PSD – to estimate change in porosity from *in situ* value	Changed porosity (using I_d) & isomaterial line	Section 3.6

This document provides guidance on the measurement of thermal properties and the selection of design values for cable design and condition monitoring software. The guidance is divided as follows:

- Section 2: Guidance on options for measuring the thermal properties of marine soils.
- Section 3: Guidance on the selection of design thermal properties, understanding uncertainty, when equipped with different types of data (representing typical different survey stages). This guidance includes approaches for adjusting thermal properties to allow for soil disturbance effects associated with the trenching and burial process of cables.

In addition, Appendix A complements the guidelines by discussing currently available techniques for measuring thermal conductivity.

2. Thermal soil property collation and measurement

2.1 Thermal properties within the site investigation process

To properly characterise the soil thermal environment along a cable route section, a sufficient number of thermal conductivity/resistivity measurements should be performed to fully characterise the near seabed geology and the requirements for cable burial and cable protection. It is recommended that both preliminary (typically based only on geophysical survey data and desk study geotechnical data) and final (integrated, site specific geophysical and geotechnical data) ground models are consulted to inform the location and frequency of sampling. Thermal measurements should extend to below the target burial depth. Materials that potentially limit the thermal diffusion (e.g. organic or carbonate rich soils) should be specifically targeted.

Due to the variability in the length and criticality of cables, and the variability in the degree of soil heterogeneity, no ideal number or spacing of tests can be provided. Sufficient measurements should be made to provide statistically significant sets that support mean and low/high estimates of thermal properties for each distinct soil unit. These typically require at least several hundreds to 1000+ tests per OWF, also depending on the cable route length and encountered soil conditions.

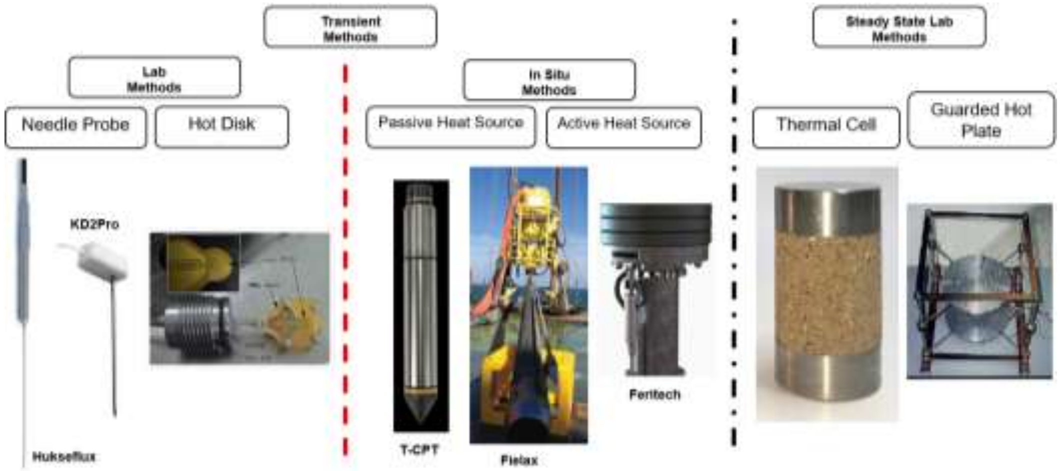
2.2 Methods for measuring thermal conductivity

The most common approach in site investigation studies has been to measure thermal conductivity on retrieved soil samples in the laboratory using a range of both transient and steady state methods. This approach requires sampling cores from the seabed and either measuring directly on the cores offshore after retrieval, or on samples onshore. The samples tested onshore may be intact or may have been reconstituted/remoulded from disturbed (e.g. bagged) samples. Intact samples still require handling and preparation for laboratory testing, and the testing process can also introduce disturbance.

It can therefore be challenging to recreate the in situ ground conditions – i.e. voids ratio/porosity and soil fabric/structure – in the laboratory and requires sufficient expertise. For this reason, the development of robust and well validated methodologies for in situ measurement of thermal properties is the focus of current research and innovation.

Common methods for evaluating thermal conductivity of marine sediments are shown in Figure 2-1.

Figure 2-1: Common methods for evaluating thermal conductivity of marine sediments



2.3 Laboratory testing techniques

Laboratory techniques are subdivided into two broad groups:

- Transient methods (needle probe and hot disk) which measure the temperature variation of the sediment in response to an instantaneous heat pulse;
- Steady state methods (guarded hot plates and thermal cells) that apply a constant heat flux to the sample until a stable temperature distribution is achieved.

Table 2-1 presents a summary of the advantages and disadvantages for the four primary laboratory methods used to measure thermal conductivity. A detailed review of each method and the commonly available systems is provided in Appendix A.

Table 2-1: Comparison of laboratory test methods

Test Method	Advantages	Disadvantages	Accuracy and Precision
Needle Probe	• Short test duration • Suitable for most soils • Standardised test method	• Ensuring good contact with soil sample • Delicate • Not suitable for coarse soil	ASTM D5344 (2014): Precision ±10-15% (Repeatability and Reproducibility)
Transient Plane Source (Hot Disk)	• Short test duration • Minimal sample preparation • Also determines thermal diffusivity & heat capacity	• Requires two identical specimens • Limited experience in being used for testing soils	No standards for soils but BS EN ISO, 22007-2 (2015) for plastics & thermal insulation material suggest an accuracy of ±2-5% and a precision (repeatability) of ±1-2%
Guarded Hot Plate	• Standardised method • Easy to use • Effective for gravels	• Long test duration • May not be suitable for most soils (< 2W/mK) • Moisture migration	BS 12664 (2001) – Based on Building Materials Accuracy ±2% Precision ±0.5-1% (Repeatability and Reproducibility)
Thermal Cell	• Suitable for most soils • Minimal sample disturbance	• Long test duration • Moisture migration • Bespoke equipment	Comparable to Guarded Hot Plate method BS 12664 (2001) Accuracy ±2% Precision ±0.5-1% (Repeatability and Reproducibility)

To achieve the highest accuracy and precision of the thermal conductivity measurements the following requirements should be met:

- Device specification, procedures and calibration steps should meet the relevant standards and the manufacturer's requirements;
- The sample should be in equilibrium with the ambient temperature prior to testing;
- All devices should be calibrated with an appropriate medium and the calibration should be applied to the final results. It is recommended to use Ballotini as an effective calibration material for marine soils;

- A constant and stable power supply should be applied during the test;
- Metadata of all of these aspects should be well recorded and included in the test reporting.

Additional requirements specifically for needle probe tests, which are the most commonly used test:

- The device should be fully embedded and have good contact with the soil sample (for example. the insertion process should be a clean direct push without lateral movement);
- The device should be installed without hammering or excessive force;
- For multiple measurements, tests should be performed with sufficient distances between them and from the sample boundary to avoid interaction effects;
- The needle probe should have a diameter greater than the grain size of the soil sample;
- Heating boundary effects should be avoided. This is often approximated by ensuring the diameter of the soil sample container is 50x the needle diameter, which gives typical sample diameters of 50-100mm.
- The sensitivity of the calculated thermal conductivity to the choice of the section of the cooling or warming curve should be quantified and recorded.

In addition, for best practice, it is recommended that:

- The results and interpretation (i.e. the measured test response and the interpretation or graphical construction used to find thermal properties) should be inspected by the user or report writer visually to identify possible errors or alternative interpretations;
- The results should be 'sense checked' against other available data for similar soil conditions and properties, to highlight any gross differences and unexpected results, which merit further investigation;
- Information relevant to the specific soil conditions should be considered prior to testing to ensure that the test arrangements are appropriate for the soil type;
- The derived thermal properties should be evaluated in combination with the soil characterisation (for example, by plotting trends of thermal conductivity with moisture content or voids ratio in each soil unit, to assemble sets of similar results from which statistical measures of best, low and high thermal conductivity can be identified).

2.4 Sample preparation

Heterogeneity and sample disturbance (either during sampling, transportation or reconstitution in the laboratory) are considerable sources of variability in thermal conductivity measurements and can often exceed the uncertainty associated with the measurement and its interpretation. Consequently, it is suggested that all laboratory samples are prepared with the following considerations:

- Saturation states should be close to 100% and always above 80%, with saturation ideally being undertaken with a saline solution;
- Where reconstitution/compaction is attempted, the source of the target densities should be clearly defined, and attempts to recreate the in situ density should avoid creating artificial levels of anisotropy perpendicular to the applied stress planes, which can occur from tamping;
- Where possible laboratory measurements of density should be compared with measurements taken on the vessel immediately on retrieval of the specimen. Even though disturbance is inevitable during the sampling process, water loss is common on retrieval/splitting of the

cores. Therefore, measurements of moisture content and/or density from the vessel provide data closest to the natural condition and therefore a suitable benchmark;

- The sample being prepared should aim to represent the in situ soil structure and fabric in terms of grain sizes and mineralogy and also small scale heterogeneities such as fine scale bedding. Consideration should be given to how this structure and fabric could change during the process of sampling and thermal testing, but also how it may change during cable installation (see Section 3.6).

2.5 In situ measurement techniques

To make in situ measurements of thermal conductivity there are currently three principal approaches:

- A heat pulse is produced from an active source that is located along a linear sensor string that is attached to a coring system or solid probe. A range of instruments are available typically derived from an early "violin bow" design developed for academic research. The temperature decay curve of the heat pulse is recorded at multiple sensors from which a profile of thermal conductivity is calculated along the length of the probe;
- A passive source, where the heat pulse is generated through friction between the probe and the seabed soil during insertion of the probe. This approach has recently been developed as a modification of a conventional CPT with an added temperature sensor, frequently in the tip, and known as a T-CPT. As for active sources, the sensor records the rate of temperature decay to calculate thermal conductivity at a set depth. As these systems only have a single temperature sensor, multiple pushes are required to get measurements at different depths.
- Conversion from standard CPT parameters (cone resistance and friction ratio) to give bulk thermal conductivity values through correlations. These correlations usually first estimate the bulk density, with correlation parameters being linked to grain mineralogy. The voids ratio and porosity is then estimated from the bulk density, based on an assumed grain specific gravity linked again to the soil mineralogy. From porosity the bulk thermal conductivity is then estimated, using assumed values for the pore fluid and grain thermal conductivities (with the grain thermal conductivity also being estimated from the soil mineralogy).

For successful deployment and the acquisition of reliable measurements it is important to consider the following, for the active and passive sources:

- The ambient temperature should be well constrained. For active systems a time lag of several minutes is advised for the frictional heat pulse from installation to dissipate prior to generating the controlled heat pulse. For passive systems the ambient temperature can either be backcalculated (but with inevitable uncertainty) or temperature measurements should be continued until the ambient temperature has been achieved again;
- The specific thermal properties of the probe (i.e. the parts, their shapes and their thermal properties) and the specific contact thermal resistance with the surrounding soil require all in situ probe thermal measurements to be calibrated either against theoretical models or conventional needle probe measurements either in the field or the laboratory. The contact thermal resistance can be affected by liquefaction of the surrounding soil during installation, convection in the pore water and disturbance of the adjacent grains resulting in a local change in porosity. As discussed in Sections 2.3 and 2.4, for in situ tests to be calibrated against needle probe measurements, they should themselves be calibrated against appropriate

standards. Whatever approach to calibration is used it needs to be clearly recorded and set out in the test report;

- A measurement time of at least 500 – 1200 seconds is required to record the full response.

For passive systems it is also important to consider that:

- The initial temperature rise ΔT should exceed 3°C, to provide a clear decay curve. This is usually achieved in sands where probe shaft friction is high, but is difficult in fine grained soil.

There are still few publicly available studies that have tested the accuracy and precision of all of the active and passive in situ techniques. Published results indicate that the "relative accuracies" of active systems are within ±5% of laboratory thermal conductivity measurements for the same material. Unpublished commercial studies have shown thermal conductivity measurements in sands using an in situ passive system that are 20% higher than measurements from needle probe tests on collocated samples. However, as further experience of the passive in situ CPT systems is gained, this observation may not be universal. There is therefore an urgent requirement for such systems to undergo well documented benchmark testing, comparable to that undertaken for the ASTM D5344 needle probe standards.

The CPT correlation approach to estimate thermal conductivity from standard CPT data are attractive due to the simplicity and potential time and cost savings that arise from eliminating any specialised thermal testing. However, at present there are quite large differences both when compared against laboratory needle probe measurements and collocated in situ T-CPT and certainly at levels that could significantly impact on cable design as described in Section 1.2. Consequently, this approach should at present be treated with caution until a realistic accuracy and precision can be determined. It will remain a useful tool to gain estimates of thermal conductivity from early site investigation campaigns where thermal test data does not yet exist, or to supplement actual measurements across a project or soil unit after the correlation has been checked and/or recalibrated against either laboratory or other in situ measurement methods.

A summary of the relative merits of laboratory based and in situ thermal property tests is presented in Table 2-2. This comparison highlights that several factors influence the optimum choice of test and there is no single test type that is preferred.

Our expectation is that in situ testing will become the default approach to measuring thermal conductivity for cable design, with laboratory based measurements being used to further analyse complicated and thermally limiting soils (e.g. gravels, very fine grained over consolidated materials, organic and carbonate rich materials). However, since active in situ testing apparatus is not widely specified for site investigations and passive in situ tests are relatively new, with limited published experience, in situ testing is not yet accepted as the default approach, and best practice is currently to use both types of testing. Needle probe laboratory testing of tube samples remains currently the primary source of thermal conductivity data on projects.

Table 2-2: Laboratory based versus in situ geotechnical tests

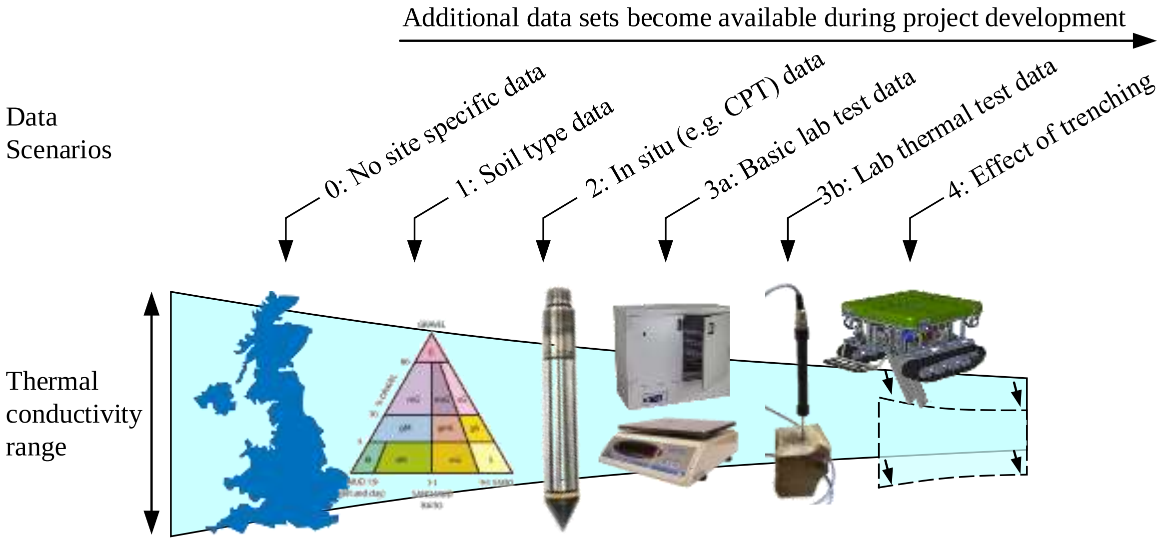
	Laboratory based measurement	In situ measurement
Control of experimental conditions	Easily control both environmental, testing and boundary conditions. NB. Boundary conditions can be restricted depending on the equipment	Experimental environmental, testing and boundary conditions difficult if not impossible to control
Interpretability	Generally yes as the sample is logged i.e. well characterised	Interpretation is difficult without adjacent laboratory soil samples
Representative sample volume	Can be restrictive to unrepresentative, small sample volumes introducing uncertainty in laboratory to field scale comparisons	Generally larger volumes are sampled better approximating a continuous media
Preservation of sample quality	Possible disturbance due to: Fabric changes, stress relief and desiccation	Techniques considered here are intrusive generating possible disturbances due to: Generation of excess pore pressure in saturated soils, unavoidable localised disturbance,
Ability to vary the properties of the tested material	Possible to simulate e.g. trenching and loading of laboratory samples, parametric sensitivity and long time span studies	Not possible to simulate drift in environmental conditions and expensive to simulate long term investigations
Time (test and interpretation duration)	Time consuming and laborious to conduct. Requires both sampling and laboratory sample preparation and measurement.	Can vary depending on ease of deployment and length of time held static at each sampling point.
Cost	Can be economic under certain conditions, although time delay relative to in situ testing may offset any cost reduction.	Passive systems are low cost as integrated within standard CPT. Active systems less widely used, so can be costly to mobilise and operate.
Equipment	Prevalent, well established	Relative infancy in the commercial sector, though being actively developed. Future developments must include robust determination of accuracy and precision

3. Selection of soil thermal properties

3.1 Introduction

This section provides guidance on the selection of design values of thermal properties from different data sources – ranging from preexisting databases to project specific sets of measurements (Table 3-1). These data scenarios are illustrative of different project stages (Figure 3-1). As the data scenarios become more advanced, the design range (or the uncertainty) in thermal conductivity will reduce. Although each scenario refers to a particular data type, in practice all data types available to the project should be combined or compared, to take most value from the available measurements.

Figure 3-1: Illustration of data scenarios (Figure 1-4 repeated)



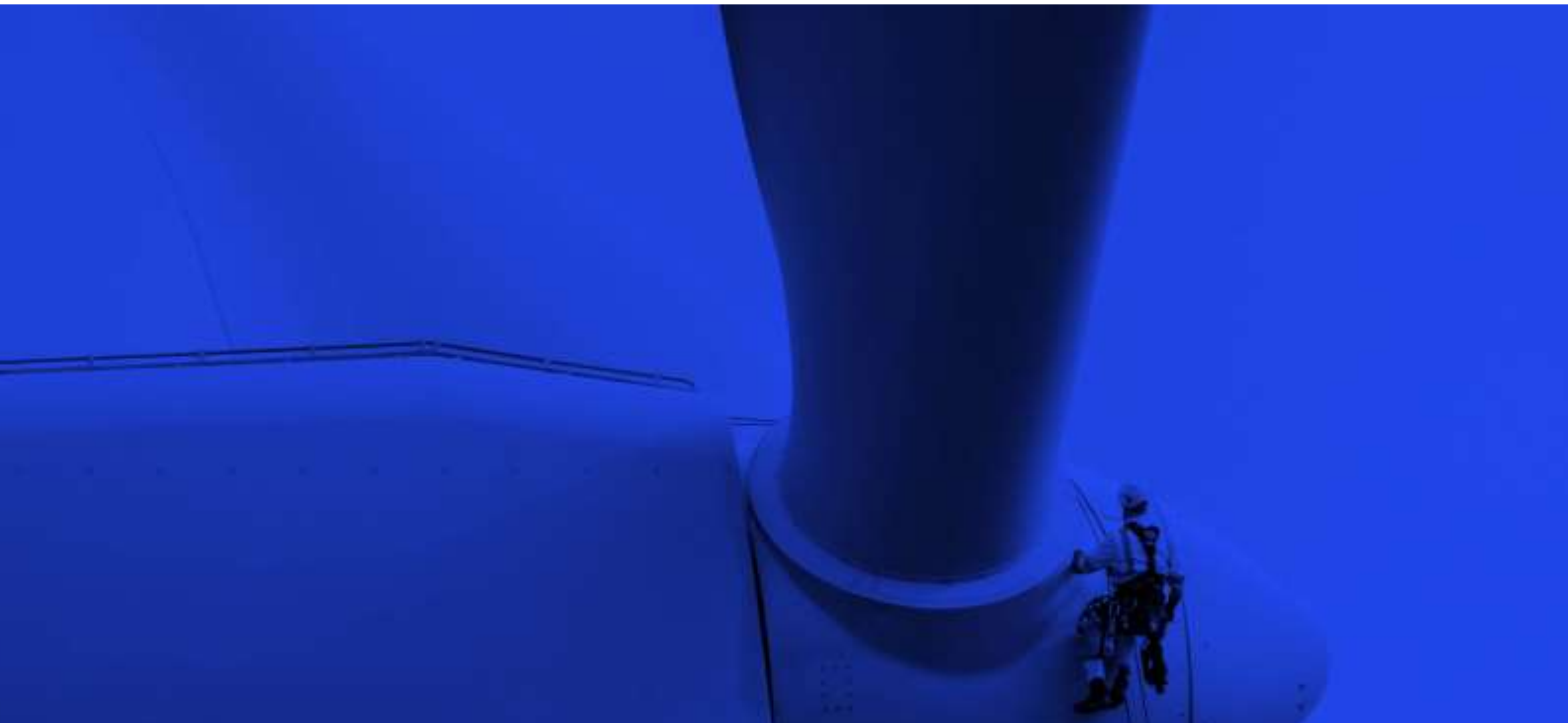


Table 3-1: Data scenarios for Thermal Conductivity estimation (Table 1-1 repeated)

Data scenario / survey stage	Data type	Key data	Basis for estimating Thermal Conductivity	Section
0	No site specific data	None	Full thermal database scaled for region	Section 3.3.1
1	Geological setting	Soil type	Soil type database subset	Section 3.3.2
2	*In situ* testing	T-CPT measurement or CPT profile	Direct Thermal Conductivity measurement or Correlated porosity & database	Sections 2.5 and 3.4.1
3a	Basic lab testing	Moisture content, specific gravity	Correlated soil type, porosity & database	Section 2.3 and 3.4.2
3b	Thermal Conductivity lab test	Measurement of Thermal Conductivity	Measured soil type, porosity & database	Section 2.3 and 3.5
4	Modelled Effect of trench on Thermal Conductivity	PSD – to estimate change in porosity from *in situ* value	Changed porosity (using I_d) & isomaterial line	Section 3.6

3.2 Thermal property geodatabases

Thermal property geodatabases can be produced based on available data, for instance needle probe thermal conductivity (TC) measurements, from a range of seabed soils from different projects. These databases can be used in early phases of the project for pre survey estimation of TC (see Section 3.3).

Detailed information on mineralogy, grain size and other physical parameters (bulk and dry densities, moisture content, porosity) should be evaluated together with the TC measurement. For instance, poorly saturated samples (saturation ratio, $S_r < 80\%$) should be excluded from any dataset, provided that sufficient metadata are available. In case these data are unavailable, the robustness of a geodatabase could be impacted and the range of correlations that could be explored becomes more limited, also hampering the evaluation of quality for each data point.

The available data points can be subdivided into five broad soil classifications: (i) quartz sand, (ii) carbonate sand, (iii) silt, (iv) clay and (v) peat.

3.2.1 Statistical analysis

Statistical analysis should be undertaken on the geodatabase, with standard parameters shown in Table 3-2. An example of presenting the data in scatter plots (combined box, whisker and "beeswarm") is shown in Figure 3-2.

Outlier detection of the normally distributed data can be calculated using a classic approach to calculate "outlier fences", to identify data points that require further investigation (potentially excluded). Where metadata are available samples should be filtered to remove measurements that do not meet the selection criteria or sample preparation standards. Measurements without extensive metadata can be retained, though this might be a source of uncertainties.

Figure 3-2: Combined box, whisker and beeswarm scatter plot - statistical parameters

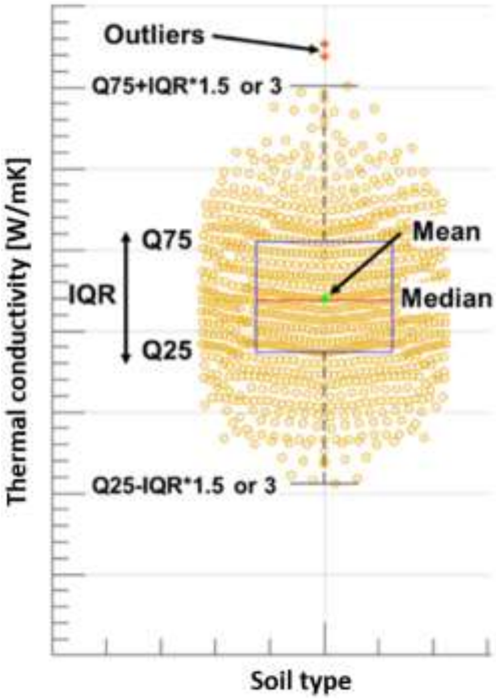


Table 3-2: Normal distribution statistical parameters – geodatabase evaluation

z	Definition
MAX TC (W/mK)	Maximum value
MIN TC (W/mK)	Minimum value
MEDIAN [P50] TC (W/mK)	Median, 50th Percentile, middle value
MEAN TC (W/mK)	Mean Value
STDEV (W/mK)	Standard Deviation
P10 (W/mK)	10th Percentile
P90 (W/mK)	90th Percentile
Upper Quartile (UQ) (W/mK)	75th Percentile
Lower Quartile (LQ) (W/mK)	25th Percentile
Inter Quartile Range (IQR) (W/mK)	UQ-LQ
IQR*1.5 (W/mK)	Mild whisker magnitude
IQR*3 (W/mK)	Extreme whisker magnitude
UQ+IQR*3 (W/mK)	Extreme upper whisker threshold – outlier identification
UQ+IQR*1.5 (W/mK)	Mild upper whisker threshold – outlier identification
LQ-IQR*1.5 (W/mK)	Mild lower whisker threshold – outlier identification
LQ-IQR*3 (W/mK)	Extreme lower whisker threshold – outlier identification
N	Number of data points

3.2.2 Repeatability-correction of TC database for each soil type

Subsets of any database might include multiple Thermal Conductivity measurements made on the same soil samples. These repeat tests on sub samples of the same soil provide different measurements of TC, indicating the repeatability error associated with the test. Based on the review of TC test repeatability, a coefficient of variance (CoV or *v*) per soil type can be applied on the raw database values, considering TC measurements with the same method (e.g. needle probe).

3.2.3 Weighted database according to seafloor soil variation

The database might contain measurements on predominantly specific soil class, e.g. more TC measurements from sands compared to clays or other soil classes. When considering a single TC value for initial design phases, the actual distribution of seafloor soils might be different compared to the database. Hence, a weighting must be applied when combining the different soil types within the database, rather than considering simply the statistics of the available database.

3.2.4 *Thermal conductivity versus porosity – trend lines per soil type*

The key relationships relevant to the calculation of porosity from standard laboratory measurements are shown in Table 3-3. These are standard relationships that rely only on the assumption of full saturation (i.e. they are written here for two phase materials, water and solid, with no gas phase – extensions apply for partially saturated soils). These relationships provide a route from data of moisture content, w, and grain specific gravity, G_s, to porosity, n.

Table 3-3: Relevant phase relationships to derive porosity from standard laboratory data

Relationship	Formula	Notes
Grain specific gravity, G_s	$G_s = \rho_s/\rho_w$	G_s can be estimated based on the soil mineralogy or measured with tests such as the pycnometer (density bottle). There is relatively small variation in G_s between soil minerals. Typically values: quartz sand: 2.65, other soil minerals: $2.6 - 2.8$ Grain density, ρ_s; water density, ρ_w
Voids ratio, e, from moisture content, w and grain specific gravity, G_s	$e = G_s w$	Moisture content: $w = W_w/W_s$, (weight of water / weight of dry solids Assumption: soil fully saturated
Porosity, n from voids ratio, e	$n = \dfrac{e}{1+e}$	By definition: porosity is pore volume relative to total volume, whereas voids ratio is pore volume relative to solid volume

The standard geometric relationship between the thermal conductivity of seawater (λ_{fluid}: $0.6\ W/mK$), the solid phase thermal conductivity (λ_{solid}) and porosity (*n*), to estimate the bulk thermal conductivity range for marine sediments is presented in Equation 1. Typical values for grain thermal conductivities of marine sediments are presented in Table 3-4.

$$\lambda_{bulk} = {\lambda_{solid}}^{1-n} {\lambda_{fluid}}^{n} \qquad \textbf{Equation 1}$$

Table 3-4: Typical grain thermal conductivities of marine sediments

Mineral Phase	Grain Thermal Conductivity [W/mK]	Source
Quartz	7.7	Horai, 1971
Calcite	3.5 – 3.6	Clauser & Huenges, 1995; Horai, 1971
K-Feldspar	2.3 – 2.4	Horai, 1971; Clauser & Huenges, 1995
Illite	1.8	Midttømme et al., 1998
Montmorillonite*	1.4	Knutsson (1983)
Chlorite	3.1 - 5.25	Clauser & Huenges, 1995
Kaolinite	2.8	Brigaud & Vasseur (1989)
***Notes**: Measurements taken on compacted bentonite with a montmorillonite composition*		

When the database measurements correlate well with theoretical relationships between porosity and TC, the resulting scatter can be used to establish confidence bounds. Hence, new correlations for estimating TC from porosity and mineralogy can be established, providing initial estimates of thermal conductivity in the absence of direct thermal measurements. Specifically, Equation 1 can be calibrated to the sub database of each soil type of the database, by adjusting λ_{solid} to find a best fit (P50) value, denoted μ_{λ}, and evaluating the standard deviation of this parameter, $\sigma_{\lambda s}$. By considering a normal distribution for the database, the P10 and P90 values of λ_{solid} can also be calculated.

3.3 Pre survey estimation from databases

3.3.1 No site specific data available (Data Scenario 0)

At early stages of a project, when no site specific information is available (Data Scenario 0 in Figure 3-1 and Table 3-1), the Thermal Conductivity can be estimated by assuming that available thermal conductivity database(s) of all soil types is relevant.

Within a specific database the scatter due to measurement repeatability error can be removed based on the repeatability evidence, as described in Section 3.2.2. Moreover, depending on the prevalence of each soil type at the seafloor across the site (for instance UK waters or any specific region of interest), the database can be weighted accordingly (Section 3.2.3).

Based on the distribution of sediments, mean and standard deviation values can be calculated by combining weighted populations. From this, the mean, standard deviation, lower (e.g. P10) and upper (e.g. P90) percentile values of Thermal Conductivity can be provided (Section 3.2.1).

3.3.2 Soil type data available (Data Scenario 1)

In cases where the likely seabed soil type is known (Data Scenario 1 in Figure 3-1 and Table 3-1), without any other site specific data available, the Thermal Conductivity can be estimated by assuming that the available thermal conductivity database for that specific soil type is relevant. The corresponding statistical values can be used, after measurement repeatability error has been removed as described in Section 3.2.2.

For each soil type the statistics of the repeatability corrected database can be used to provide mean, standard deviation, lower (e.g. P10) and upper (e.g. P90) percentile values of Thermal Conductivity (Section 3.2.1).

In summary, for Data Scenario 1, where the seabed soil type is known or estimated, the repeatability corrected geodatabase statistics provide soil type specific design values.

3.4 Site specific data available excluding thermal properties

3.4.1 In situ CPT data available (Data Scenario 2)

Data Scenario 2 is where site specific in situ CPT testing has been performed (Figure 3-1 and Table 3-1).

Standard CPT data can be used to estimate soil type, and then bulk density and therefore porosity using correlations based on the CPT parameters (see also Appendix A.2.3). The soil type can be estimated using conventional Soil Behaviour Type charts (e.g. Robertson charts). From this, a soil mineralogy can be estimated, potentially using insight from the regional geology, from which the grain specific density and thermal conductivity can be estimated. Further information is provided in Appendix A.2.3.

Following this step, the Thermal Conductivity can be estimated from thermal conductivity relationships for two phase materials, as discussed in Section 3.2.4. A similar approach to find thermal conductivity from CPT data is set out by Vardon & Peuchen (2021).

In summary, for Data Scenario 2, where CPT data is available, a chain of correlations can be applied to estimate the soil type (including mineralogy) and the porosity. From these values the thermal conductivity can be estimated using porosity-Thermal Conductivity relationships developed for a specific soil type (see Section 3.2.4). The repeatability error correction is incorporated in these trend lines (see Section 3.2.2). For other soil mineralogies, different to the database soil types, Equation 1 can be used directly with the grain mineralogy (with the λ_{solid} values for various minerals given in Table 3-4).

Where campaigns of direct, in situ, thermal conductivity has been measured, using either passive or active approaches, then significantly more reliable measurement are available at this stage. As described in Section 2.5 these measurements are still in their relative infancy in terms of OWF projects and these techniques still require more research before their accuracy and precision can be fully determined. At present they should be used in tandem with conventional laboratory based measurements which have been prepared in a manner that confidently replicates the in situ conditions. The sector should be striving to ensure that these approaches undergo an extensive multi OWF testing campaign to provide this confidence.

3.4.2 Lab test data available (Data Scenario 3a)

In Data Scenario 3a, basic soil classification data is available, so the soil type, mineralogy and porosity are assumed to be known – with a reduced uncertainty compared to the CPT based estimates of Data Scenario 2 (Section 3.4.1). Porosity can be calculated from measures of bulk density or voids ratio, following the relationships given in Table 3-3.

Following this step, the Thermal Conductivity can be estimated from thermal conductivity relationships for two phase materials (see also Section 3.4.1), using database trend lines as described in Section 3.2.4.

In summary, for Data Scenario 3a, where basic soil lab test data is available, the thermal conductivity can be estimated using porosity-Thermal Conductivity relationships developed for a specific soil type (Section 3.2.4) or grain mineralogy (Table 3-4).

The repeatability error correction is incorporated in the soil type trend lines (see Section 3.2.2).

3.5 Site specific thermal property data available (Data Scenario 3b)

In Data Scenario 3b, project specific thermal conductivity measurements have been obtained. These data can be used directly to specify design values, taking statistical estimates of Thermal Conductivity for each soil unit. However, part of the scatter within the measurements is repeatability and the remainder represents the actual natural variability. The repeatability correction method is also applicable to sets of data gathered from the same soil unit during a site survey. It is therefore possible to estimate the actual range of thermal conductivity by correcting the collected data using the same approach (as described in Section 3.2.2).

It is recommended that from these final measurements, and where appropriate these laboratory based measurements are combined with in situ directly measured thermal conductivities. The following statistics should be calculated: Maximum, P90 and P75 values are calculated for each soil unit and used for sensitivity testing of different cable designs. Reference should be made to the spatial location of the values in the top 10% of the measurements to identify, from any available ground model, if these values are actually spatially restricted and/or related to a single soil type. Ultimately, these values should drive risk based decision making and should not be seen as single values to which a whole windfarm cabling system is designed. Mitigation strategies such as: changes in cable sizing at different sections of the route; minor cable rerouting; and shallowing depth of lowering (with or without surface protection) should be considered.

3.6 Modelling trench effects – allowing for soil disturbance (Data Scenario 4)

Data Scenario 4 represents a situation in which the effect of a trench on the soil thermal conductivity is to be considered. The database and mixture models (Equation 1) can be used to estimate the effect of the trenching process, by linking the mechanical effect of the trenching process to the thermal properties.

For sandy soils, the trenching process may loosen the soil, leading to lower thermal conductivity. The Thermal Conductivity porosity trend lines given by Equation 1 provide a basis to link the loosening (change in porosity) to the reduction in conductivity. These trend lines represent a single material, with a given mineralogy (so can be referred to as an iso-material line). As the porosity is altered by the trenching process, the thermal conductivity will follow the iso-material line. The limits on porosity change from the trenching process can be estimated through maximum and minimum voids ratio test data, and/or relative density analysis of CPT data.

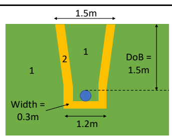
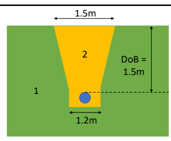
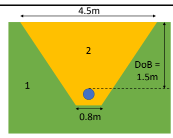
For clay soils, the trenching process may produce a more complex situation with blocks of intact clay surrounded by muddy water or clay slurry. In the long term, the clay will reconsolidate but now in a normally consolidated condition, at a higher voids ratio (and porosity) compared to the initial condition – but on the same isomaterial line.

These concepts for estimating the thermal conductivity (and permeability) of the trenched material were explored in WP3 of this project, through numerical modelling (different trenching and burial methods). A brief summary of key results include:

- The burial process tends to loosen the seabed material, reducing the thermal conductivity, therefore tending to increase the cable temperature for a given load;
- Ploughing disturbs a larger zone of soil than jetting, so affects the cable temperature more;
- An exception is in stiff clay, which forms a blocky backfill with large voids. If these voids remain filled with water, then convection is significantly enhanced, leading to significant cooling of the cable. If the voids fill with sand or reconsolidated clay, then the net effect on cable temperature could be either an increase or a decrease.

Figure 3-3 illustrates typical results of these effects for sand and soft clay for example installation scenarios. The predicted changes in cable temperature are specific to the cable and soil properties modelled in this study, so are only indicative of general trends and should not be relied on for design.

Figure 3-3: Cable temperature change due to burial - induced seabed properties changes

Scenario		A. Wished-in-place - perfect simultaneous lay & burial	B. Pre-cut plough - post-backfilling	C. Plough - simultaneous lay & burial
Legend (1 - Undisturbed sediment; 2 - Disturbed sediment)	0 < ΔT < |5| °C |5| < ΔT < |10| °C ΔT > |10| °C			
SAND	**Void ratio: 0.49/0.90** Prosity: 0.31/0.47 TC: 3.49/2.30 W/mK Load: 1400 A	5.5 °C	7.8 °C	8.9 °C
	Void ratio: 0.55/0.95 Prosity: 0.36/0.49 TC: 3.11/2.22 W/mK Load: 1370 A	4.7 °C	6.5 °C	7.5 °C
	Void ratio: 0.80/1.20 Prosity: 0.44/0.55 TC: 2.48/1.91 W/mK Load: 1300 A	4.0 °C	5.6 °C	6.4 °C
	Void ratio: 1.00/1.40 Prosity: 0.50/0.58 TC: 2.15/1.74 W/mK Load: 1265 A	3.4 °C	4.8 °C	5.5 °C
SOFT CLAY	Void ratio: 0.45/0.90 Prosity: 0.31/0.47 TC: 3.49/2.30 W/mK Load: 1090 A	1.6 °C	2.1 °C	2.7 °C

Appendix A – Techniques for measuring thermal conductivity

Appendix A.1 **Laboratory techniques**

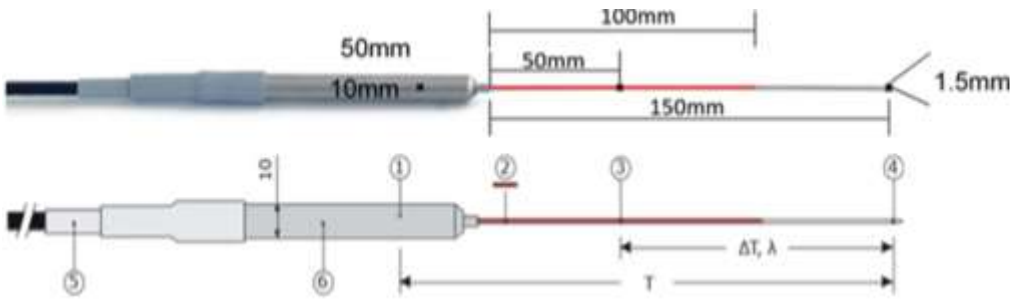
Appendix A.1.1 **Needle probe**

The non steady state (transient) needle probe (NSSP) accounts for the vast majority of published thermal data for geomaterials. It is one of the oldest most established techniques, and the only one with standards dedicated to geomaterials (ASTM D5334-2014 & IEEE Std-442-2017). Needle probes are preferred for their short test duration, low levels of sample preparation and the standardised method with accurate results obtained.

The needle probe test consists of heating a wire in addition to a thermocouple temperature sensor and is used to solve analytical calculations for the temperature rise at the thermocouple. During measurement, the probe is inserted and allowed to equilibrate within a sample before a constant power q (W/m) is applied for a transient period t_{heat} (s) inducing a temperature rise $(\Delta\theta)$ in the source.

The present standards outline the factors that influence the results including sample preparation, experimental configuration, contact resistance, calibration, heat time and power (Section 1.1). Several geometries and iterations are available for both laboratory and direct field measurements, e.g. instance TP02/TP08 (Hukseflux) and KD2/KD2-Pro (Decagon).

Figure A.1: Diagram of TP02 needle probe



Notes: *1: Reference temperature sensor pt1000. 2: Heating element (wire) runs across 2/3 needle length. 3: Hot joint thermocouple junction. 4: Cold joint thermocouple junctions. 5: Power supply.*

Typical, experiments demonstrate an initial nonlinear, transient, section (Figure A.2) which reaches a quasi-steady state after overcoming contact resistance and the thermal properties of the probe (Vos, 1956). After longer periods the temperature variation with time becomes nonlinear again due to edge effects, axial heat flow (Vos, 1956) and potentially moisture migration or convective heat transport (ASTM D5334-14). The influence of convection may be removed by ensuring that the gradient of the slope is calculated from the linear section only. The cooling section of the curve can also be used in addition to the heating curve, providing additional results (Low et al., 2015 and 2016).

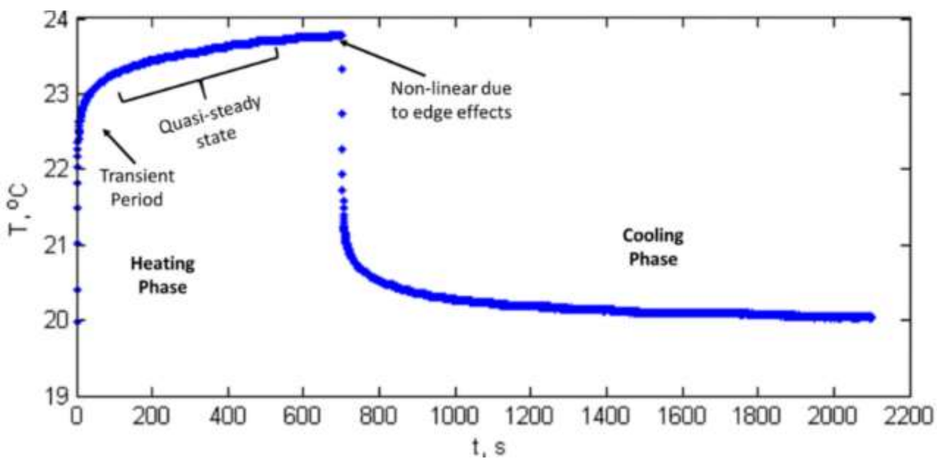
In deriving the slope, both IEEE Std 442-2017 & ASTM D5334-14 plot the results on a semi-log graph, i.e. $\Delta\theta$ against $\ln t$. The quasi-linear segment is then determined by excluding the first 10-30s for small diameter probes (ASTM D5334-14) or visually by selecting two appropriate times between which a straight line can be fitted to the data and its gradient calculated.

The use of visual inspection introduces interpretive variability. Automated analysis of the results through regression could be beneficial in standardizing interpretation through the selection of the quasi-linear segment. In (Low et al., 2015 and 2016) the propagation of errors method was used to indicate errors of 12.7% due to uncertainty in gradient evaluation.

To obtain appropriate time ranges for accurate calculations a simulation investigation using finite element analysis was undertaken based on the TP02 design matching experimental conditions by the University of Southampton. To define the best calculation periods for different TC ranges, assessment was performed to highlight the overlaps of low error calculation periods:

- At the lower end of the TC spectrum (0.75 to 1.75W/mK) a 100 seconds measurement window, with a starting time of ~ 150 seconds is best applied.
- The middle range (1.85 to 2.85W/mK) the low error calculation periods become more constrained. Periods are closer to the start of the heating cycle, meaning that the transient period is shorter. A starting time of at least 60 seconds and a calculation window of 130 seconds is recommended.
- The higher end of the TC spectrum (2.95-3.95W/mK), the range of accurate calculation periods can have a starting time anywhere between 30–70 seconds and a duration of 10–80 seconds.

Figure A.2: Example of needle probe test results (Low, 2016)

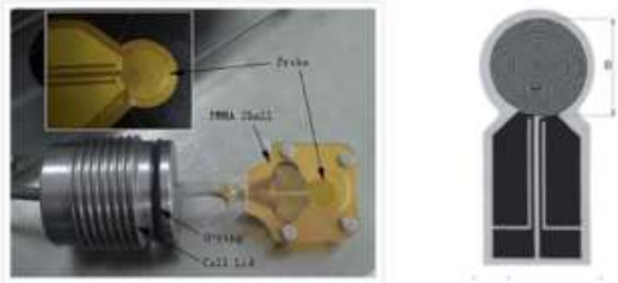


Notes: TC can be determined by using both heating and cooling phases, but the heating phase is by far the most common approach

Appendix A.1.2 **Transient plane source (hot disk)**

The transient plane source (Hot Disk) method was developed to determine both TC and diffusivity, which allows the determination of specific heat capacity of a specimen. Two configurations of the probe are available, the hot plate/square or the hot disk onto which a thin bifilar spiral, is applied by a deposition technique or through using thin metal foils enclosed between thin insulating films (BS EN ISO, 22007-2, 2015). This results in the disk acting as both heat source and temperature sensor (Figure A.3).

Figure A.3: The Transient Plane Source Technique (Gustafsson, 1991)



The theory presumes the source is surrounded in an infinite homogeneous medium and the probe is situated between two identical specimens of the same solid. Once equilibrated, the temperature is increased by 1 to 2K through the application of a constant current therefore as the temperature changes so does the resistance. The heat transfer model for the hot disk method does not have a theoretical analytical solution as it is an absolute technique. Commercially available hot disks come with software developed to solve partial differential heat transfer equations iteratively.

This method is favoured for its speed and low sample disturbance, accuracy and simultaneous resolution of TC and thermal diffusivity. There are no standards for applying hot disk to geomaterials, however (Gustafsson, 1991) demonstrated a 3% uncertainty when applying it to solids. Accurate readings are predicated on good thermal contact, which for coarser unconsolidated geomaterials becomes difficult.

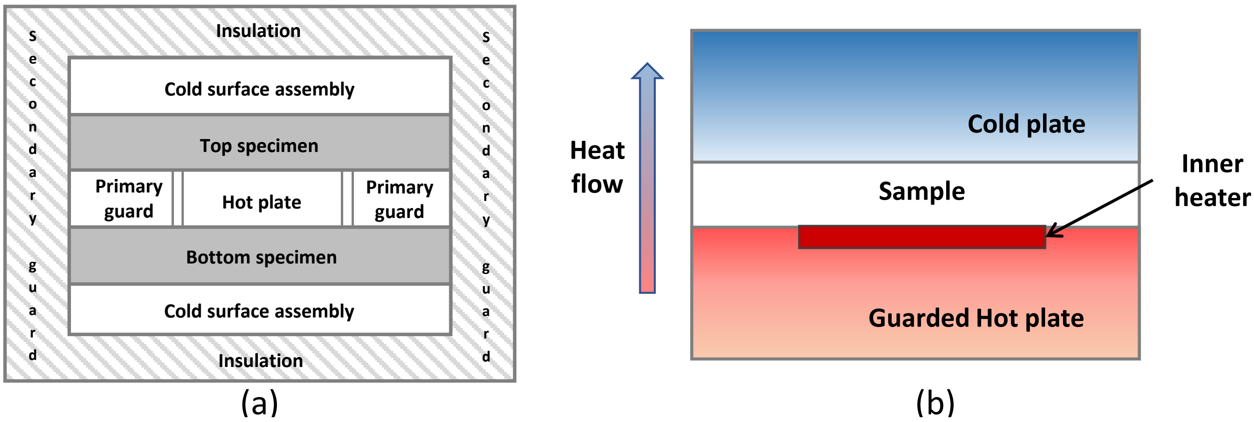
Appendix A.1.3 **Guarded hot plate**

The guarded hot plate is a versatile, non intrusive, plane source technique for determining TC with the direct application of Fourier's Law. There are two principal configurations although many geometries are possible: the first sandwiches a hot plate between two samples of the same specimen (Figure A.4a) and the second shown in (Figure A.4b) sandwiches a single sample of the specimen above a hot and below a cold plate. Both rely on the axial generation of a steady state temperature gradient, the first up through the top and down through the bottom samples, the second just axially up through the sample.

The theory is predicated on the development of one directional flow which requires adequate application of insulating guards to prevent losses at the base and radial flow from the sides. Insufficient insulation will result in an overestimation for the applied power and consequently the TC. This effect is reduced in the two specimen configuration.

Guarded hot plate are easy to construct and operate, relying on simple analysis and the generally sample preparation is minimal. However, the variants of this technique are well established in the determination of the thermal conductivity of building materials, while for geomaterials, there are uncertainties related to the equipment, test procedure, sample size and sample preparation. Ensuring construction and operation follow the specified standards the corresponding accuracies (±2% BSI 12664, 2001), repeatability (±0.5% BSI 12664, 2001 and ±1% ISO 8302,1991) and reproducibility (±1% BSI 12664, 2001; ISO 8302,1991) can be achieved. These standards were not written specifically for soils and practicalities of this approach might be challenging on a project basis.

Figure A.4: The two forms of guarded hot plate method



Notes: (a) hot plate sandwiched between two specimens of a sample with steady state temperature gradient being achieved up through the first specimen and down through the lower specimen (ASTM C177-19, 2019). (b) is a single sample, heat is generated by the base plate and transmitted up through the sample to the cold plate generating a steady state temperature gradient

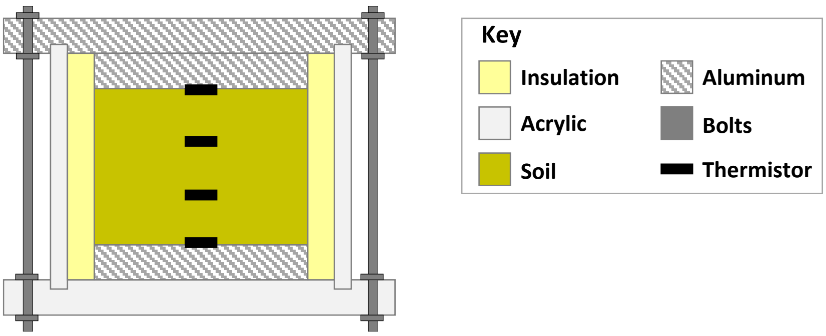
Appendix A.1.4 **Thermal cell**

The thermal cell is also a non intrusive plane source technique and is theoretically identical to the guarded hot plate and so can be considered an iteration of this method. It has been specifically developed to analyse thermal properties of U-100 cores and BS 5930:2015+A1 (2020).

The theory is based on the generation of constant axial (1D) thermal gradient produced by an embedded heater in the base which dissipates heat from the top (Clarke et al, 2008). Once steady state is achieved, if power is measurable, thermal conductivity can be derived through the direct application of Fourier's Law otherwise, the lumped capacitance method can be used in special circumstances to evaluate power (Clarke et al, 2008).

This method is suitable for most soils and relies on simple analysis directly suited to U-100 cores. Although, there are no official standards for the thermal cell or alternatives, the 'Thermal Pile Design, Installation & Materials Standards' recommends the thermal cell as the laboratory method along with needle probes. There are uncertainties related to the equipment, test procedure, sample size and sample preparation, noting that the Clarke et al (2008) cell and University of Southampton cell are presently not recommended over transient methods (Low et al, 2017).

Figure A.5: Schematic of a thermal cell (Low, 2016) based on (Clarke et al., 2008)

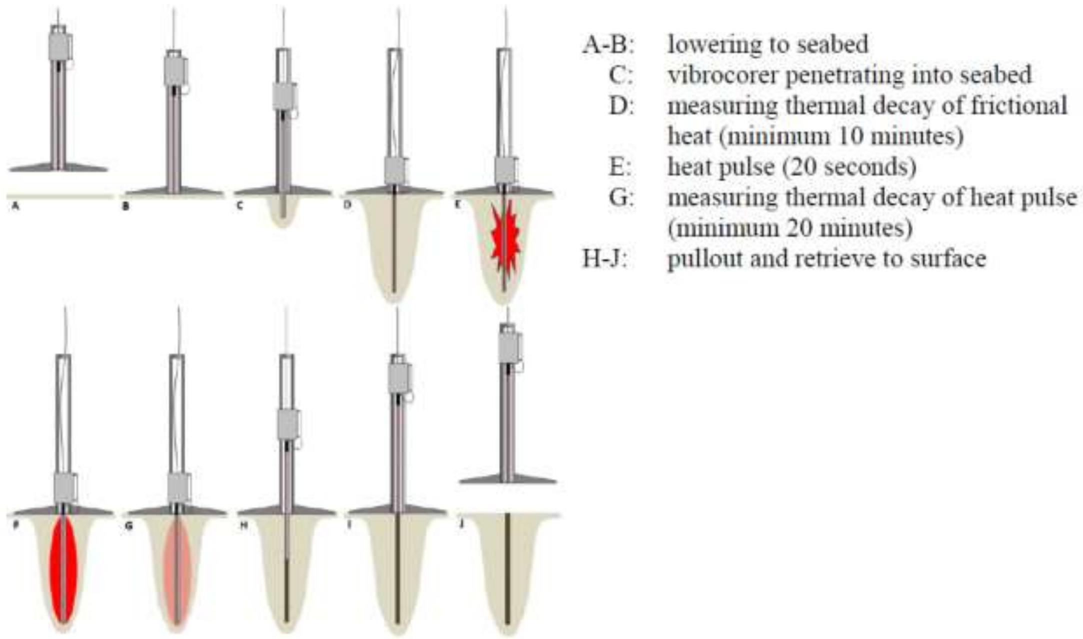


Appendix A.2 **In situ techniques**

Appendix A.2.1 **Passive and active thermal probes**

The most widely known, actively heated, thermal probe system that is available for commercial use is the Fielax VibroHeat, which can be deployed on a Vibrocorer or integrated into CPT systems above the cone tip. The device combines passive and active heating phases and is deployed into the seabed penetrating the soil. During this process (shown in Figure A.6): during penetration the temperature usually rises from frictional heating but settles on an ambient soil temperature. This allows for relative soil temperature to be recorded as a function of depth determining the temperature gradient. After allowing the dissipation of the frictional heat (at least 10 minutes of stabilisation time), a heat pulse with a 20 second duration is enabled and heats the sensor tube and surrounding soil generating a sharp temperature spike. To measure the decay of thermal energy, the probe remains in the soil for at least 20 minutes allowing for a depth dependent result for the TC of the soil. highlights this process.

Figure A.6: Method of deployment of Fielax VibroHeat system (Evensett et al., 2016)



It can be difficult to establish the accuracy and precision for these instruments and often making the information public is not possible. However, the individual components give temperature measurements to an accuracy of < 100mK with a precision of ± 1mK.

A second heat probe system used in industry with a similar design is the FERITECH FT580 Heat Flow Probe. Real time TC, spot temperature and thermal gradient measurements can be produced from this probe within the seabed. The system is a standalone system with a uniform heat source along the length of the probe including high density (0.05m resolution) array of thermistors. As mentioned, data can be collected in real time or collected automatically and stored internally and then extracted when the instrument is recovered. Due to the nature of this system, it can also be left on the seabed for longer periods of time in a passive mode recording seasonal changes. Currently there are no published or publicly available work into assessing the performance of this system.

A further active method for in situ TC measurement is the use of a needle probe that is attached to the tip of a conventional cone penetrometer (CPT). The device operates and is interpreted in the same way as a lab based needle probe (see Appendix A.1.1) and is usually of slightly greater dimensions, to be more robust when used offshore. For example, the probe may be 4-8 mm in diameter and extend by 150-200 mm beyond the tip of a conventional 35.7 mm diameter CPT. These devices are available for commercial use, but the passive Thermal-CPT is becoming more commonly used (see Section Appendix A.2.2).

Based on physical experimental investigation and modelling works (undertaken by Emeana et al, 2016; Hughes et al, 2015a and Callender et al, 2021) the following should be considered:

- Permeability can play a major role within heat dissipation from HV cables. Especially in high permeability soils, the main mode of heat transportation is through convection, which if occurring when undergoing in situ testing would be reflected in higher TC measurements.
- There might be discrepancies in comparison to the laboratory testing results, especially in silty sand or fine and medium sands with low relative densities (c. < 50%).
- It is considered that the main mode of heat transportation is through convection (for high permeability soils). Currently there is no theoretical or experimental work into the effects convection may have with these in situ probes.
- Similarly, to date there have been no systematic investigation into the effects of liquefaction and soil disturbance and how these events may affect the permeability of the soil which could impact the measurements (see also remarks on sample preparation for laboratory testing).

Appendix A.2.2 **Passive method – thermal CPT**

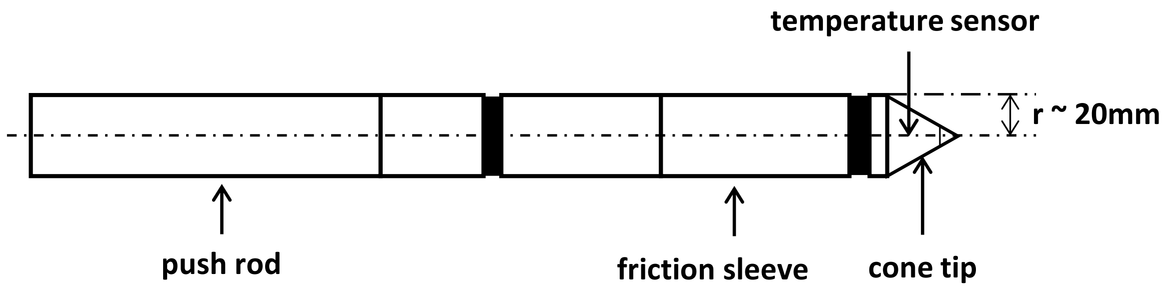
Thermal-CPT (T-CPT), Figure A.7, uses an added temperature sensor on a standard cone penetrometer and follows the same protocol as a CPT (e.g. ISO, 2021). To measure TC the test is stopped and during this state of static penetration the temperature decay is recorded and from this the temperature time series measurements for TC can be calculated (Vardon et al, 2018).

The T-CPT system generally performs best in sandy sediments with sufficient friction to generate a temperature difference between the ground. TC is calculated using one of the two mathematical methods presented by Vardon et al (2019) within sufficient time the solution will converge. To generate robust measurements, the critical terms include (see Figure A.8):

- The temperature change needs to be at least 3°C.
- Measurement time should be between 500 and 1000 seconds.

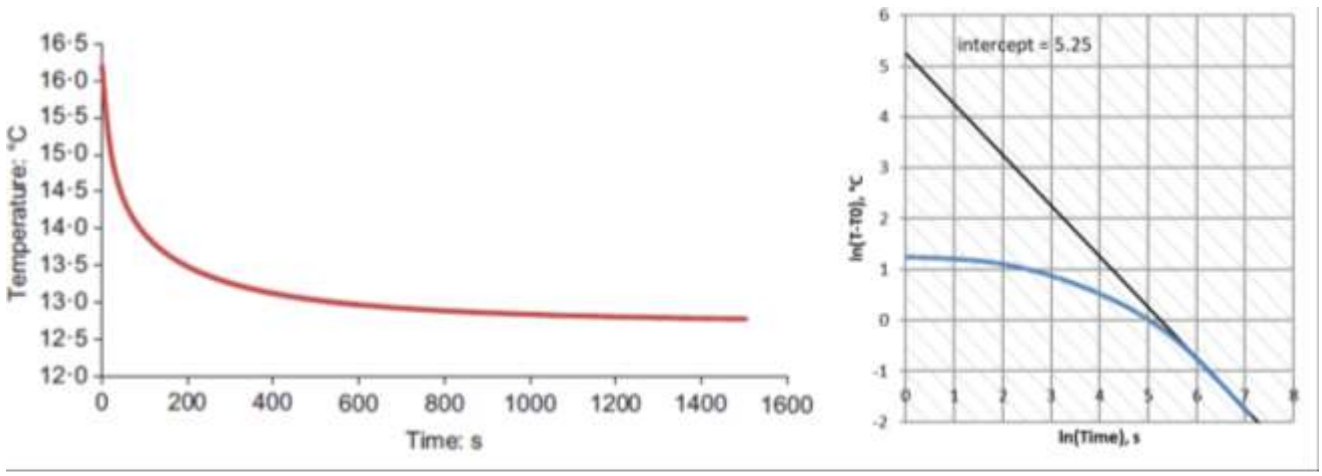
- At that time after plotting a *ln(T-T₀) / ln(t)* graph the gradient should be -1 (Figure A.8).
- The calibration factor is cone specific and needs to be generated from a 2D axisymmetric model for the deployed cone, including the precise location of the temperature sensor within the cone. Prior knowledge of the material being used is needed as the calibration factor changes with the thermal conductivity of the material being used.
- Accurate calculation of T_0, this can be achieved through either ensuring sufficient time for heat dissipation or using the associated equation.

Figure A.7: Thermal cone penetration test (T-CPT) (Vardon et al., 2018)



It is important to recognise that the T-CPT approach offshore is very new within the offshore industry, with limited available information to conclude whether that measurements taken *in situ* would be any more representative of conditions around an installed cable than those taken in the laboratory. For instance, there has to be consideration that the pushing of the T-CPT into the seabed may in itself change the thermal properties, via inducing soil volume changes during both the initial penetration phase and the actual heat dissipation test.

Figure A.8: Example of T-CPT for recorded TC of 1.97W/mK (Vardon et al., 2019)



Appendix A.2.3 **Passive method – correlation with conventional CPT measurements**

Standard measurements from CPT data can be used to estimate TC including tip resistance, sleeve friction and pore water pressure. These parameters are all measured in the CPT tests and can be used to estimate soil type and mechanical properties. The acquired data correspond to continuous profiles and input data is typically taken as part of site investigations; hence they represent a potentially cost effective approach.

The primary measurements during a CPT are (i) tip resistance, q_c, (ii) sleeve friction, f_s, and (iii) pore water pressure, u_2. These parameters are measured during continuous penetration of the cone at a standard rate of 20 mm/s. The parameters provide an indirect indicator of the soil mechanical properties. Many correlations exist to estimate parameters such as soil type, and soil strength and unit weight from CPT data (Lunne et al. 1997). Using these correlations, CPT data can be used to estimate porosity and soil type, and thereafter the methods set out in Section 3.2.4 can be applied to estimate TC from porosity and soil type. The approaches to find porosity and soil type are as follows:

1. Estimate the soil unit weight, using correlations based on the CPT parameters
2. Estimate porosity from unit weight, using an estimated soil grain specific gravity, G_s
3. Estimate the soil type and mineralogy based on the CPT parameters

Based on the calculated porosity and estimated soil type and mineralogy, TC can be estimated following the method set out in Section 3.2.4.

Vardon & Peuchen (2021) used a similar approach to assess TC based on CPT parameters, and examined the reliability of this method. Their study provides additional information including simple look-up charts to estimate thermal properties directly from CPT parameters. Their approach is the same as outlined in this report, but with different values assumed for the apparent solid fraction thermal conductivity to link porosity and TC.

The measured CPT parameters are converted to normalised CPT parameters as follows:

Q_{tn} is the normalised cone resistance, calculated as $Q_{tn} = \left[\frac{(q_t - \sigma_{vo})}{P_a}\right] / \left(\frac{P_a}{\sigma'_{vo}}\right)^m$, where q_t is the corrected cone resistance, σ_{vo} is the *in situ* vertical total stress at the cone tip, σ'_{vo} is the *in situ* vertical effective stress at the cone tip, P_a is atmospheric pressure and m is a stress exponent related to the soil type.

F_R is the normalised friction ratio, calculated as $F_R = 100 \cdot f_t / q_n$ where f_t is the corrected sleeve friction and q_n is the net cone resistance, $q_n = q_t - \sigma_{vo}$.

Robertson & Cabal (2010) provided the following correlation that provide soil bulk unit weight, γ, as the following ratio of the unit weight of water, γ_w:

$$\frac{\gamma}{\gamma_w} = 0.27 \log F_r + 0.36 \log Q_{tn} + 1.236 \qquad \textbf{Equation A-1}$$

Subsequently, an alternative formulation was developed by Lengkeek et al. (2018), using a database that included soils with organic content, and so captures the lower unit weight of these soils:

$$\frac{\gamma}{\gamma_w} = \frac{\gamma_{ref}}{\gamma_w} - \beta \frac{\log\left(\frac{Q_{tn,ref}}{Q_{tn}}\right)}{\log\left(\frac{F_{r,ref}}{F_r}\right)} \qquad \textbf{Equation A-2}$$

The reference values in this expression that best fit the database of Lengkeek et al. (2018) are:

γ_{ref} = 19 kN/m^3, $Q_{n,ref}$ = 150, $F_{r,ref}$ = 30 and β = 0.412

The bulk unit weight of saturated soil is linked to the unit weight of the solid and fluid phases via following relationship:

$$n = 1 - \frac{\left(\frac{\gamma}{\gamma_w} - 1\right)}{(G_s - 1)} \qquad \textbf{Equation A-3}$$

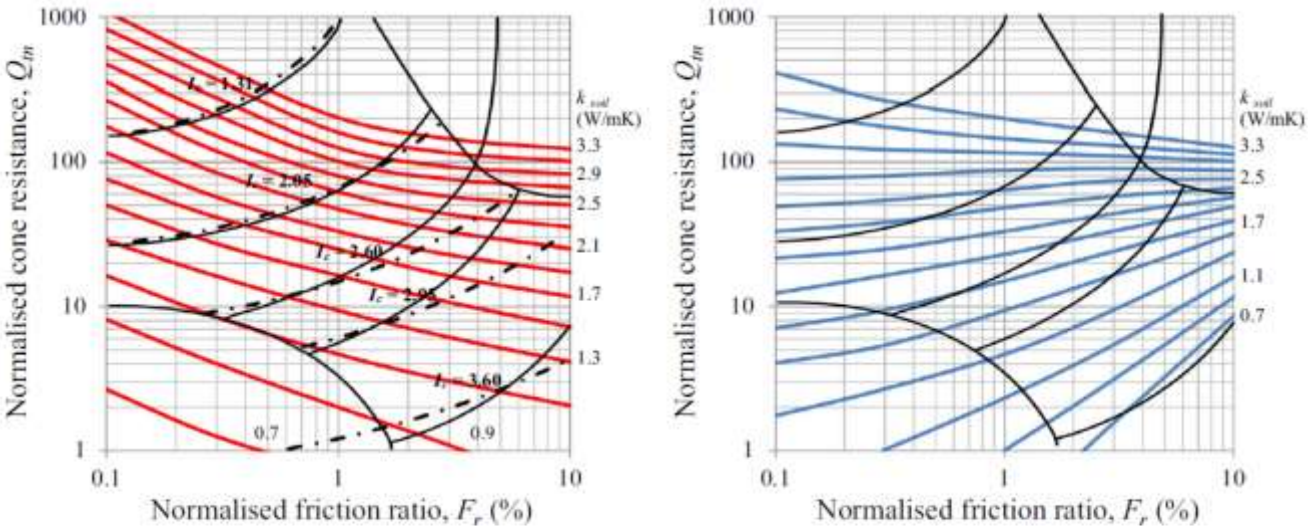
The grain specific gravity is a parameter that varies only slightly between different mineralogies. If it is assumed that G_s = 2.65, then the Robertson & Cabal (2010) approach can be used to estimate porosity from the CPT parameters as:

$$n = -0.164\, log F_r - 0.218 \log Q_{tn} + 0.857 \qquad \textbf{Equation A-4}$$

In order to estimate TC from porosity, it is necessary to adopt a value of thermal conductivity for the solid grain fraction, λ_{solid}. This parameter varies significantly between clays, sands and peat due to their different mineralogical composition. The soil type and the mineralogical composition may be known based on the geological setting, lab testing or other data, which supports estimation of λ_{solid}. Alternatively, the CPT parameters can be used to estimate the soil type, via methods such as the approach outlined by Robertson (2016).

Two similar approaches were set out by Vardon & Peuchen (2021) to identify correlations for TC and volumetric heat capacity for saturated soils. From these relationships theoretical TC correlations can be developed and similar correlations for volumetric heat capacity. Proposed theoretical correlations from standard CPT measurements are shown in Figure A.9. These have been tested at 7 locations from both in situ T-CPT data and needle probe measurements on the specific materials which is recognised as a very small number of samples. There is a level of uncertainty surrounding them, as CPT measurements are influenced by multiple soil properties. There is no strong bias correlating the results but still a high scatter suggesting the initial tests are producing accurate but not precise measurements.

Figure A.9: Correlations for TC and CPT based on Vardon and Peuchen (2021)



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