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Multi-sensor core logging of marine sediments for continuous thermal conductivity profiles

Scott Adam Smith[1#], *Maarten* Vanneste[1], *Thea Sveva* Faleide[1] and *Antoine* Bertrand[2]

[1] *Norwegian Geotechnical Institute, Sandakerveien 140, Oslo, Norway*
[2] *Equinor ASA, Martin Linges vei 33, 1364 Fornebu*
[#] *Corresponding author: scott.adam.smith@ngi.no*

ABSTRACT

Thermal conductivity of shallow (<5m) soil is a critical property for the design of subsea cables and pipelines. In complex geological settings, thermal conductivity can vary greatly both with depth and along the cable or pipeline route, and the standard laboratory approach of discrete needle probe testing can fail to characterise thin layers or gradual changes. In this paper, continuous depth profiles of thermal conductivity are predicted from Multi-Sensor Core Logging (MSCL), a non-destructive, high-resolution (cm-scale) method to measure soil properties on recovered samples. A porosity-thermal conductivity relationship is derived and is well approximated with the weighted geometric mean equation, with the coefficient of determination r^2 = 0.77 and root-mean squared error RMSE = 0.3 W/mK. Furthermore, bulk density and natural gamma data from the MSCL is used to automatically classify soil samples into three categories: clay, sand, and organic soils. Soil-specific relationships between porosity and thermal conductivity improve the prediction of thermal conductivity with r^2 = 0.84 and RMSE = 0.25 W/mK. This study highlights the ability to predict thermal conductivity and soil type from MSCL data, and the implication that including MSCL in a laboratory program can reduce the total volume of destructive testing required.

Keywords: Multi-sensor core logging (MSCL); thermal conductivity; porosity.

1. Introduction

Thermal conductivity of shallow (<5m) sediments is a critical parameter for the design of subsea cables and pipelines, with low thermally conductive soils such as peat and calcareous sediments posing the highest risk to overheating cables. It is therefore important to map the depth and spatial dependence and variability of thermal conductivity in the shallow subsurface, with special attention to low thermal conductivity layers.

One standard approach to estimate thermal conductivity along cable routes is to take discrete needle probe measurements on recovered sediment samples and present thermal conductivity with depth. The limitations of this approach are a) cable routes over long distances may require a large volume of laboratory testing, b) discrete measurements, such as every 1m, can fail to capture thin layers or gradual changes in sediment properties and c) thermal conductivity measurements using needle probes are sensitive to sample preparation methods which can alter saturation ratio (Tucker et al. 2023).

Multi-Sensor Core Logging (MSCL) is a non-destructive method to collect continuous measurements (typically every 1 – 2 cm) of soil properties, popular for several decades in marine research and mineral exploration (e.g. Weber et al. 1997; Vatandoost et al. 2008; Vardy et al. 2012). Samples are run through the MSCL within the core liner (or as unlined rock cores), with no specific need for sample preparation. Sensors include, but are not limited to, attenuated gamma density (analogous to bulk density), natural gamma, *P*-wave velocity and attenuation, magnetic susceptibility, and electrical resistivity.

Porosity can be calculated from the MSCL through the bulk density measurements and estimates of mineral grain density, fluid density and saturation ratio. Thermal conductivity is dependent on mineralogy and porosity, and this property can be well approximated with the weighted geometric mean equation (Woodside & Mesmer. 1961).

In this study we use data from a site investigation in the Southern North Sea to investigate whether profiles of thermal conductivity can be reliably estimated from density measurements with the MSCL, through the common relation of porosity. Furthermore, MSCL data is used to automatically classify samples by soil type. Bulk density measurements are used to classify soils as organic or inorganic. Natural gamma, related to silt and clay content (e.g. Ayres and Theilen. 2001) is used to classify inorganic samples as coarse-grained or fine-grained. This information allows us to investigate whether or not a soil type-specific model performs better than one generic model for all soil types.

2. Methodology

As part of a site investigation for an offshore wind farm in the Southern North Sea, vibrocore sampling and CPTu tests were conducted at 45 locations. Soil profiles include sand, low strength clay, over-consolidated gravelly clay, peat and closely spaced laminae of clay and organic material, labelled in figures as organic clay.

MSCL was conducted on the top ~3m of vibrocore samples, for a total length of 140m, using the system by

Geotek Ltd. Attenuated gamma density, natural gamma, *P*-wave velocity and attenuation, magnetic susceptibility and electrical resistivity were recorded at 1cm intervals. Attenuated gamma measurements were related to bulk density using an empirical calibration against a stepped aluminium piece of known thickness and density, following the procedure outlined by Weber et al. (1997). Samples were logged in liners as received from offshore. Measurements from the MSCL including *P*-wave attenuation and electrical resistivity were used to assess sample disturbance such as cracks, voids, or partial drainage of sand samples.

Following MSCL, a targeted laboratory program was conducted including geotechnical description of samples, index and thermal conductivity tests. The grain size distribution was determined by the falling drop method for the silt and clay particles (Moum, 1965) and by wet/dry sieving for coarser particles (ISO 17892-4, 2016). Soil type was classified manually based on CPTu data, samples descriptions and grain size distribution results.

Thermal conductivity was measured at 51 selected depths using a TP02 Non-Steady-State probe in accordance with the ASTM D5334 (2022) standard. Thermal conductivity tests were performed with the sample in liner as received, i.e. without reconstitution or re-saturation, at room temperature. Three repeat measurements were performed per test and the mean and standard deviation were calculated. The uncertainty in thermal conductivity tests is summarized by the median standard deviation of all sets of three measurements.

Porosity, Φ, was calculated from attenuated gamma density measurements, ρ_b, with the following equation:

$$\Phi = \frac{\rho_m - \rho_b}{\rho_m - \rho_f} \qquad (1)$$

assuming a mineral grain density, ρ_m, of 2.65 g/cm^3, a fluid phase density, ρ_f, of 1.026 g/cm^3, and a saturation ratio of 100%. The measurement uncertainty of attenuated gamma density, ρ_b, and hence porosity, was estimated by calculating the standard deviation between consecutive sets of three measurements, then taking the median value of all standard deviations.

The thermal conductivity of fully-saturated marine sediments can be estimated from porosity using the weighted geometric mean equation:

$$k_b = k_s^{(1-\Phi)} k_f^{\Phi} \qquad (2)$$

where k_b is the thermal conductivity of the bulk sediment, k_s is the average thermal conductivity of the solid particles and k_f is the thermal conductivity of the fluid (taken to be 0.57 W/mK for seawater).

The average thermal conductivity of the solid particles k_s was estimated as the value that minimised the root-mean squared error (RMSE) between measurements and predicted values, once for the entire dataset and separately for each soil type. A search algorithm was used to find low and high estimates of k_s as values that produce lines at which 15% and 85% of the measured values lie below.

MSCL data was used to automatically classify samples into categories of sand, clay, and organic material. The broad category of organic material includes peat and clay with pockets or laminae of organic matter. First, samples with a bulk density of less than 1.9 g/cm^3 (Φ > 0.46) were classified as organic material. Then, natural gamma measurements were used to automatically distinguish between fine- and coarse-grained samples.

Finally, continuous profiles of thermal conductivity k_b were calculated from the MSCL measurements of attenuated gamma density through Eqs. (1) and (2). The results are interpreted and compared with adjacent CPTu profiles.

3. Results

Measured thermal conductivity varied between 0.57 and 2.73 W/mK, increasing with decreasing porosity in accordance with the weighted geometric mean equation (Fig. 1). The median standard deviation of thermal conductivity tests was 0.04 W/mK, or ~2% expressed as a percentage of the mean result. The measurement uncertainty of bulk density with the MSCL was estimated to be 0.014 g/cm^3, resulting in an associated measurement uncertainty in porosity of 0.009.

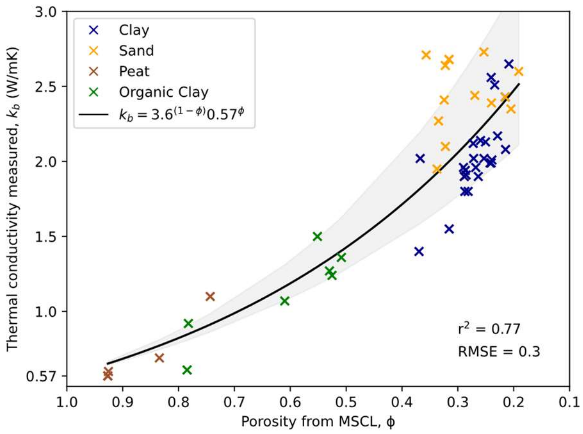

Figure 1. Measured thermal conductivity against porosity measured with the MSCL. Black line of best fit is Eq. (2), with k_s equal to 3.6 W/mK. Grey zone is area between low and high estimates calculated with k_s equal to 2.9 and 4.8, respectively.

Using Eq. 2, the value of k_s that best fit the data, i.e. that minimised the RMSE between measurements and predictions, is 3.6 W/mK (Fig. 2a). Comparing predicted values against measurements, the r^2 value is 0.77 and RMSE is 0.3 W/mK.

Twenty-one measurements of ρ_m gave a mean value of 2.64 g/cm^3, a median of 2.66 g/cm^3 and a standard deviation of 0.07 g/cm^3. The lowest values of 2.42 and 2.46 g/cm^3 were measured for organic samples.

Natural gamma measurements varied between 0 and 46 counts per second (Fig. 3). Higher natural gamma measurements correspond well with a higher fine-grained fraction, i.e. the percentage of silt and clay sized particles (grain diameter < 0.063mm). Samples with natural gamma > 20 were automatically classified as fine-grained, and samples with natural gamma < 20 were classified as coarse-grained.

The values of k_s that best fit clay, sand and organic material separately are 3.3, 4.2 and 3.4 W/mK. Applying these soil-specific values to predict thermal conductivity from porosity by Eqs. (1) and (2), the RMSE of all predictions is 0.25 W/mK (Fig. 2b).

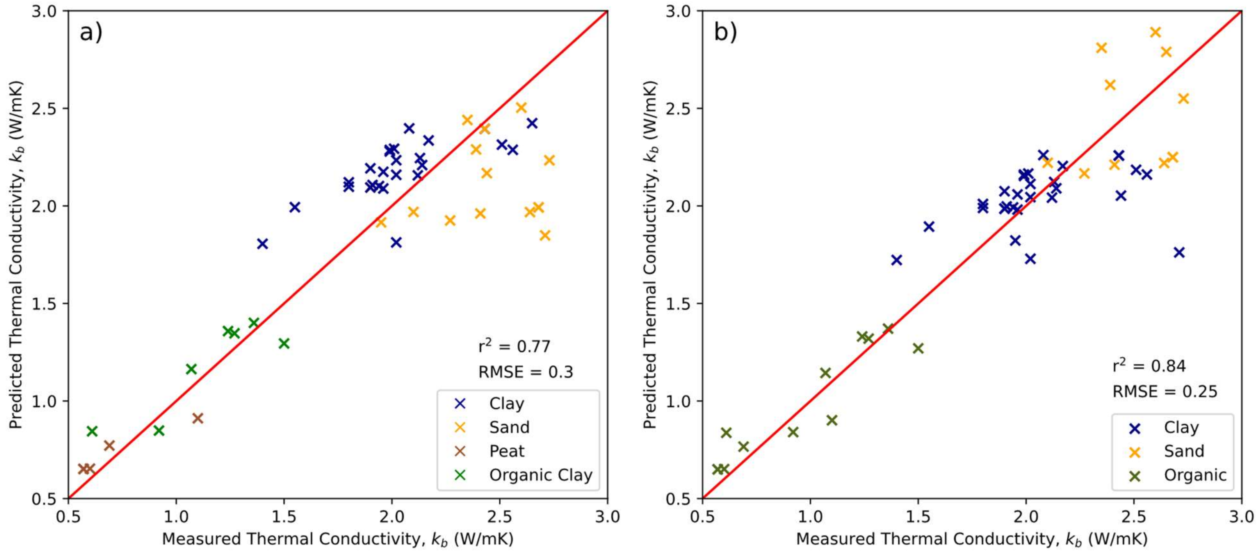

Figure 2. Comparison of a) thermal conductivity predicted using Eq. 1 with k_s equal to 3.6 (soil type from manual classification) and b) thermal conductivity predicted using Eq. 1 with k_s equal to 3.3 for clay, 4.2 for sand and 3.4 for organic samples (soil type from automatic classification), against thermal conductivity measured with the needle probe.

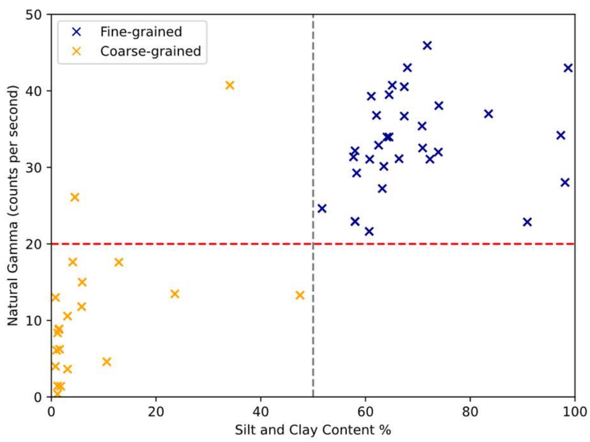

Figure 3. Natural gamma measurements were used to classify non-organic samples into fine-grained (clay) and coarse-grained (sand), with the threshold at 20 counts per second.

Soil type, CPTu, selected MSCL and thermal conductivity profiles for two locations are presented to demonstrate the suggested approach against a range of soil types and thermal conductivity values (Fig. 4).

4. Discussion

4.1. Interpretation

At location #1, 0.3m of sand overlays a layer of peat between 0.3 and 1m below seafloor (see Fig. 4, top). Thermal conductivity is highest at ~2 W/mK in the sand and reduces to a minimum of 0.57 W/mK in the organic layer (i.e., similar to the thermal conductivity of seawater). The transition from the sand into peat, from 0.3m to 0.6m, is captured by the MSCL as decreasing density and natural gamma and is reflected in the CPTu data by increasing friction ratio. From 0.6 to 1m, there is a homogenous low density (1.1 g/cm^3), low thermal conductivity peat layer. The MSCL data show a distinct boundary at 1m, marking a sharp transition into alternating laminae of clay and organic material, which is not immediately evident from the CPTu data alone. The frequency and or thickness of organic laminae increases with depth, as indicated by the trends of decreasing density, natural gamma, and thermal conductivity. At the same time, corrected cone resistance, q_t, increases slightly, friction ratio decreases and there is no clear trend in pore pressure ratio. All three thermal conductivity measurements correspond well with estimates from MSCL.

Similar to location #1, the top 0.35m of location #2 is sand of relatively high (>2 W/mK) thermal conductivity (see Fig. 4, bottom). From 0.35 to 1m is a homogenous peat layer as marked by its low density (1.1 g/cm^3) and high friction ratio. From 1m, a transition into clay is seen in the MSCL data as increasing density and natural gamma, though this transition is less clear in the CPTu data. A medium bed of sand from 1.7 to 2.05m is identifiable in the MSCL data as an increase in density and decrease in natural gamma, and in the CPTu data by an increase in q_t and decrease in friction ratio. Both thermal conductivity measurements at this location agree with the trend of the predicted thermal conductivity profile.

The porosity-thermal conductivity relationship derived in this study fits well with published trends (e.g. Dix et al. 2017; Vardon & Peuchen. 2021). The general model (k_s = 3.6) seems to best fit the organic material, while systematically overpredicting thermal conductivity of clay and underpredicting thermal conductivity of sand (Fig. 2a). Making soil type-specific predictions of thermal conductivity increased the model performance, increasing the r^2 value from 0.77 to 0.85 and reducing the RMSE from 0.3 to 0.25 (Fig. 2b). The greatest improvement was for the sand samples, since the k_s value that best fit the sand data, 4.2, is furthest from the average of 3.6.

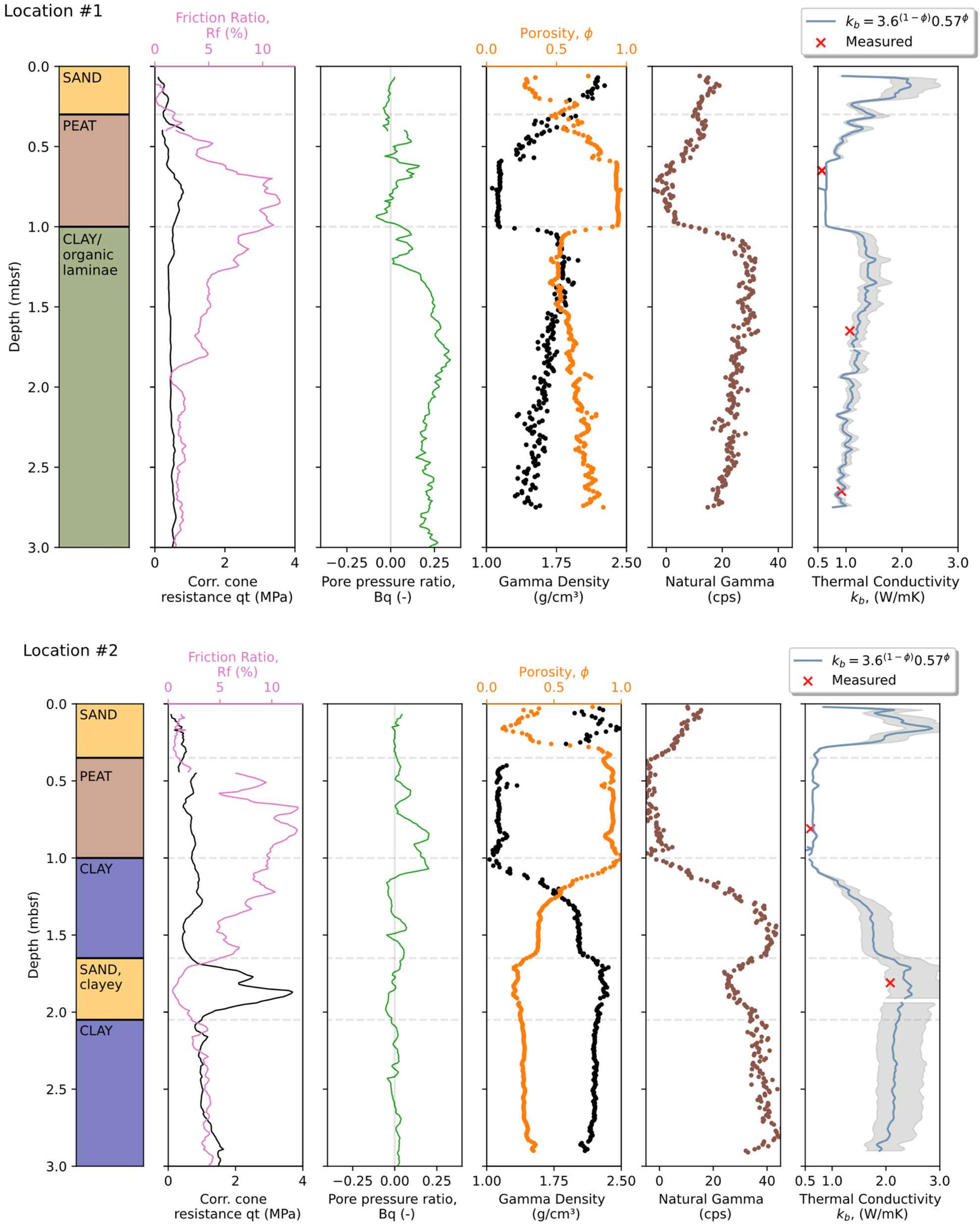

Figure 4. Soil type, CPTu, selected MSCL data and thermal conductivity profiles from locations #1 (top) and #2 (bottom). The grey zone indicates low and high estimates at 15 and 85% confidence, following Fig. 1. The distance between adjacent vibrocores and CPTu profiles is approximately 0.8m.

Natural gamma measurements were used effectively to classify material as fine-grained or coarse-grained. 51 out of 53 measurements were correctly classified, with two coarse-grained samples with measurements over 20 counts per second misclassified (See Fig. 3, top left quadrant). One of the misclassifications (27 cps) is a sample described as very gravelly, and the gravel is thought to contribute to the natural radioactivity. The second misclassification (40 cps) has a fine-grained fraction of 34% and is described as sandy CLAY. Though the automatic classification performed well as part of a preliminary assessment, there is potential to further improve automatic recognition of soil type, perhaps including complementary measurements from the other sensors of the MSCL.

4.2. Relationship to literature

Vardon and Peuchen (2021) suggested that the weighted geometric mean equation, Eq. (2), can be modified to include fraction of sand, f_{sand}, as:

$$k_b = 2.9^{(1-\Phi)(1-f_{sand})} 8.4^{(1-\Phi) f_{sand}} 0.57^{\Phi} \qquad (3)$$

where 2.9 W/mK is the average thermal conductivity for silt and clay minerals and 8.4 W/mK is the thermal conductivity of quartz sand.

In our dataset, Eq. (2) was best fit for sand samples with $k_s = 4.2$, which is approximately equal to Eq. (3) and $f_{sand} =$ 0.3, suggesting that f_{sand} for sand samples is close to 0.3 (Fig. 5). However, f_{sand} for sand samples were measured to be between 0.75 and 0.99 (Fig. 3). This comparison could suggest that a significant proportion of f_{sand} in sand samples is not quartz, but rather minerals of a lower thermal conductivity. For our dataset, Eq. (3) then overpredicts thermal conductivity of sand in the porosity range 0.2 – 0.35, to be 2.75 – 4.8 W/mK, compared to the measured range of 2.0 – 2.7 W/mK. Caution should then be taken to use Eq. (3) if the mineralogy is unknown. Similarly, Dix et al. (2017) highlighted results of apparently low thermal conductivity in sand and reinforced that for accurate prediction of thermal conductivity, the mineral composition must be known.

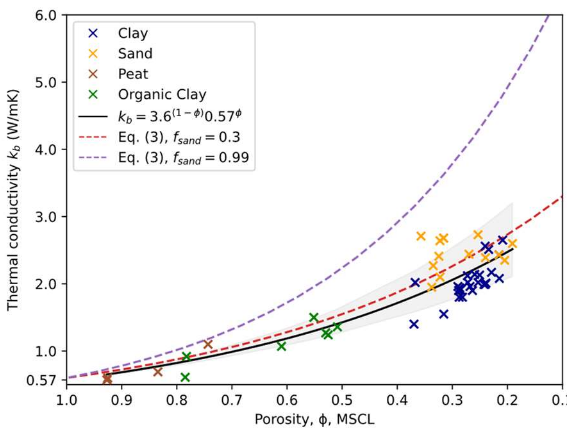

Figure 5. Eq. (3) is approximately equal with Eq. (2) for fine-grained samples where f_{sand} = 0.3, but overpredicts thermal conductivity for coarse-grained samples where f_{sand} was measured between 0.75 and 0.99.

Though the empirically derived, site-specific porosity-thermal conductivity model presented (Fig. 1) fits the data well, it could possibly be improved by including some mineralogy data. Further work could investigate if magnetic susceptibility measurements from the MSCL, sensitive to mineralogy, could be used to improve prediction of thermal conductivity.

4.3. Uncertainties and limitations

Measurement uncertainties are considered negligible relative to the scatter seen within soil groups, thought to be a result of variations in particle size distribution and mineralogical composition. The measurement uncertainty of bulk density with the MSCL, 0.014 g/cm^3, is consistent with previous studies (Weber et al. 1997; Vatandoost et al. 2008). While the assumed ρ_m of 2.65 g/cm^3 in Eq. 1 matches well with the mean and median measurements for sand and clay of 2.64 and 2.65 g/cm^3, it is higher than ρ_m measured for organic samples, which is as low as 2.42 g/cm^3. This has a minor effect on calculated porosity. For example, porosity of a sample with ρ_m = 2.42 g/cm3 and ρ_b = 1.1 g/cm3 will be overestimated by 0.008.

It is not suggested that the thermal conductivity profiles presented are more or less representative of in-situ conditions compared to other laboratory measurements. Rather, the benefit of the MSCL-based approach is the continuous nature of the results. In-situ measurements could be used to validate lab measurements, or to create new relationships with MSCL data directly. The uncertainty in a relationship between MSCL data and in-situ test data will likely be controlled by the variability in soil profiles between the sampling and the in-situ test locations, uncertainty in the in-situ test itself, and the amount of sample disturbance.

Though recovered samples are always in some sense disturbed, a non-destructive, quantitative assessment of sample disturbance is possible with the MSCL. High *P*-wave attenuation and electrical resistivity can be related to cracks, voids, or partial drainage of sand samples. Laboratory testing can then be planned to avoid more disturbed sections or include sample preparation methods such as reconstitution.

4.4. Prospects for future progress

Geophysical survey data is used to map the thickness and spatial variability of sediments away from sampling and CPTu locations. MSCL data supports the processing and interpretation of seismic data by collection of continuous profiles of density and *P*-wave velocity, which are used to calculate acoustic impedance. An integrated approach using MSCL data together with seismic inversion could be used to map variations in acoustic impedance, porosity (e.g. Vardy et al. 2015; O'Niell et al. 2023) and hence thermal conductivity using a site-specific correlation such as in Fig. 1.

MSCL data, with its high vertical resolution, continuous profiles of several independent measurements, is well suited to machine learning or other statistical methods (e.g. Paulson et al. 2006). The authors see potential for further development of automatic classification of samples into soil type as well as improved prediction of thermal conductivity and other parameters of interest (e.g. organic content, undrained shear strength, plasticity). The continuous estimates of geotechnical properties from MSCL can be used to better plan laboratory testing, reduce the total volume of testing required, and reduce uncertainties.

5. Conclusions

In this paper, a method utilising MSCL to estimate continuous thermal conductivity profiles from recovered samples has been demonstrated. The conclusions of this study are:

- Continuous profiles of thermal conductivity can be reliably estimated from porosity as calculated from bulk density measurements with the MSCL. These profiles can be used to better allocate discrete measurements and reduce the volume of destructive testing required.
- Automatic classification of soil type with natural gamma and density measurements further improved predictions of thermal conductivity (r^2 increased from 0.77 to 0.84, RMSE decreased from 0.3 to 0.25 W/mK).
- Multi-Sensor Core Logging provides more precise stratigraphy and soil type classification compared to CPTu data alone, highlighting low thermal conductivity organic layers with cm-scale precision.

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