Proceedings of the 9ICEG
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece

https://doi.org/10.53243/ICEG2023-184

Effect of the physical properties on the thermal conductivity of marine sediments

A. Deu[1], A. Vancells[2], M. Colomer[2], E. Arzani[2], A. Rodríguez[1] and M. Devincenzi[3]

[1] *Geociencias y Exploraciones Marítimas (GEM), Cerdanyola, Spain, email: amadeu@gemigeo.com, arodriguez@gemigeo.com*

[2] *IGEOLAB, Figueres, Spain, email: alexv@igeolab.com, marc.colomer@igeolab.com, enrique.arzani@igeolab.com*

[3] *Control y Prospecciones IGEOTEST, Figueres, Spain, email: marcelo@igeotest.com*

ABSTRACT

The thermal properties of soils and rocks are a key parameter for the proper design of thermally active ground structures such as geothermal energy foundations, borehole heat exchange systems, energy geo-storage and deep geological disposal of heat-emitting and long-lived radioactive waste deposits, etc. In case of offshore renewable energy systems, there has been an increase of site investigations due to the proliferation of offshore wind farms and electrical submarine trans-national interconnections grids around the world. In these cases, both the geotechnical parameters and thermal properties are relevant for the design of the geometry and the insulation type for each cable as well as for the cable burial assessment. Nevertheless, the evaluation of the thermal properties is not an easy task since they are very sensitive to other parameters such as the particle size distribution, moisture content, density, organic content and mineralogy of the sample, among others. In this paper, the results of a laboratory campaign on different soils collected in marine site investigations related to offshore wind farms and electrical interconnections around Europe and the Gulf of Guinea are presented. Samples were characterized by means of common geotechnical tests. The influence of the thermal balancing effect, moisture content and the dry density on the thermal conductivity/resistivity was evaluated by a series of tests at different soil conditions. The thermal conductivity measured in this study is an initial database for marine soils which might be used in geo-energy related projects with a null or limited number of reliable thermal measurements.

Keywords: geo-energy, laboratory testing, offshore environmental geotechnics, material characterization, thermal conductivity

1 INTRODUCTION

There are many fields where the thermal properties of the ground are a key design parameter, such as in geothermal energy foundations and borehole heat exchange systems, pipelines and in energy geo-storage and deep geological disposal of heat-emitting and long-lived radioactive waste, among many others. In case of submarine electrical connections, there has been an increase of site investigations related to the development of the intra and trans-national electrical connection grid as well as the proliferation of offshore renewable energy systems worldwide. The aim of these investigations is to determine the geotechnical and thermal behaviour of the ground for the proper design of the cable, the burial assessment analysis and the definition of the suitable cable route. 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. Since the cables are generally buried within the sediments, the heat produced by the cable during its functioning is transmitted to the ground. The way the sediments dissipate this increase of heat will affect on the quality of functioning of the cable throughout its live. 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). Furthermore, the design of the cable itself is also affected by the thermal properties of the ground. The following figure presents a typical 3-phase AC power cable cross-section. Highlighted in red are the components affected by the thermal conductivity of the soil/rock where the cable is layered or buried.

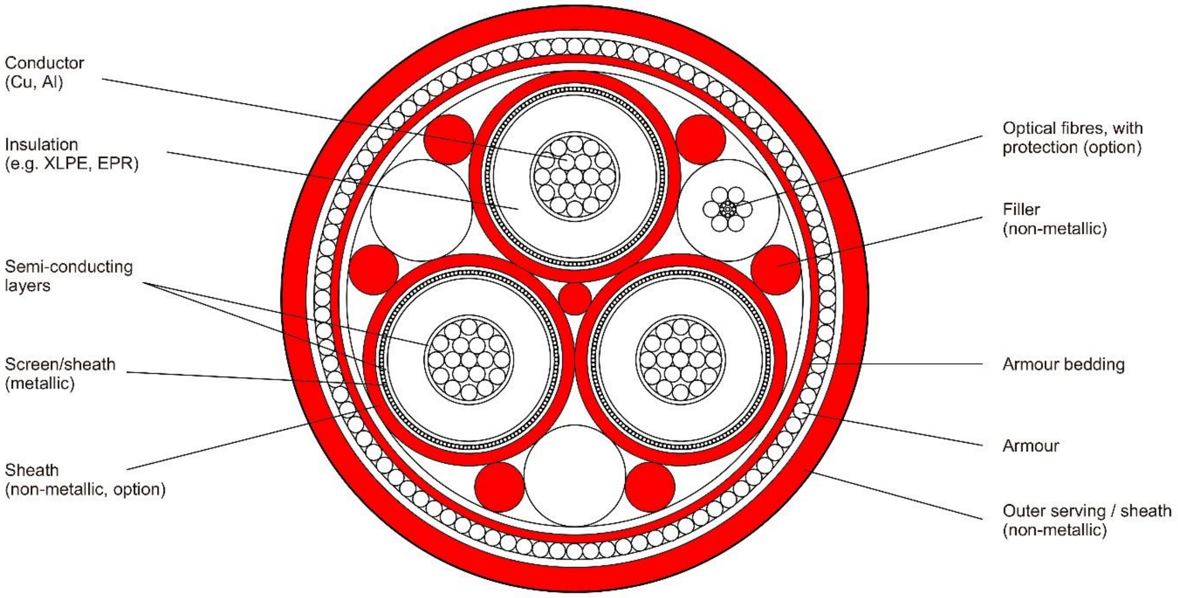

Figure 1. *Typical 3 phase AC power cable cross-section. Highlighted in red the components affected by the thermal conductivity. Modified from DNV (2016)*

The calculation or estimation of the thermal conductivity is not trivial since it is sensitive to some other geotechnical parameters such as the moisture content, the density, the mineralogical composition and the organic content, among others. Moreover, it is also sensitive to minor changes from the in-situ soil state, such as the soil disturbance during sampling or the increase of soil temperature before testing. Hence, any calculation should take into account all these parameters. Due to generally this information is not known for each particular soil involved in the project, it is of high-importance the use of reliable methodologies to measure the thermal conductivity in any particular condition and for each specific type of soil.

There are some empirical equations and theoretical approximations to calculate the thermal conductivity since the early 1940s. The most well-known proposals were published by Kersten (1949), Johansen (1975) and Faraouki (1981). More recent contributions such as numerical methods allow predicting not only the thermal properties but also the impact of additional heat through power cables or seasonal variations in sediment temperature during the year. Nevertheless, although these methods are used and have evident benefits, in case of marine investigations for submarine electrical interconnections or cables related to offshore wind farms (export cable, inter-array, HDD), the thermal conductivity of the ground is a significant design parameter of high importance which should be established through in-situ testing and/or laboratory analysis (GNV, 2016). In this sense, the measurement of the thermal properties of the ground can be done by different methodologies. Generally, the theoretical approach is to increase the temperature by a sudden heat flow from an external device and let the soil/rock dissipate the heat naturally until the equilibrium, allowing the measurement of the thermal conductivity/resistivity. The most common methodologies are: (i) in-situ measurements, (ii) hand-held devices and (iii) specific laboratory tests. The firsts are generally performed using a heat flow probe that penetrates into the first meters below the seafloor. It is assumed that the data obtained is the most reliable due to the minimum disturbance of the soil. However, the time consuming and hence the limited number of tests per day on board is a high economical constraint with respect to other available options. The second methodology is based on the insertion of a hand-held easy-manoeuvre device into the sample. This equipment allows performing a large number of measurements in a relative fast way either on board or in the laboratory. Nevertheless, it is mandatory to ensure the non-disturbance of the sample during sampling, handling and transporting operations as well as to stablish a quality control of measurements to ensure its reliability. Some results using hand-held devices were published by, Chen et al. (2011), Barry-Macaulay et al. (2013), Garitte et al. (2014) and Zhang et al. (2019), among others. Finally, special laboratory tests 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 behaviour of the ground.

This paper is aimed to study the influence of the moisture content, the dry density and the thermal balancing effect on the thermal conductivity of 15 marine samples collected from 5 different sites offshore Europe and in the Gulf of Guinea. Tests were conducted by a hand-held device in the onshore laboratory, allowing the analysis of the effect of changes in each parameter on the thermal conductivity.

2 SOIL CHARACTERIZATION

The samples used in this study were collected either by vibrocorer, pistoncorer or borehole in marine site investigations related to offshore wind farms or submarine interconnection cables. They were stored in a reefer in the same orientation in which were obtained, away from sources of vibration and near the central axis of the vessel where least movement occurs. Samples were selected from 5 different sites with the aim to cover the maximum soil types, ranging from very soft CLAY to medium SAND. A general description of the soil and the methodology used to recover it in each site is shown below:

- Site 1: Medium to fine SAND with rare to abundant shell fragments. Samples were recovered by a 6 m length vibrocorer at a site with water depths ranging between 8 and 81 m.
- Site 2: Silty fine to medium SAND with punctual to abundant shell and coral fragments and occasional fibrous organic matter. Samples were recovered by a 6 m length vibrocorer at a site with water depths ranging between 10 and 60 m.
- Site 3: Clayey SILT with occasional fine sand, organic matter and shell fragments. Samples were recovered by a rotary drilling rig from a jack-up platform in an area with water depths ranging between 8 and 17 m. Samples were collected as undisturbed samples.
- Site 4: Very soft CLAY. Samples were recovered by a 12 m length pistoncorer at a site with water depths between 1150 and 1250 m.
- Site 5: CLAY with widely laminated organic matter and rare organic matter pockets. Samples were collected by a 6 m length vibrocorer in an area with water depths between 92 and 95 m.

The samples used for this study were not opened or analysed previously and were transported and stored in the laboratory in the same conditions that were on board with the aim to avoid physical and temperature disturbance. Hence, they were only opened for the purpose of this study. Nevertheless, the soil was previously fully characterized both on board and in the onshore laboratory with geotechnical purposes. A complete set of tests were conducted on samples just above or below with the aim to determine their identification and classification, strength parameters, deformation characteristics and general chemical components. It is not the objective of this paper to provide the complete geotechnical description of each site but to provide general information to characterize the different soils analysed. In this sense, the natural moisture content and Atterberg limits with depth of each site are shown in Figure 2 (left) while the dry & bulk density and the particle density are shown in Figure 2 (right). Moreover, the particle size distribution by both sieving and hydrometer is shown in Figure 3.

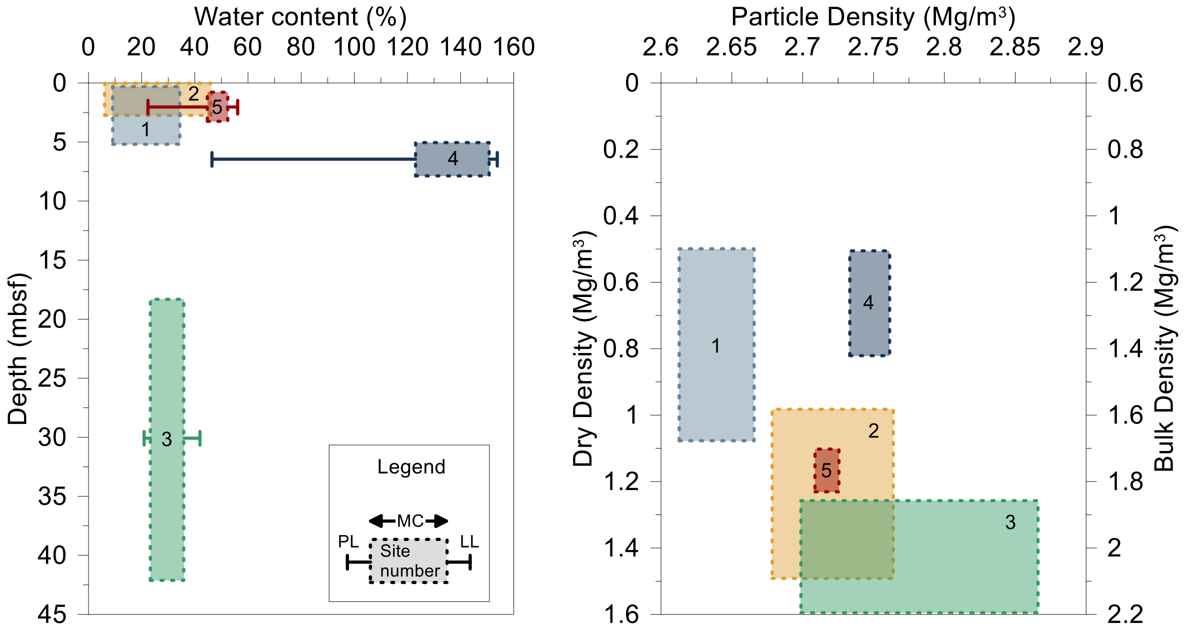

Figure 2. *Moisture content and Atterberg limits (left). Dry & bulk density, and particle density (right)*

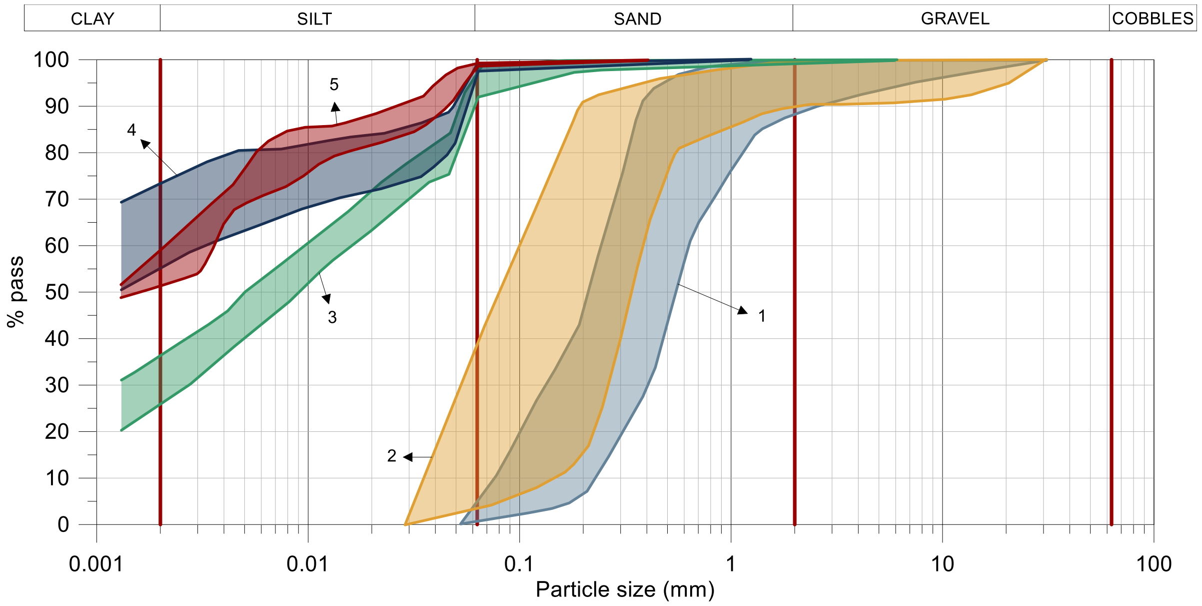

Figure 3. *Particle size distribution by sieving and hydrometer*

The granular or cohesive nature of the 5 different soils used for this study is highlighted in Figure 3. The sand content in Site 1 and 2 is between 87 and 97% and between 60 and 95%, respectively, while is generally less than 5% in samples from sites 3, 4 and 5. On the other hand, samples from sites 3, 4 and 5 are mainly cohesive. The clay component is between 26 and 35% in Site 3, between 55 and 73% in Site 4 and between 51 and 59% in Site 5.

3 RESULTS

The measurements were done with a hand-held thermal needle probe in the onshore laboratory. It is an easy-manoeuvre device that is inserted into the soil sample for testing. The Thermal Resistivity Test (TRT) is based on the infinite line heat source theory and it allows calculating the thermal conductivity by monitoring the dissipation of heat from the needle probe (Barry-Macaulay et al., 2013). The dimension of the sensor used meets the specifications established in the IEEE 442 and ASTM 5334 standards.

This equipment allows performing a large number of measurements in a relative fast way. Nevertheless, in order to provide reliable results, there are two important drawbacks which imply that a strong quality control and a strict methodology should be considered: (i) the soil might be disturbed during sampling, handling, storing and transport and (ii) the dimensions of the sensor inducer 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. Furthermore, a minimum of three measurements were conducted in every test. In all cases, before each set of measurements a verification of the equipment was done using backelite as a reference sample.

The thermal conductivity is influenced by many factors such as the composition of the soil, the water and its migration and the direction of the heat flow. Generally, in marine sediments it 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 on the mineralogical composition, especially the quartz content since it is a high-thermal conductivity mineral compared with most of other soil minerals. This effect was not analysed in this paper and will be included in further stages of this investigation.

3.1 Balancing effect

It is generally recommended in devices' manuals and in the common practice to allow the sensor to become thermally stable with the sample before starting the test. This can be done by waiting for 5 to 10 minutes with the probe inserted into the soil. Between measurements without extracting the probe, a

5 to 10 minutes wait is also advised to allow the sample to return to thermal equilibrium conditions. Nevertheless, in marine site investigations there are several specific conditions that should be taken into account when performing a TRT. The temperature on deck is high, especially during the summer season. Hence, in order to perform the test when the soil temperature is similar to the in-situ one, it is advisable to carry out the test as soon as possible once the sample is recovered on deck. Otherwise, the temperature of the soil raises rapidly and the test might not be representative of the actual soil conditions. On the other hand, in order to perform the TRT in an undisturbed soil, this test is done before any geotechnical soil description, which requires to touch and stir the soil, or any other in-situ tests such as pocket penetrometer, torvane, etc. Finally, depending on the distance between geotechnical locations and on the water depth, if the productivity is high, it might be that there is not much adequate time between tests. In this sense, it is mandatory to finish all tests and store the sample before recovering the next samples on deck. For all these reasons, it is generally not possible to follow the recommendations with regard to thermally stabilization between measurements and they are done as soon as the sample is recovered. If more than one measurement is required, which is the common practice, then the 5 to 10 minutes wait is neither considered and measurements are done continuously either extracting or not the probe from the soil. If three measurements are required, it would take around 45 minutes if the sensor has to be come thermally stable while it will take around 16 minutes if measurements are done continuously.

With the aim to analyse the thermal balancing effect, two different types of measurements were done: (i) continuous measurements without extracting the probe, simulating in the laboratory what is the common practice on board. As soon as a test was finished, it was started again without thermal equilibrium, (ii) measurements letting the sensor to become thermally stable by waiting 9 minutes between tests, simulating what should be done according to recommendations. The two types of measurements were done at the same time, using two different hand-held devices of the same manufacturer. Both devices were calibrated and the sensor performance was verified before it’s use by measuring in a well-known thermal conductivity material. The results of this analysis are shown in Figure 4. Only one sample of each site is shown in the Figure as an example.

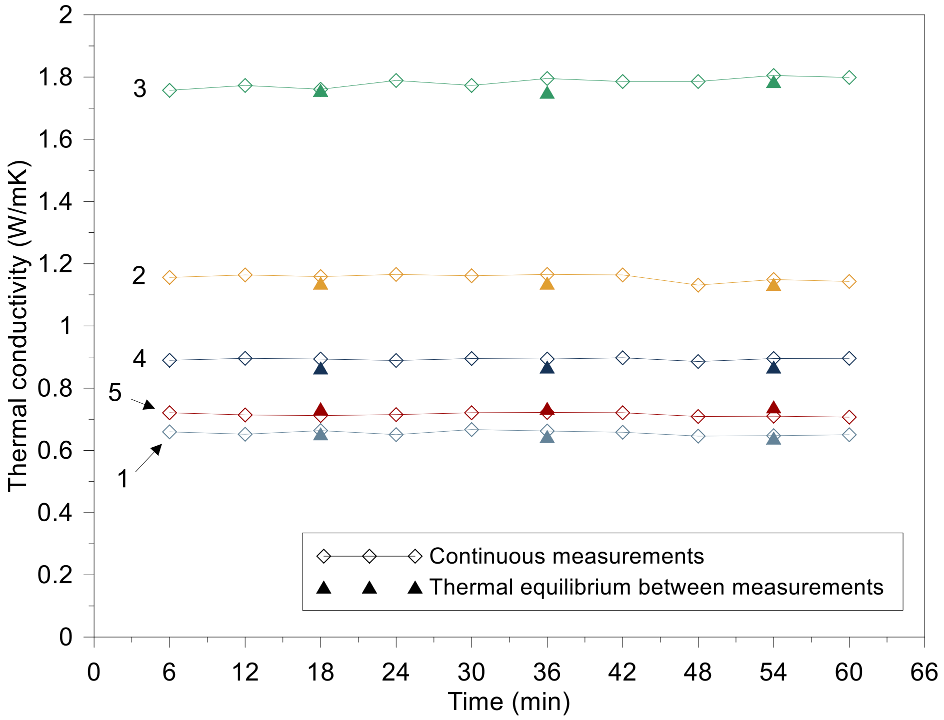

Figure 4. *Balancing effect analysis on one sample from each site*

Results in all samples were similar. The maximum difference between measurements was 4.2% although it generally ranged between 1.15 and 2.65%. It is assumed that these differences are acceptable and are in line with the typical errors of thermal tests in heterogeneous materials.

3.2 Effect of the moisture content

The effect of the moisture content on the thermal conductivity was determined in each sample. There were differences whether the soil was granular or cohesive. In granular soils, the samples were firstly introduced in a proctor mould before the first set of measurements. Then they were left to dry at 20ºC for 2 days and a new set of tests were performed. This procedure was repeated to let the sample get dry naturally until it was finally oven dried at 105ºC for 2 days in order to get the final set of measurements. In all cases, the final moisture content value was very close to 0%. In cohesive soils, the sample was kept with the natural structure but the procedure to measure the thermal conductivity at different moisture content values was the same. All measurements were performed by keeping the needle probe inserted into the soil for 10 to 15 minutes before starting the test to avoid temperature drifts. In soils from Site 4 and 5, the final moisture content was between 10 and 11%. The relationship between the moisture content and the thermal conductivity in each site is illustrated in Figure 5.

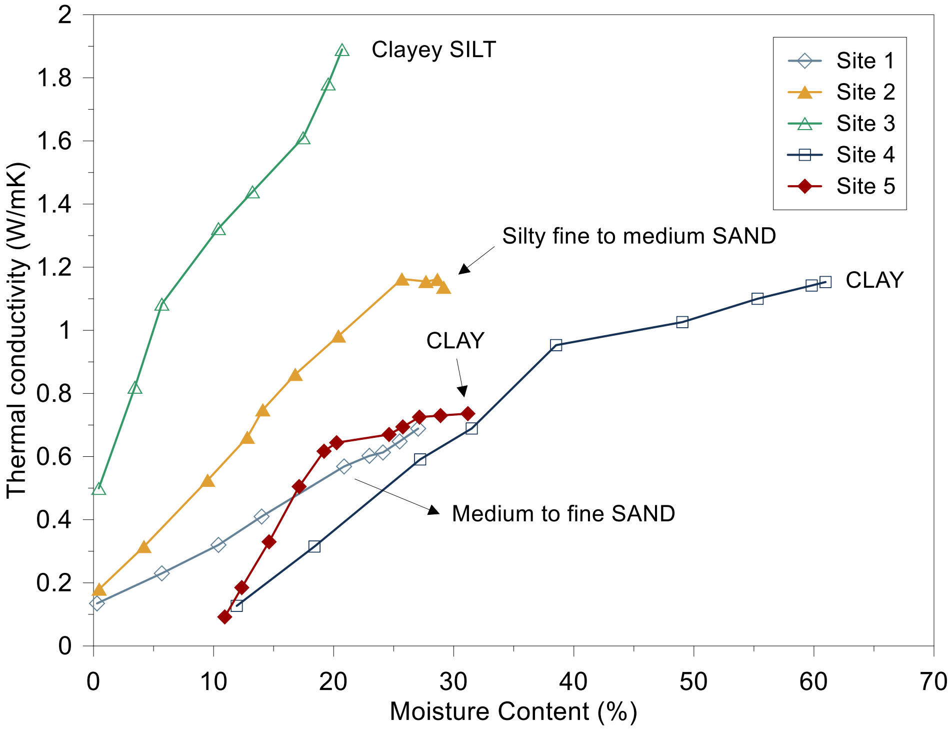

Figure 5. *Relationship between the moisture content and the thermal conductivity in each site*

There is a general trend for both granular and cohesive soils to increase the thermal conductivity with the increase of moisture content. Granular soils contain less particle contact points and hence only a small addition of water is needed to saturate the inter-particle contact points. This significantly increases the thermal conductivity since the thermal conductivity of water is 25 times larger than air. (Barry-Macaulay et al. 2013). Therefore, it is expected a rapidly increase of thermal conductivity at low saturations and then only slightly thereafter. This behaviour is well observed in site 2. The inflexion point in which the nonlinear rate of increase of the thermal conductivity is reduced at certain moisture content was observed in several previous experimental investigations and come out as a result of the application of some models. Although the reason for this inflexion point was not properly clarified, Tokoro et al. (2016) suggested that it corresponds to the inflexion point of electrical resistivity in which there is water continuity inside the porosity. In this sense, Kamoshida et al. (2013) suggested that water at lower moisture contents does not contribute to thermal conduction. This is thought to be because most pore water does not continue at moisture contents lower than the inflexion point. Alternatively, the increase of thermal conductivity in cohesive soils is relatively at a uniform rate with increasing moisture content. It is well observed in site 3 and 4. In any case, the rate of increase is variable in each site and depends not only on the particle size distribution but also on some other parameters that were not taken into account in this study, such as the organic content, the mineralogy, the soil anisotropy, etc.

3.3 Effect of the dry density

The effect of the dry density on the thermal conductivity was only analysed on samples from sites 1, 2 and 3. Firstly, samples were previously oven dried at 105ºC. Then, a CBR mould was used with the aim to get four different qualitative dry densities:

- Density 1: introducing carefully the sample into the mould without any compaction.
- Density 2: introducing carefully the sample into the mould with very low compaction by 5 strokes.
- Density 3: introducing the sample into the mould in 3 different layers and applying 15 strokes per layer.
- Density 4: introducing the sample into the mould in 5 different layers and applying 60 strokes per layer.

When the sample was ready, the thermal needle probe was inserted into the compacted soil sample and the thermal conductivity was measured. Readings were carried out by keeping the needle probe inserted for 10 to 15 minutes before starting the test in order to avoid temperature drifts.

The effect of dry density on the thermal conductivity of samples from site 1, 2 and 3 is illustrated in Figure 6 together with the results published by Barry-Macaulay et al. (2013). In that paper, different soils sampled from drill spoil from the Melbourne (Australia) region were tested at a range of moisture content and densities. Two soils (BGS and BGCS) were granular similar to samples from site 1 and 2 while three soils (BC, RS, CIS) were cohesive soils similar to samples from site 3. Thermal conductivity values for sites 1, 2 and 3 in the Figure are the average of the three samples analysed.

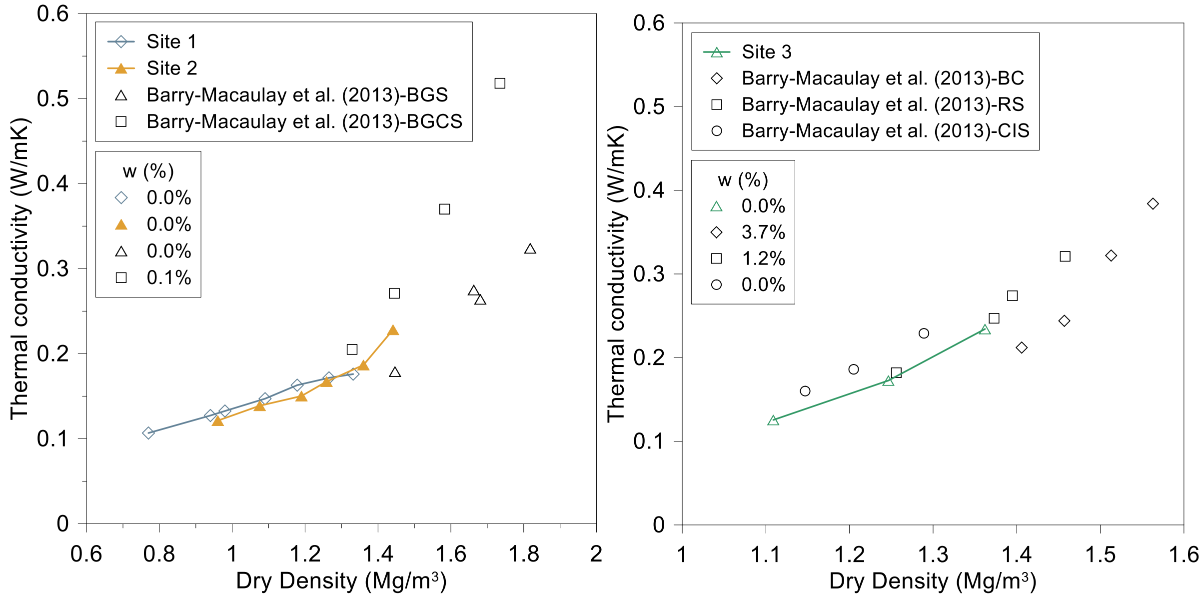

Figure 6. *Relationship between the dry density and the thermal conductivity in sites 1, 2 and 3 compared with the results published by Barry-Macaulay et al. (2013).*

The results of the current investigation are in line with those already published. The thermal conductivity increases with the increase of dry density. The strong correlation between air volume and thermal conductivity was attributed by Ochsner et al. (2001) to the low thermal conductivity of air compared to the thermal conductivity of water or soil solid minerals. The thermal conductivity of the air is 25 times lower than water and approximately 100 times lower than most soil minerals. As pointed out by Marry-Macaulay et al. (2013), any change of air volume in the sample will also affect the interfacial conduction characteristics of the soil. A reduction in the volume of air due to an increase in volume of solids will cause greater packing of the soil particles, and hence, lead to better interfacial conduction characteristics. Hence, the less distance between particles the less air volume and the more thermal conductivity through the soil.

3.4 Future perspectives

A multiparameter approach should be considered when analysing the thermal behaviour of marine sediments. Not only the soil characteristics of the soil/rock have to be taken into account but also the specific equipment and typical performance of an offshore survey. This paper is a first step on a more complete analysis on this topic by evaluating the effect of some parameters on the thermal conductivity. Future investigations will include the mineralogical perspective as well as the in-depth analysis of the minor changes on thermal behaviour during hand held measurements.

4 CONCLUSIONS

The thermal conductivity of marine sediments is a critical parameter in the design of submarine cables, the burial assessment analysis and the definition of the suitable cable route. In this paper, a laboratory analysis of the thermal conductivity of 5 different marine soils collected in projects related to offshore wind farms and electrical interconnections around Europe and the Gulf of Guinea are presented. The balancing effect as well as the effect of moisture content and dry density on the thermal conductivity was analysed by means of Thermal Resistivity Tests (TRT) by a handheld thermal needle probe.

No differences were observed when letting the sensor to become thermally stable with the sample before starting the test or measuring without any thermal stabilization. The thermal conductivity of all soils was observed to increase with an increase in moisture content and dry density. Nevertheless, other parameters affect the thermal conductivity such as the organic content and the mineralogical composition, that were not taken into account in this study and will be included in further analysis.

The thermal conductivity values presented in this study are expected to be an initial database for marine soils which might be used in geo-energy related projects with a null or limited number of reliable thermal measurements.

REFERENCES

Barry-Macaulay D., Bouazza A., Singh R.M., Wang B. and Ranjith P.G. (2013). Thermal conductivity of soils and rocks from the Melbourne (Australia) region. Engineering Geology 164, 131-138.

Chen G.J., Sillen X., Verstricht J. and Li X. (2011). ATLAS III in situ heating tests in Boom Clay: field data, observation and interpretation, Computers and Geotechnics 38(5), 683-696.

Deu, A. & Devincenzi, M. (2021). Thermal properties of marine sediments. International Conference on Soil Mechanics and Geotechnical Engineering, (pp. 3751-3756). Sydney, Australia.

DNV-GL (2016). Recommended practice. Subsea power cables in shallow water.

Farouki O.T. (1981). Thermal properties of soils. US Army Cold Regions Research and Engineering Laboratory CRREL, Monograph 81-1.

Garitte B., Gens A., Vaunat J. and Armand G. (2014). Thermal conductivity of argillaceous rocks. Determination methodology using in situ heating tests. Rock Mechanics and Rock Engineering 47(1), 111-129.

Goto, S., Yamano, M., Morita, S., Kanamatsu, T., Hachikubo, A., Kataoka, S., Tanahashi, M. & Matsumoto, R. (2017). Physical and termal properties of mud-dominant sediment from the Joetsu Basin in the eastern margin of the Japan Sea. Marine Geophysical Research 28, 393-407.

Johansen O. (1975). Thermal Conductivity of Soils. Ph.D. Thesis. Trondheim University. Norway.

Kamoshida, T., Hamamoto, S., Kawamoto, K., Sasaki, T &Komatsu, T. (2013). Thermal properties of sands at variably-saturated condition: effect of particle size and shape, and quarts content. Japan. Soc. Soil Phys. 124, 11-16

Kersten M.S. (1949). Thermal properties of soils. University of Minnesota Institute of Technology, Engineering Experiment Station. Bulletin no. 28.

Müller, C., Usbeck, R. & Miesner, F. (2016). Temperatures in shallow marine sediments: Influence of thermal properties, seasonal forcing, and man-made heat sources. Applied Thermal Engineering. 108, 20-29.

Ochsner, T.E., Horton, R. & Renen, T. (2001). A new perspective on soil thermal properties. Soil Science Society of America Journal 65 (6), 1641-1647.

Tokoro, T., Ishikawa, T., Shirai, S & Nakamura, T. (2016). Estimation methods for thermal conductivity of sandy soil with electrical characteristics. Soils and Foundations 56 (5), 927-936.

Zhang T., Liu S., Zhang N., Duan L. and Cai G. (2019). Research of Soil Thermal Conduction Properties and Its Thermal Conductivity Model. Journal of Building Materials 22(1), 72-80.

The paper was published in the proceedings of the 9th International Congress on Environmental Geotechnics (9ICEG), Volume 3, and was edited by Tugce Baser, Arvin Farid, Xunchang Fei and Dimitrios Zekkos. The conference was held from June 25th to June 28th 2023 in Chania, Crete, Greece.