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Thermal properties of marine sediments

Propriétés thermiques des sédiments marins

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ABSTRACT: The need for electrical interconnection between different regions as well as the proliferation of offshore wind farms all over the world has led to the installation of hundreds of kilometers of submarine electric cables in recent years. In addition, the large number of projects pending of execution, as well as those currently under way, ensures a notable increase in this type of operations over the next few years. For a proper design of the geometry, the insulation type for each cable and the selection of the most suitable cable route, it is essential to determine with high reliability both the thermal and geotechnical properties of the soil/rock in which the cable is going to be laid or buried. The soil behavior against thermal increase will directly influence the quality of the operation and cable life. Moreover, the heat flow around the cable during its operation might affect the marine fauna and flora. Therefore, the thermal properties of the terrain where the cable will be laid or buried will directly influence the environmental impact of the infrastructure. This paper analyses the temperature and thermal conductivity of different types of marine soils from several offshore site investigations using in-situ equipment and manual probes. The reliability of these results is also analyzed.

RÉSUMÉ : Le besoin d'interconnexions électriques entre différentes régions ainsi que la prolifération des parcs éoliens offshore dans le monde entier ont conduit à l'installation de centaines de kilomètres de câbles électriques sous-marins ces dernières années. De plus, le grand nombre de projets en attente d'exécution ainsi que ceux qui sont actuellement en cours, assurent une augmentation notable de ce type d'opération dans les années à venir. À fin d'avoir un bon design de la géométrie et un bon mode d'isolation de chaque câble, ainsi que pour choisir la meilleure route, il est essentiel de déterminer avec une grande fiabilité les propriétés thermiques et géotechniques du sol/roche sur lequel le câble doit être posé ou enterré. Le comportement du sol face à l'augmentation de la température aura une influence directe sur la qualité de l'exploitation et la durée de vie du câble. D'autan plus le flux de chaleur autour du câble pendant son fonctionnement ne pourrait avoir un impact sur la faune et la flore marine. Par conséquent, les propriétés thermiques du sol où le câble sera posé ou enterré influenceront directement l'impact environnemental de l'infrastructure. Cet article analyse la température et la conductivité thermique de différents types de sols marins de différentes études offshores à l'aide d'équipements in situ et de sondes manuelles. La fiabilité de ces résultats est également analysée

KEYWORDS: In-situ temperature measurements, Marine geosciences, Seafloor characterization, Thermal properties

1 INTRODUCTION

The demand for subsea HV cable systems has increased in the recent years due to the proliferation of offshore renewable energy systems, especially wind farms, and for the development of the intra and trans-national submarine electrical interconnections net. The thermal properties of the soil/rock where the cable is buried play a key role on cable rating and cable losses along the route. A "cool" cable is more efficient for power transmission whereas heating of the sediments is important because of a possible negative influence on benthonic biological communities (Müller et al 2016). Therefore, the design of the cable itself, the most suitable cable route and the cable burial study, among others, are strongly influenced by the thermal properties of the ground.

There are many other fields where the thermal properties are of great importance: the design of thermally active ground structures such as geothermal energy foundations and borehole heat exchange systems, pipelines and power cables in unfrozen ground, any kind of structure in cold regions as well as in energy geotechnics, energy geo-storage and deep geological disposal of heat-emitting and long-lived radioactive waste, among others.

The calculation or estimation of the thermal conductivity of a soil or rock is not an easy task since it is quite sensitive to many other parameters such as the moisture content, the density, the mineralogical composition and the organic content. This paper presents the temperature and thermal conductivity of marine sediments from 11 offshore surveys related to wind farms and submarine electrical interconnections conducted in Europe in the recent years. Data were obtained by in-situ heat flow probe penetrated into the seafloor by pushing and by handheld thermal needle probe on samples recovered by different sampling methods. Data were split according to their cohesive or granular behavior once described and tested in the laboratory. Moreover, a comparison between the thermal conductivity obtained by both methods at the same locations was also performed. These results belong to larger investigative project which pretends to increase the knowledge of the thermal properties of marine sediments.

2 THERMAL CONDUCTIVITY

2.1 *Methods for calculating the thermal conductivity of soils*

Many authors have proposed either empirical equations or theoretical approximations to calculate the thermal conductivity of frozen and unfrozen soils since the early 1940s. Some of the latter were updated considering experimental data hence could be considered as semi-empirical.

Kersten (1949) proposed a prediction of thermal conductivity based on tests on 19 different soils in terms of the moisture content and the dry density. The equations were separate for frozen and unfrozen and for fine and granular soils. (Johansen 1975) expressed the thermal conductivity of a saturated soil as a function of the thermal conductivity of the components and their respective volume fractions, which is based on the precisely knowledge of the quartz content while assuming a mean conductivity of 2.0 W/m K for the other soil minerals. Other authors such as (Mickley 1951, Gemant 1952, De Vries 1952a, 1952b, Kunii & Smith 1960, among others) did important contributions, especially for unfrozen soils. Farouki (1981) provided a framework of the factors influencing the thermal properties of the soils and evaluated the most used empirical and semi-empirical methods, comparing the results for a set of various experiments and suggesting the most suitable for moist coarse and fine soils, unfrozen or frozen and for dry soils.

More recent contributions such as numerical methods fine-tune these estimations and allow predicting some other important aspects such as the impact of additional heat through power cables or seasonal variations in sediment temperature during the year. Nevertheless, although predictions and numerical modeling are also used, projects related to submarine electric cables require the measurement of actual thermal properties of the soil along the route with high reliability and accuracy for a proper cable burial and cable route assessment as well as for a calibration and verification of any numerical model. Thermal conductivity of the ground is a significant design parameter which should be established through in-situ testing and/or laboratory analysis (DNV-GL 2016).

2.2 *Methods for measuring the temperature and thermal conductivity of soils*

2.2.1 *In-situ measurements*

The in-situ thermal measurements are generally performed using a heat flow probe that penetrates into the first meters below the seafloor. The temperature sensors and heating wire are installed along the tube. For soft deep sea sediments, the penetration can be performed by its own weight while for shear resistant shallow sea soils it can be performed by vibrocoring. A more recent development was used for this study, designed and manufactured by Fielax and Marine Sampling Holland, which combines the thermal probe with a 2 cm^2 CPT cone that allow penetrating by pushing in order to overcome problems like liquefaction in sandy soils (see Figure 1).

Figure 1. Fielax-Marine Sampling Holland "PushHeat" equipment

The thermal properties at different depths are calculated after a sudden heat pulse that heats up the sensor tube and the surrounding sediment, resulting in a sharp peak. The decay of the thermal energy is measured during some minutes towards the undisturbed sediment temperature, allowing the determination of the depth-dependent thermal conductivity of the sediment. A principle of in-situ thermal parameters measurement by a heat flow probe used in combination with a 2 cm^2 CPT cone is shown in Figure 2. A: Heat flow probe lowering to the seabed. B: Penetrating into seabed. C: Recording temperatures of thermal decay of frictional heat for the determination of undisturbed sediment temperatures. D: Artificial heat pulse. E: Recording decay of temperatures of decay of heat pulse for determination of thermal conductivities and diffusivities. F: Retrieval to surface. The lower panel shows the corresponding temperature recordings of each thermistor.

It is assumed that thermal conductivity and temperature data obtained from in-situ measurements are the most reliable due to the minimum disturbance of the soil. However, the necessary time to perform one test and hence the limited number of tests per day on board is a high economical drawback with respect to other methodologies.

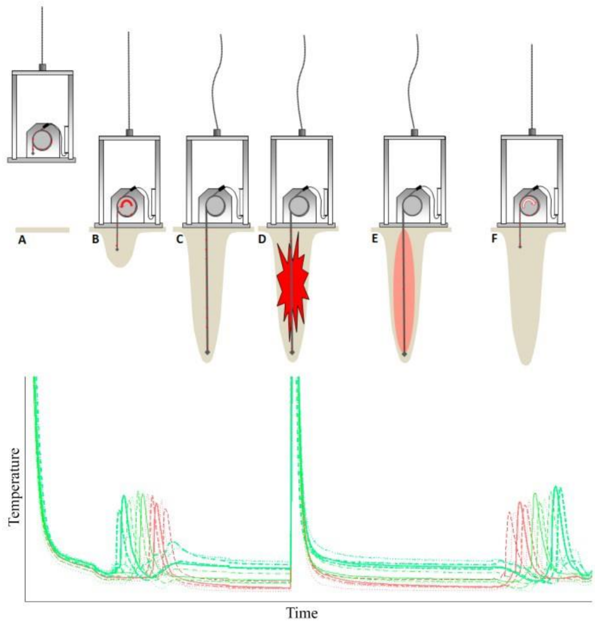

Figure 2.Principle of in-situ thermal parameters measurement used in combination with a 2 cm^2 CPT cone

2.2.2 *Thermal needle probe*

The thermal needle probe used in this study was the KD2 Pro thermal properties analyzer, manufactured by Decagon Devices. It is a handheld easy-maneuver device that is inserted into the soil sample for testing. It is based on the infinite line heat source theory and calculates the thermal conductivity by monitoring the dissipation of heat from the needle probe (Barry-Macaulay et al. 2016). The sensor used was the TR-1, a 2.4 mm diameter and 10 cm long sensor designed primarily for soil and other granular or porous materials. The dimensions of this sensor meet the specifications established in the IEEE 442 and ASTM 5334 standards.

This equipment allows performing a large amount of measurements on board in a relative fast way. Thus, it is the most used methodology for measuring the thermal properties of marine soils. Nevertheless, there are two main drawbacks which imply that a strong quality control and a strict methodology should be considered: (i) the soil is disturbed during sampling and handling operations and (ii) the dimensions of the sensor induces either soil disturbance when inserted and heating may drive water away from the sensors. In this sense, long heating times were used as it minimizes contact resistance that results in water movement away from the sensor. Moreover, 3 different probes were used, all of them calibrated and daily verified following manufacturer instructions and up to 6 measurements at the same depth were carried out. The time between sampling recovery and each measurement was also registered.

Tests were generally undertaken onboard on the top and bottom of each subsample (typically 1m length) recovered by either vibrocoring or pistoncoring. With the aim of avoiding heat up due to the air temperature and loss of natural moisture content, tests were carried out as soon as the samples were extracted from the caisson and before any visual description or local disturbance by strength in-situ test was performed. In any case, if the sediment core was disturbed during the core recovery or during handling operations, measurements were discarded. A few number of tests considered for this study were also conducted in the onshore laboratory.

There are several publications related to experimental studies with thermal needle probe in the laboratory. (Barry-Macaulay et al. 2016) studied the influence of the moisture content, density and mineralogical composition of six soils from the Melbourne (Australia) region. According to the results, coarse grained soils have a larger thermal conductivity than fine grained soils. In addition, the thermal conductivity increased with an increase in dry density and moisture content. Some other contributions both in soils and rocks were also published by (Chen et al. 2011, Garitte et al. 2014, Zhang et al. 2019) among many others.

2.2.3 *Laboratory tests*

Special laboratory tests on well preserved samples are not the common procedure for determining thermal properties of the soil for connection of offshore wind farms and submarine electrical interconnection projects. Nevertheless, they are commonly used for specific purposes such as radioactive waste repositories, when dealing with specific effects on thermal conductivity under better controlled conditions or the study of the anisotropic thermal behavior of the ground, among others. Some interesting contributions were published by (Lima 2011, Low et al. 2015, Romero et al. 2016 and Sau et al. 2019), among others.

3 RESULTS

The thermal conductivity obtained in marine sediments with both in-situ measurements and thermal needle probe in 11 different offshore soil investigation campaigns in Europe is analysed. Three surveys were conducted in the west Mediterranean Sea, 1 in the North Sea and 6 in the French Atlantic Coast and 1 in the Spanish Atlantic Coast. Projects were related to wind farm inter-array and export cables and intra and trans-national submarine electrical interconnections. Geophysical and geotechnical surveys were also conducted together with the determination of the thermal properties of soils along the routes for a wide range of objectives: cable route study and engineering, determination of ground properties for evaluating the effects of relevant installation and operational conditions, cable burial study, cable protection study, design of HDD trajectories, etc. The number of locations and the total number of tests considered in this study are detailed in Table 1.

Table 1. Number of locations studied and the total tests considered in this study.

	Locations	*Tests*
Total measurements	160	*678*
In-situ measurements	19	177
Thermal needle probe on board	134	490
Thermal needle probe in laboratory	11	11

The methodology used in each survey was the one specified in the scope of work and technical requirements of each project. In-situ measurements were conducted up to the required investigation depth with thermistors located at regular distances along the sensor tube, typically around 0.3 m. Measurements with needle probe on board were performed on the top and bottom of each subsample, allowing acquiring data every 1 m approximately along the vibrocore or pistoncore subsamples. Finally, the depth of each test in the laboratory was established after a preliminary analysis of field data. The location of the surveys included in this study is shown in Figure 3. The methodology used in each case for the determination of the thermal properties of the soil is also specified.

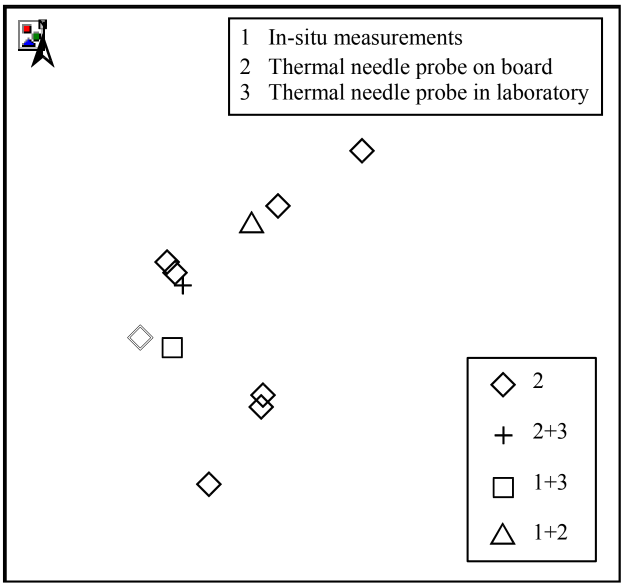

Figure 3. Location of the surveys included in this study. The methodology used for the determination of the thermal properties in each case is specified

3.1 S*oil temperature*

The main driving force for the sediment temperature distribution is the seasonal heating and cooling through the sea water strongly modified by the thermal properties of marine sediments (Müller et al. 2016). Large temperature differences in the upper sediments are therefore expected depending on when the measures were performed. For this study, only in-situ measurements of temperature were considered. Data from needle probe from both on board and laboratory shows a spread in results which is not representative of actual marine soil temperature. It is fully expected as the soil has been extracted from the ground and the temperature has been measured on board, normally during summer season. The more time passes after the sample extraction and the performance of the test, the less reliability of test results. The soil temperature measured by the in-situ heat flow probe in the first 4.5 mbsf in two different projects in the French Atlantic coast is shown in Figure 4. Measurements were performed in May and September.

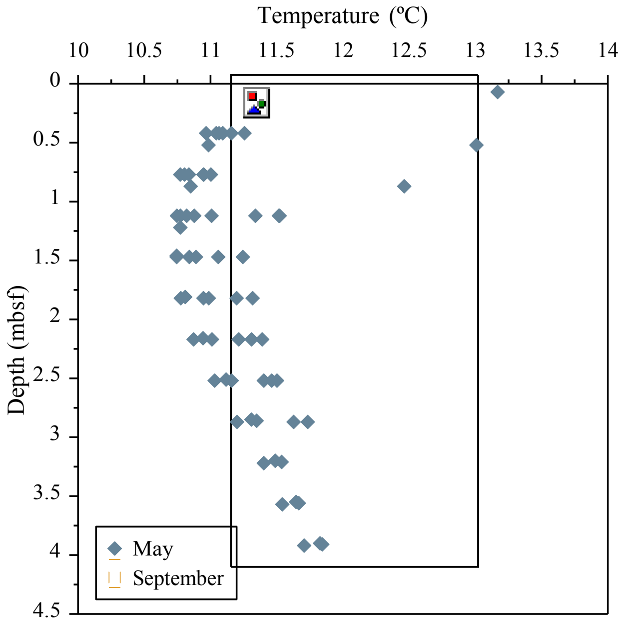

Figure 4. Soil temperature measured by in-situ heat flow probe in two different projects in the Atlantic coast

The influence of the warm summer temperatures is observed in the upper meters in both cases. Then, the temperature increases as the general positive temperature gradient.

3.2 *Soil thermal conductivity*

The thermal conductivity is influenced by many factors such as the composition and structure of the soil, the water and its migration and the direction of the heat flow, among others. From a general point of view, thermal conductivity in marine sediments increases with depth because it is inversely correlated with porosity, which decreases exponentially with depth from the seafloor because of the compaction effect of the sediment (Goto et al. 2017). There is also a strong influence of the mineralogical composition of the soil, since quartz is a high-thermal conductivity mineral (7.7 W/mK) compared with most other soil minerals which values are generally less than 3 W/mK.

This paper is a first step on a further investigation focused on the relationship between the thermal conductivity and soil properties of marine sediments with the aim to increase the knowledge for submarine cable design and burial assessment in offshore renewable energy systems and electrical interconnections. The thermal conductivity related to the main granular/cohesive behavior is shown for some offshore soil investigations in Europe. The relationship between thermal properties and some other parameters such as the moisture content, density or porosity will be included in a further analysis. The following Figure 5 includes the 661 thermal conductivity data obtained by in-situ measurements and handheld needle probe for all soil types.

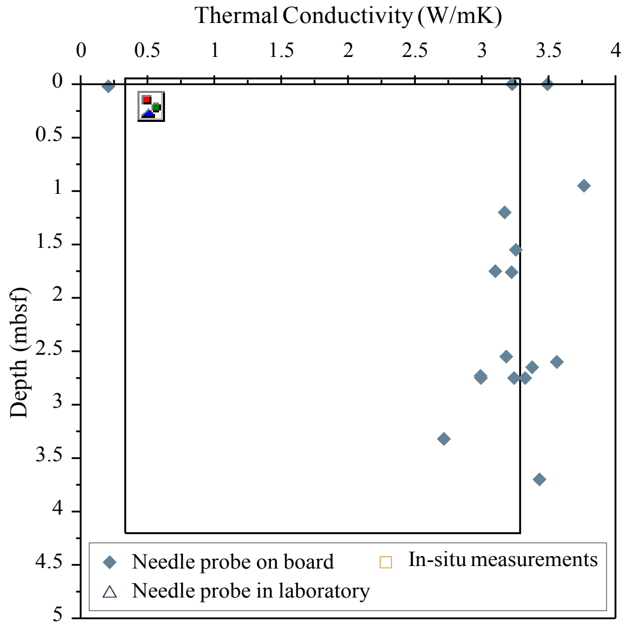

Figure 5. Thermal conductivity values measured by the in-situ heat flow and the manual needle probe for all soil types.

Values generally range between 1 and 3 W/mK with a remarkable spread and a slight trend to increase with depth. These values are in line with common values in marine sediments as well as with the existing bibliography. No remarkable variations between the different methodologies for measuring the thermal conductivity are observed. Few values around 0.5 W/mK were also obtained although only in isolated measurements.

All thermal conductivity values were split mostly in cohesive and granular behaviour of the soil, based on the particle size distribution both by sieve and hydrometer. More specifically, Figure 6 and Figure 7 show the thermal conductivity of the following type of soils:

- Peat & cohesive soils: from clay to sandy silt
- Granular soils: from silty sand to gravel

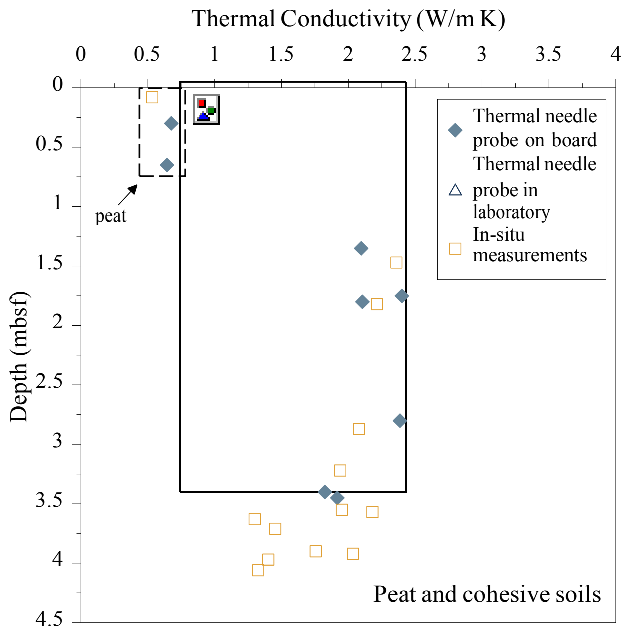

Figure 6. Thermal conductivity values for peat and cohesive soils (from clay to sandy silt)

Values generally range between 1 and 2 W/mK with a slight trend of increase with depth. The spread of values is around 1 W/mK, mostly due to differences in the mineralogical composition of the soil and density in each location. These parameters will be considered in a further analysis. No significant differences were observed between thermal needle probe and in-situ measurements. On the other hand, values in peat soils were less than 0.75 W/mK.

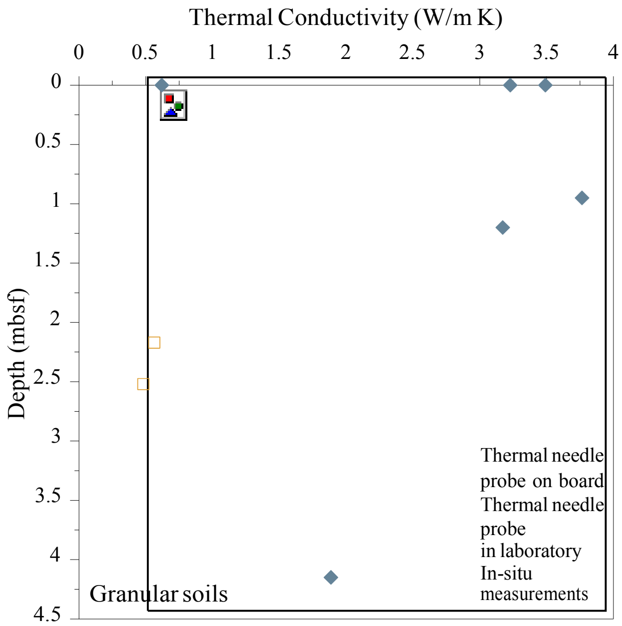

Figure 7. Thermal conductivity values for granular soils (from silty sand to gravel)

The spread of data is significant at all depths. Values range from 1 to 3 W/mK but no evident trend is observed with depth. This spread is assumed to be due to (i) differences in the composition and structure of the different soils studied and (ii) the unavoidable disturbance of sandy and gravelly soils when extracted by vibration of even when the sensor tube is penetrated into the ground.

Although no significant differences were observed in thermal conductivity values when measuring with different methodologies (Figure 6 and Figure 7), in-situ measurements are expected to be more accurate since less soil disturbance is produced during testing whereas thermal measurements with needle probe were conducted with up to 3 different devices and following a strict methodology. Therefore, a good quality of data is also expected.

One project allowed comparing both methodologies at the same location since some double points (in-situ measurement + thermal needle probe onboard on vibrocore subsamples) were included in the scope of the project. The comparison in four double points is shown in Figure 8. The soil description is also included based on laboratory results.

The in-situ measurements provide a more continuous profile of with depth as data were obtained every 0.35 m. There are some variations in the thermal conductivity even when the type of soil is continuous up to the bottom of the vibrocorer. It is assumed that these differences are related to local variations in moisture content, porosity, density, organic content and mineralogy, among other parameters. From a general point of view, there is a good agreement between both methodologies in all type of soil. Therefore, it is assumed that the soil disturbance caused during soil recovery and handling to perform measurements by the thermal needle probe is counteract by a strong quality control of data and a strict methodology on board.

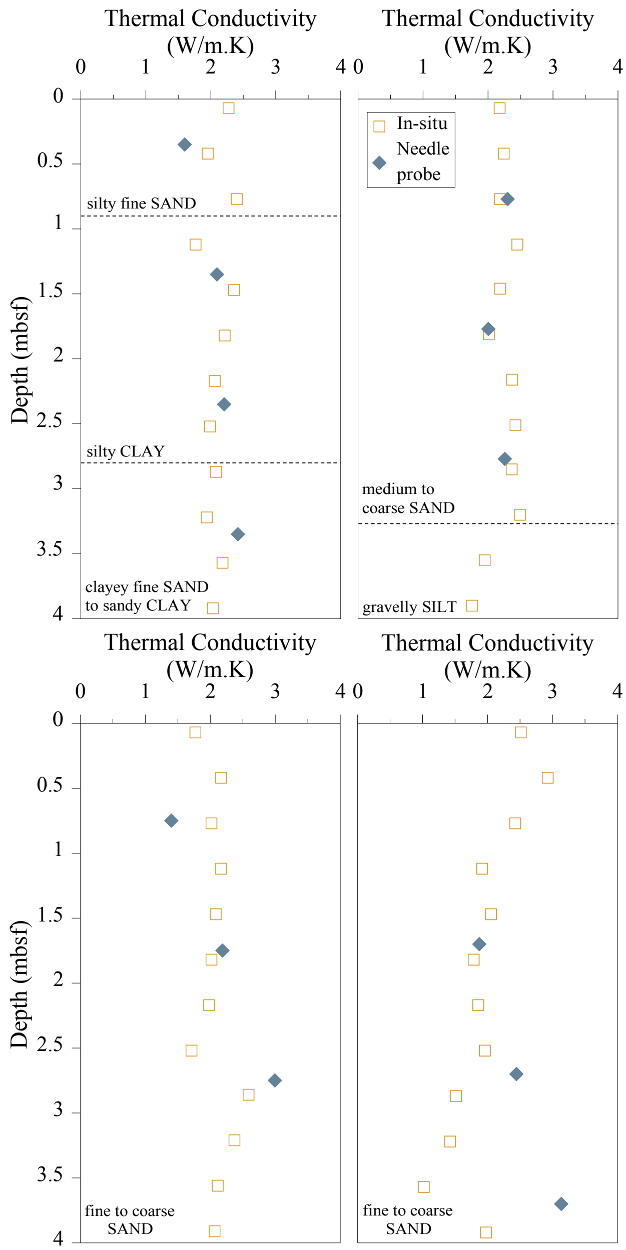

Figure 8. Thermal conductivity by in-situ measurements and thermal needle probe on board in four double points

4 CONCLUSIONS

The temperature and thermal conductivity of marine sediments from 11 offshore surveys related to offshore wind farms and submarine electrical interconnections conducted were analysed. Data were obtained by in-situ heat flow probe penetrated into the seafloor by pushing and by handheld thermal needle probe on samples recovered by different sampling methods, both onboard and in the onshore laboratory.

The soil temperature was measured by the in-situ heat flow probe in the first 4.5 mbsf in two different projects in the French Atlantic coast. Values were in line with expected values of the study area. The influence of the warm summer temperatures was observed in the upper meters in both cases.

The thermal conductivity values show a spread in results due to differences in the composition and structure of each soil and in soil disturbance during testing. Values for cohesive soils (from clay to sandy silt) range between 1 and 2 W/mK with a slight increase with depth. In case of granular soils, thermal conductivity values range between 1 and 3 W/mK with a spread at all depths and no evident trend with depth.

The comparison between in-situ measurements and handheld thermal needle probe on board in double points allow ensuring that both methodologies provide similar results when needle probe is used following a strict methodology and with a quality control of data.

The relationship between thermal properties and some other parameters such as the moisture content, density or porosity will be included in a further analysis.

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