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Thermal Conductivity of Saturated Soils

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ABSTRACT: Soil thermal conductivity is critical for the design of subsea cables for offshore wind farms. This study presents the results for a series of needle probe thermal conductivity tests conducted on silica fine sand, kaolin clay, and mixtures of silica sand and natural offshore carbonate soils to investigate the effect of soil mineralogy, soil packing and carbonate content on soil thermal conductivity. The test results indicate that soil thermal conductivity is dependent on soil packing, soil mineralogical composition and soil saturation. The findings of this study underscore the importance of site-specific testing, thorough characterization of soil thermal properties and careful consideration of the impact of soil disturbance caused by cable burial and operational processes on soil thermal conductivity for accurate cable performance prediction and the development of robust and optimized cable design. Drawing from the insights gained in this study, a strategy has been proposed to characterize the thermal properties of seabed soils along cable routes, as well as to assess the impact of soil disturbances caused by cable burial and operational processes on soil thermal conductivity.

Keywords: thermal conductivity; buried cables; saturation; porosity; mineralogy

1 INTRODUCTION

Soil thermal conductivity is an important soil parameter for the design of buried cables for offshore wind farms. This is because when the electricity is transmitted through the cable, the cable will heat up and the surrounding saturated soil insulates the cable from heat dissipation. Therefore, proper characterization of soil thermal conductivity is important for realistic prediction of cable performance during operation and for optimized and robust cable design. Cable repair or replacement is a costly operation and will disrupt power generation to the communities that the offshore wind farms are servicing.

This paper presents the results of a series of needle probe thermal conductivity tests that were conducted in the laboratory on silica sand, kaolin clay, mixtures of silica sand and natural offshore carbonate soils to study the thermal conductivity characteristic of each soil type. Thermal conductivity tests were conducted on each of these soil types at a range of densities or porosities to investigate the effect of soil packing and cable burial induced soil disturbance on the thermal conductivity of each soil type. In addition, recommendations on methods to prepare saturated soil samples at a range of densities for thermal conductivity tests that prevent unrealiable measurements due to unsaturated soil samples are also provided. Finally, a strategy to characterise seabed soil thermal conductivity for offshore cable design is proposed.

2 TESTING PROGRAMME

A programme of laboratory needle probe tests was conducted to investigate the effects of soil mineralogy, soil packing and carbonate content on soil thermal conductivity. In addition, the effects of sample saturation on soil thermal conductivity are also investigated to illustrate the importance of ensuring sample saturation when preparing samples for measuring thermal conductivity of saturated offshore soils. The tests conducted for this study are:

- 28 tests on the manufactured fine clean silica sand (with median particle size, D_{50} of 0.22 mm) and kaolin clay (with liquid and plastic limits of 58% and 28%, respectively) to investigate the effect of soil porosity and sample saturation on the measured thermal conductivity; and
- 36 tests on mixtures of silica sand and natural offshore carbonate soils to investigate the effect of carbonate content on soil thermal conductivity.

In this study, thermal conductivity measurements were taken using a Decagon KD2 Pro Thermal Analyser following the ASTM International Standard ASTM D5334-14. Measurements were taken in samples of 200 mm in length and 70 mm in diameter.

3 SOIL SAMPLE PREPARATION METHODS

In this study, samples of three distinct soil types, i.e. silica sand, kaolin clay, and carbonate-silica soil mixtures were systematically prepared for thermal conductivity testing. Each soil sample underwent specialized preparation methods to ensure consistency and accuracy in the measured results.

The fine clean silica sand samples were reconstituted using four preparation methods described below:

- Method 1 – Moist tamping with vacuum saturation. The sand sample with target moisture content was prepared by moist tamping in 10 layers in the testing mould. The sand sample and testing mould were then placed in a tub of saline water (with salinity similar to sea water, 30g/L) in a vacuum chamber. Vacuum saturation of about an hour was then applied up to two times.
- Method 2 - Moist tamping without vacuum saturation. The sand sample with target moisture content was prepared by moist tamping in 10 layers in the testing mould and without additional sample saturation procedure.
- Method 3 - Sedimentation in water column. The sand sample was funnelled through a saline water column with an approximate height of 5 cm until the testing mould was slightly overfilled. The sand sample was then left in the saline water for about 2 hours before being levelled at the top and tested for thermal conductivity.
- Method 4 - Air pluviation with vacuum saturation. Dry sand was rained into the testing mould from an approximate height of 5 cm until slightly overfilled. The sand sample was then levelled and placed in a tub of saline water in a vacuum chamber. Vacuum saturation of about an hour was then applied up to two times.

Methods 1 and 4 were used to create medium dense to dense sand samples with high degree of saturation whereas Method 2 was used to create sand samples with a range of densities and degree of saturations. Method 3 was used to generate loose sand samples with high degree of saturation.

The vacuum saturation procedure adopted in Methods 1 and 4 aims to extract any trapped air and ensure high degree of saturation. After the sand samples were prepared to the desired densities, filter papers and porous discs were placed at both ends of the testing moulds and sealed with tape to prevent sample movement. The samples were then saturated by immersing them in a tub of saline water and subject to negative pressure inside a vacuum chamber until no visible air bubbles emerged from the samples. Following vacuum saturation, the sand samples were soaked in water overnight and tested the next day.

The kaolin clay samples tested in this study were initially prepared as a slurry by mixing them at twice their liquid limit using saline water. The slurry was poured into a mould and then placed in a vacuum chamber to remove trapped air. The samples were then consolidated with vertical stresses of 25 kPa, 75 kPa and 150 kPa until settlement ceased to create clay samples with a range of moisture contents. The consolidated samples were then tested for thermal conductivity.

The carbonate and silica sand mixtures were prepared by mixing different proportions of natural carbonate soil and silica sand to form soil mixtures with carbonate contents range from 20% to 96%. The mixtures were then prepared using Method 1 that was used to prepare the silica sand samples.

4 EFFECT OF POROSITY ON SOIL THERMAL CONDUCTIVITY

The effect of porosity on soil thermal conductivity was investigated through conducting needle probe tests on highly saturated sand and kaolin clay samples that were reconstituted to a range of porosities using the preparation methods described in Section 3. The tests results are presented on Figure 1 together with the data reported in the literature.

As shown on Figure 1, soil thermal conductivity is dependent on soil porosity or particle packing, with soil thermal conductivity reducing hyperbolically toward a thermal conductivity value of about 0.6 W/mK (thermal conductivity of seawater) as soil porosity increases toward unity.

In addition, it can also be observed on Figure 1 that the rate of change in thermal conductivity due to the change in soil porosity is dependent on soil type with the thermal conductivity for silica sand being the most sensitive to the change in porosity while the thermal conductivity for carbonate soils being the least sensitive to the change in porosity. These observations suggest that the thermal conductivity for silica sand will be more susceptible to soil density change caused by cable burial processes than the thermal conductivity for carbonate soils.

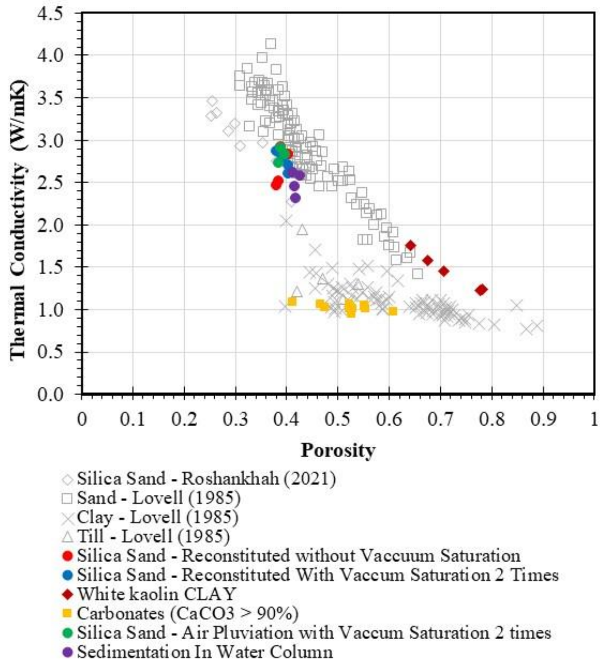

Figure 1. Porosity effects on thermal conductivity for near to nearly fully saturated soil (with degree of saturation greater than 70%)

Note that the clay samples tested by Lovell (1985) were marine origin and were described as pelagic ooze, calcareous pelagic clay, turbidite and nanofossil turbidite. This explains why the measured thermal conductivities for these clay samples are close to the carbonate soil thermal conductivity measured in this study.

5 EFFECT OF SAMPLE SATURATION ON MEASURED THERMAL CONDUCTIVITY

When conducting thermal conductivity test on in-situ intact soil samples or soil samples reconstituted to different densities in the laboratory, great attention needs to be paid to the saturation of soil samples to ensure soil thermal conductivity representative of the fully saturated seabed soil condition is measured.

Figure 2 shows the effect of sample saturation on the measured thermal conductivity for soil samples prepared using the preparation methods described in Section 3. As shown on Figure 2, sample saturation has significant impact on the measured thermal conductivity, especially for soil samples with degree of saturation lower than 70%. The measured thermal conductivity reduced from about 3 W/mK to about 1.5 W/mK when the degree of saturation decreases from about 95 % to 35 % even though the soil sample porosity only increases slightly from 0.38 to 0.44. This is because the thermal conductivity of air that partially filled the voids between soil grains for partially saturated soil is much lower than the thermal conductivity of saline water. This observation highlights the importance of ensuring soil sample saturation when preparing soil sample for thermal conductivity testing to avoid misleading results being measured.

5.1 Recommended Sample Reconstitution Procedure

The sand sample reconstitution procedure adopted in this study involved preparation without saturation (Method 2) and preparation with saturation aided by vacuuming (Methods 1 and 4) or through sedimentation in water column (Method 3).

As shown on Figure 2, Method 2 resulted in sand samples with a wide range of saturation levels and did not reliably produce highly saturated sand samples. On the other hand, Methods 1 and 4, which involve vacuum saturation procedure, are found to be able to produce highly saturated medium dense to dense sand samples more consistently, provided adequate vacuum saturation procedure is carried out. In these methods, vacuum saturation helps to extract trapped air from the reconstituted sand samples to produce highly saturated sand samples that are representative of the soil condition on the seabed. However, these methods were found to be less consistent and effective for preparing very loose to loose sand samples. This is because the vaccum saturation procedure disturbs the loose sand sample when extracting the trapped air and resulted in a non-uniform sand sample that lead to variable thermal conductivity measurements between soil samples.

To prepare very loose to loose saturated sand samples, Method 3 is found to be more effective and consistent than Methods 1 and 4. Therefore, the recommended methods for preparing reconstituted sand samples for thermal conductivity testing are as

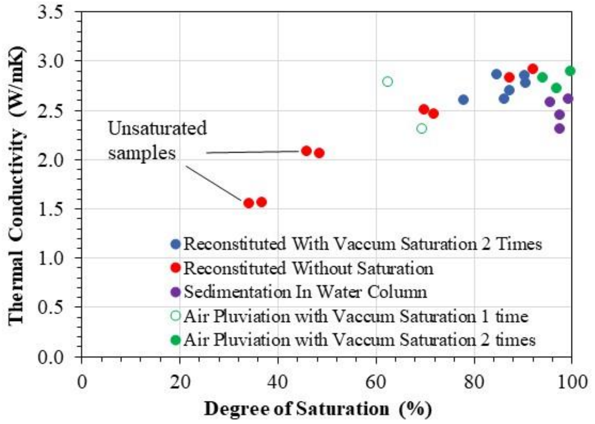

Figure 2. Effects of sample saturation on thermal conductivity

follow: Method 3 for preparing very loose to loose sand samples and Methods 1 or 4 (with adequate vacuum saturation effort) for preparing medium dense to very dense sand samples. However, since the soil sample used in Method 1 does not need to be fully dried before sample preparation, Method 1 is preferred for preparing natural soil samples for thermal conductivity testing.

If the preparation of clay or fine-grained soil samples with a range of moisture contents for thermal conductivity testing is required, it is recommended that the clay samples are prepared by consolidating vaccuum saturated slurry of high water content (say 1.5 to 2 times liquid limit) to the targeted moisture content to ensure fully saturated clay samples are prepared for thermal conductivitiy testing.

6 EFFECT OF CARBONATE CONTENT ON SOIL THERMAL CONDUCTIVITY

Carbonate sediments are primarily derived from the skeletal remains of once-living marine organisms, such as corals, foraminifera, and mollusks. These sediments are predominantly present in tropical to subtropical climates. Figure 3 shows the distribution of various known and potential areas around the world where these sediments are found. These areas are typically characterized by warm, shallow marine environments that facilitate the growth of organisms contributing to carbonate sediment formation. It is expected that some offshore wind farm projects could be located in these areas. Therefore, understanding of carbonate sediment thermal characteristics is important for designing robust and cost-effective cable solutions for offshore wind farms to be constructed in these areas.

Figure 4 shows the effect of carbonate content on soil thermal conductivity. The presented data were obtained from thermal conductivity tests conducted on soil mixtures of varying amounts of natural carbonate soil and silica sand. In addition, thermal conductivity data for silica sand (0% carbonate content) from Roshankhah (2000) and for pure shells (~100% carbonate content) from Lovell (1985) are also plotted on Figure 4 for comparison with the data obtained from this study.

The data presented on Figure 4 indicate that soil thermal conductivity generally decreases with increasing carbonate content. This observed trend could be attributed to (i) the lower thermal conductivity of carbonate soil grains as compared to that for silica soil grains; and (ii) the porous nature of carbonate soil grains, which have higher intra-particle porosity as compared to the silica sand grains. Therefore, the increase in carbonate soil grains in the soil mixture introduces more intra-particle porosity and lower soil grain thermal conductivity, both of which contribute to the overall reduction in thermal conductivity for the soil mixtures.

As shown on Figure 4, in carbonate sediments with high carbonate content (>90%), the measured thermal conductivities average around 1 W/m·K which is significanly lower than the thermal conductivity for clean silica sand. This implies that the presence of high carbonate content in marine sediments could lead to cable overheating if its low thermal conductivity is not properly considered in the cable design.

The data presented on Figure 4 highlights the importance of site-specific testing to determine soil thermal conductivity for cable design. It is also crucial to know the soil mineralogy when interpreting soil thermal conductivity data, as different mineral composition can significantly influence the thermal properties of a soil.

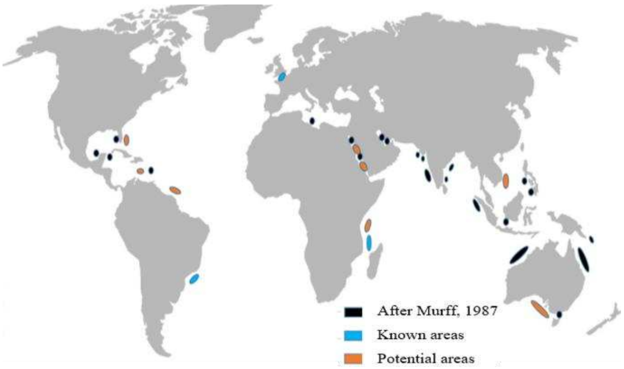

Figure 3. Map showing where carbonate sediments are important for offshore development (from Watson et. al., 2019)

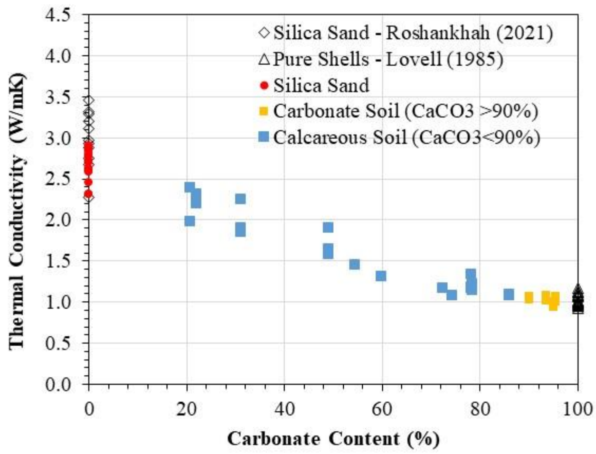

Figure 4 Effects of Carbonate Content on Thermal Conductivity

7 RECOMMENDED SEABED SOIL THERMAL PROPERTY CHARACTERISATION STRATEGY

As shown by the test results presented in this paper, the thermal conductivity of a saturated soil is dependent on its mineralogy content and packing density, both of which could vary along a cable route due to changes in environmental and geological conditions, especially when approaching a shore crossing. In addition, the impact of soil disturbance or porosity changes caused by cable burial processes on the thermal conductivity is also found to be dependent on soil type and mineralogy (see Figure 1).

In order to avoid having to design the cable for a wide range of soil characteristics that observed along the whole cable route, it is recommended that the seabed along the proposed cable route is first subzoned into seabed zones with similar soil mineralogy or characteristics. Through proper seabed zonation along the proposed cable route, a narrower range of soil properties (e.g. thermal conductivity) can be considered for the design of cable in each identified seabed zone. With the improved understanding of spatial distribution of various seabed zones along the proposed cable route, the cable engineers would be able to design and adopt the most cost-effective subsea cable solutions for an offshore wind farm project.

Proper seabed zonation for cable design can be achieved through the interpretation of the integrated geophysical and geotechnical dataset acquired along the cable route. This approach is illustrated in Figure 5 for a pipeline traversing a carbonate seabed. In this example, geophysical data (e.g. bathymetry and sub-bottom profiler data) was integrated with geotechnical data (i.e. piezocone test and borehole data). Based on the intepretation of the integrated dataset, the seabed along the pipeline route was subzoned into four separate zones. With this information, pipeline engineers were able to optimise the pipeline design using narrower range of geotechnical parameters in each identified seabed zone (e.g. by reducing concrete weight coating).

To ensure the success of this seabed zonation approach, it is important to consider all data sources available along the cable route and plan the geophysical and geotechnical site investigation campaigns carefully to ensure all the geophysical and geotechnical data required for cable design in each seabed zone are acquired (e.g. Abdel-Hakim et al., 2018; Bransby et al., 2020).

One of the greatest uncertainties in selecting representative soil thermal conductivity for the design of offshore buried cables is how much in-situ

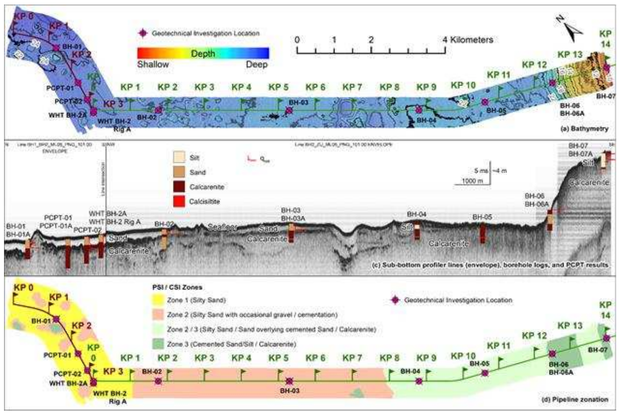

Figure 5 Zoning approach to reduce uncertainty at a given location considering bathymetry, geological features, sub-bottom profile, borehole logs and sample testing data (after Abdel-Hakim et al., 2018)

soil thermal conductivity will be changed by the soil disturbance induced by cable burial processes. Very often, the soil thermal conductivity for offshore cable design is measured in-situ using needle probes (in clay) or thermal cones (in sand) in the seabed or measured in the laboratory using needle probe tests conducted on intact soil samples. However, due to the cable burial processes, the soil around the cable will be highly disturbed. Following the cable burial processes, consolidation or redensification of the disturbed soils around the cable due to the soil self-weight consolidation, wave actions and cable heating could also lead to soil conditions that are very different from its original in-situ conditions. Therefore, the thermal conductivities measured with intact soil samples may not be representative of the actual soil thermal conductivity around the buried cable.

One possible way to assess the effect of cable burial and operation induced soil disturbance on the thermal conductivity of the soil around a buried cable is by conducting thermal conductivity tests on seabed soils reconstituted to a range of densities, water contents or porosities. The obtained test results can then be used to assess the sensitivity of the soil thermal conductivity to changes in soil density or porosity caused by the cable burial and operational processes.

As shown on Figure 1, the sensitivity of soil thermal conductivity to the change in soil porosity is dependent on soil type and soil mineralogy. For example, if a seabed soil is comprised mainly of clean silica sand grains, its thermal conductivity could be more sensitive to the porosity or density changes induced by cable burial and operational processes as compared to the thermal conductivity for a high water content (porosity) soft clay or a seabed soil that is rich in carbonate content.

Due to the natural geological and environmental processes, especially in shallow water areas, the soil grain composition and mineralogy of the seabed soils along the cable route could be highly heterogenous and vary between project sites. Therefore, it is important to conduct thermal conductivity tests on site specific seabed soil that recovered from each seabed zone identified along the cable route at different densities, water contents or porosities (e.g. from minimum to maximum density for sandy seabed soil) to characterise the sensitivity of the seabed soil thermal conductivity to the changes in soil porosity caused by the cable burial and operational processes. The data can also be used to quantify the uncertainties in soil thermal conductivity for the buried cable design.

8 CONCLUSIONS

This study underscores the necessity of accurate soil characterization for the effective design of buried cables for offshore wind farms. The test results demonstrate that soil thermal conductivity is dependent on soil packing density and mineralogy. Additionally, the collected test data provide insights into the impact of cable burial and operational processes on the thermal conductivity of each soil type. By understanding these relationships for each project site, cable engineers can design more reliable and efficient cable systems, ensuring a safe and continuous power supply to communities.

A recommended strategy for the characterization of soil thermal property for subsea cable design would be subzoning the seabed along the cable route into seabed zones with similar soil mineralogy or characteristics. Thermal conductiviy testing can then be conducted on soil samples taken from each identifed seabed zone that are prepared at different densities or porosities to characterise the sensitivity of the seabed soil thermal conductivity to the changes in soil porosity caused by the cable burial and operational processes. The acquired data can also be used to quantify the uncertainties in soil thermal conductivity for the design of the buried cable.

It is important to use site-specific soil samples recovered from along the proposed cable route for the tests because soil mineralogy and composition can affect soil thermal conductivity and its sensitivity to disturbance caused by cable burial and operational processes. In addition, measuring soil thermal conductivity in situ or using intact soil samples should be avoided because the measured soil thermal conductivity is not representative of that around a buried cable. When preparing the soil samples for thermal conductivity testing, full sample saturation need to be ensured and the sample preparation methods proposed in this paper can be used for this purpose.

AUTHOR CONTRIBUTION STATEMENT

First Author: Data curation, Formal Analysis, Writing- Original draft. **Other Author**.: Formal Analysis, Writing- Original draft.

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