Thermal Conductivity of Deepwater Offshore Sediments

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ABSTRACT

This paper describes thermal conductivity tests conducted on highly disturbed (fluidised) deepwater offshore North Sea clay sediment. The variation of thermal conductivity with moisture content was determined using a specially designed one-dimensional consolidation apparatus. Comparisons were made with results from undisturbed *in situ* soil cores. The results show very similar values of thermal conductivity for both the undisturbed and fluidised samples for given moisture contents. These values are comparable with results found for similar materials in the North Sea and Gulf of Mexico, but are lower than values typically assumed in current design approaches.

KEY WORDS: clays; jetting; burial; pipeline; thermal conductivity.

INTRODUCTION

Overview

Burial techniques are commonly used for offshore oil and gas pipelines to take advantage of the thermal insulation of the seabed sediments. Knowledge of the *in situ* thermal properties of these soils is extremely important for the design of buried pipeline systems. However, burial techniques such as jetting and ploughing can produce considerable disturbance to the structure of these sediments, leading to changes in the thermal properties. This paper describes a laboratory study to investigate the thermal conductivity of highly disturbed (fluidised) deepwater offshore North Sea clay sediment. The variation of thermal conductivity with moisture content for a consolidating clay material was determined using a specially designed one-dimensional consolidation apparatus. Comparisons have been made with results from undisturbed *in situ* soil cores and these results are presented and discussed herein.

Heat Flow Through Soil

The flow of heat through porous media such as soils and the coupled changes in moisture content can be important for many engineering structures. Examples of such structures include buried pipelines and cables, underground structures, nuclear waste storages and geothermal reservoirs. The two major modes of energy transfer in soils are conduction and convection. Conduction involves the propagation of heat within a body by internal molecular motion (and is thus analogous with diffusion) and convection involves transfer of heat due to motion of pore fluid (i.e. mass movement). It has been found that the relative proportions of these modes of energy transfer are a function of grain size, with conduction occurring predominantly in fine-grained soils and convection in coarse-grained soils (Savvidou, 1988).

The governing general equation for heat transport through porous media is:

$$C\frac{\partial T}{\partial t} = \nabla.\left(\lambda \nabla T\right) \tag{1}$$

where C = volumetric heat capacity of the soil, T = temperature, t = time and λ = thermal conductivity.

The thermal conductivity (λ) is defined as the amount of heat transferred in unit time through unit cross-sectional area, under a unit thermal gradient. This parameter has been investigated for a wide range of soil states and a comprehensive review of the literature has been presented previously by Farouki (1986). The most common method for determining thermal conductivity in soil is the transient, thermal probe method (Steinmanis, 1982). This consists of a line heat source and temperature sensor. Once the probe has reached thermal equilibrium with the surrounding soil, the temperature of the heat source is rapidly increased and heat is allowed to dissipate into the surrounding soil. Thermal conductivity is a function of the rate of heat dissipation and this can be determined from a theoretical solution of conductive heat flow from a line source through an infinite homogeneous medium (Carslaw and Jaeger, 1959). This method assumes that significant moisture migration does not occur during the measurement, which is dependent on power input and test duration (Ewen and Thomas, 1987).

Thermal conductivity has been found to be a function of dry density, saturation, moisture content, mineralogy, temperature, particle size/shape/arrangement and the volumetric proportions of solid, liquid and air phases. A number of empirical relationships have been developed to estimate thermal conductivity based on these parameters, e.g. Kersten (1949), de Vries (1963), Johansen (1975), Sundberg (1988) and Tarnawski and Wagner (1992). Whilst the thermal conductivity of onshore soils has been extensively investigated, only a few studies have been conducted on offshore deposits (e.g. Power et al., 1994; von Herzen and Maxwell, 1959). Many deepwater offshore sediments are formed with predominantly silt and clay sized particles, since sand sized particles are rarely transported this far from shore. Hence convective heat loss is limited in these soils and the majority of heat energy transfer is due to conduction. Recent measurements of thermal conductivity for deepwater soils from the Gulf of Mexico (MARSCO, 1999) have shown values in the range of 0.7 to 1.3 W/m-^{o}K, which is approaching that of still seawater (0.65 W/m-^{o}K). This is a reflection of the very high moisture contents of many offshore soils, where liquidity indices well in excess of unity can exist, which are rarely found onshore.

Figure 1: One dimensional consolidometer test apparatus

Thermal Protection of Pipelines

Oil and gas pipelines are prone to waxing and hydrate formation unless the production fluid is kept above certain temperatures. Since bare pipe can have relatively high thermal conductivity that can lead to flow temperature dropping quickly, some form of insulation is required to reduce the problem. This can be achieved in various ways, e.g. external coatings, pipe-in-pipe technology, electrical heating or hot water annulus. Unfortunately many of these approaches are expensive or difficult to commission and maintain. A cheaper alternative is pipe-burial, which utilises the thermal properties of the surrounding soil. In combination with coatings, burial has been found to produce thermal insulation properties similar to pipe-in-pipe technology, at a significantly lower cost (Loch, 2000).

Burial operations such as jetting and ploughing can highly disturb the *in situ* structure of the seabed deposits. In particular, jetting can completely destroy the soil structure by fluidisation. Many of the properties associated with the resulting trench backfill are currently poorly understood. Knowledge of the thermal insulation provided by the backfill in various states is extremely important for accurate design of buried oil and gas pipeline systems and can reduce the need additional activities such as chemical injection or line flushing. This paper describes a series of tests conducted on a clayey North Sea deposit to investigate the stress-strain behaviour of the undisturbed and fluidised states and how this affects the thermal conductivity behaviour. Comparisons have also been made with a database of thermal conductivity results from a wide range of offshore deposits from both the North Sea and the Gulf of Mexico. Typical results from the above programme are shown and discussed in the sections below.

EXPERIMENTAL METHODOLOGY

Material

The soil used for these tests was grey slightly sandy clay, with a liquid limit of 57% and a plastic limit of 28%. Specific gravity of the soil was 2.66. The material consisted of 41% clay, 54% silt and 5% sand, and the D_{50} particle size was about 5 μm. Samples were taken from vibrocores from a depth of 1.5 to 1.75m, where the moisture content was 62 to 65 % and the bulk density 1.62 t/m^3. Shear vane and undrained triaxial tests indicated that the peak undrained shear strengths for the *in situ* material were in the range of 12 to 13 kN/m^2 and the material had a sensitivity of 2.5 to 3.

Compressibility

Tests were conducted on undisturbed samples from offshore core tubes and disturbed, reconstituted (fluidised) samples. The compressibility behaviour of the undisturbed soil samples was characterised using the standard oedometer and the disturbed samples using a specially designed one-dimensional consolidometer. The latter test was utilised to reproduce the stress history of a 'trench-jetted' soil. Rather than remoulding the soil at a specific moisture content and using the standard oedometer, this involved creating a highly dilute slurry of the soil in the long column (thus simulating the jetting process) and then allowing the material to adopt its own natural density as the soil reformed by vertical settling, as would occur offshore in a pipeline trench after jetting had occurred.

The consolidometer test was performed in a tall cylindrical column (150mm diameter and 400mm high), see Figure 1. The column was initially filled with seawater and the soil was added (in slurry form) slowly with vigorous stirring and then allowed to settle through the water. Once the soil body formed at the base of the consolidometer (assumed to be at the sedimented void ratio, e_o) the excess surface water was drained off and a top cap was placed on top of the material. Loads were slowly added to the top cap to create vertical pressure and one-dimensional compression occurred. Side friction between the top cap and the side walls was reduced by using a very thin layer of silicone grease and polishing the aluminium surfaces. Top and bottom drainage was allowed and the settlements were monitored using a linear displacement transducer. Measurements of thermal conductivity were taken periodically during the loading sequence.

Thermal Conductivity Measurement

The thermal conductivity of the soil samples was measured using a transient thermal probe utilising temperature measurement around a line source. The probe is manufactured by Hukseflux (TP01) and is capable of measuring thermal conductivity over a range of 0.3 to 4 W/m-°K. Measurements of thermal conductivity are logged using a computer based system and calibration is conducted with a standard reference medium of agar gel. The core of the probe is a differential temperature sensor (2 thermopiles) that measures the radial differential temperature. Both the heater and sensor are incorporated into a very thin kapton foil (which is 0.15 mm thick) and shown in Figure 2. This allows low heater power to be used for measurements and leads to extremely high sensitivity (differential temperature measurement of 0.003 °C) and therefore reduces any potential moisture migration errors. Due to the low thermal mass, the thermal diffusivity may also be measured using this system.

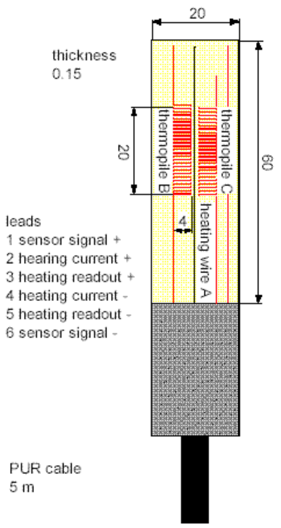

Figure 2: Hukseflux TP01 thermal conductivity probe

EXPERIMENTAL RESULTS

Compressibility

Measurement of the variation in void ratio and permeability, with increasing vertical effective stress is vital if predictions of the post-jetting consolidation behaviour of these materials are to be made. The vertical effective stress-void ratio-permeability relationships for the fluidised material for the sample are shown in Figure 3(a) to Figure 3(c). The void ratio-effective stress data is shown in Figure 3(a). The void ratio varies non-linearly with vertical effective stress from values of approximately 2.25 to 1.4 over a stress range of 0.1 to 40 kPa and the value of the coefficient of compressibility (C_c) is approximately 0.383.

The permeability (k) against void ratio is shown in Figure 3(b) and this shows a variation in permeability from $5x10^{-6}$ to $1x10^{-8}$ m/s over the same void ratio range as shown in Figure 3(a). The corresponding permeability with vertical effective stress relationship is shown in Figure 3(c).

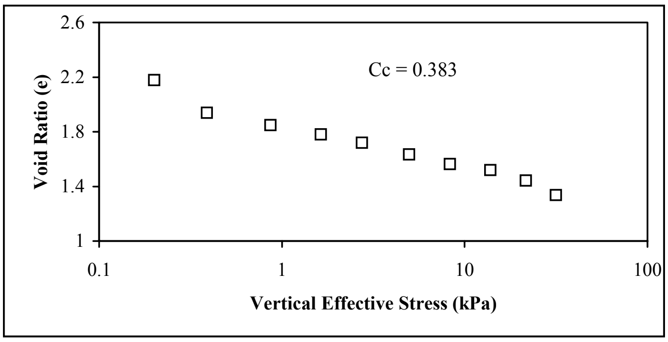

Figure 3(a): Void ratio against vertical effective stress for fluidised sample

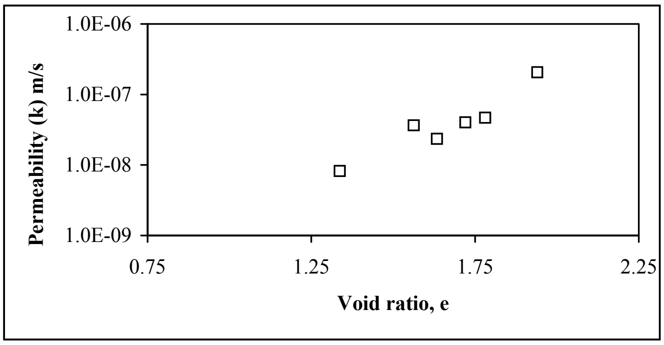

Figure 3(b): Permeability against void ratio for fluidised sample

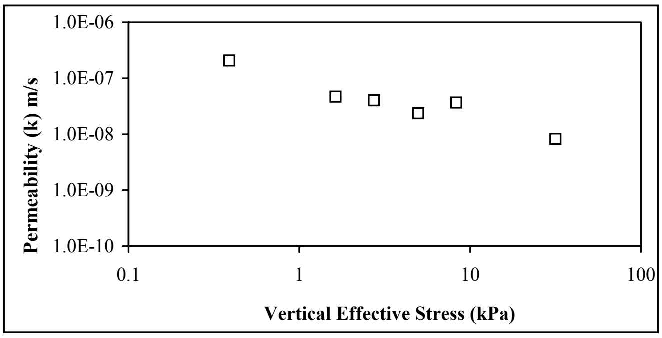

Figure 3(c): Permeability against vertical effective stress

Figure 4 shows the standard oedometer results from the undisturbed samples. For this material, the void ratio is seen to vary from 1.7 to 0.7 over a stress range of 1 to 1000 kPa. This indicates an initially overconsolidated state, showing evidence of yield at approximately 10 kPa. The coefficients of compression (C_c) and swelling (C_s) for the standard oedometer tests were found to be 0.396 and 0.05, which reflects the silt/sand content of the samples. Comparison of the consolidometer and standard oedometer data indicates reasonably good correlation, with the consolidometer (fluidised) data continuing the virgin compression line shown by the undisturbed samples. The close match of these results suggests that for this soil, the undisturbed structure is very similar to that of a sedimented material, such as the fluidised sample.

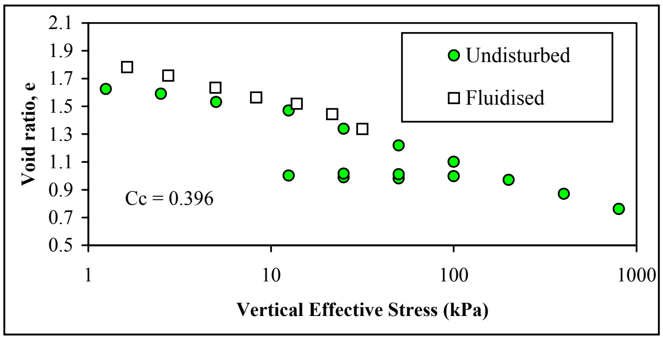

Figure 4: Undisturbed and fluidised sample compressibility

Thermal Conductivity

The thermal conductivity measurements for the undisturbed samples are shown in Figure 5, with the corresponding *in situ* moisture contents (shown as circles). These range in values from 0.97 to 1.19 W/m-^{o}K and from 63 to 46% moisture content. These results are compared to those found for the fluidised soil using the modified consolidometer tests (shown as squares in the figure). This shows a reasonable correlation between the undisturbed and fluidised material, again indicating very similar soil structures. The thermal conductivity of the fluidised material varies from 0.8 to 1.15 W/m-^{o}K over a range of moisture contents from 95 to 35%.

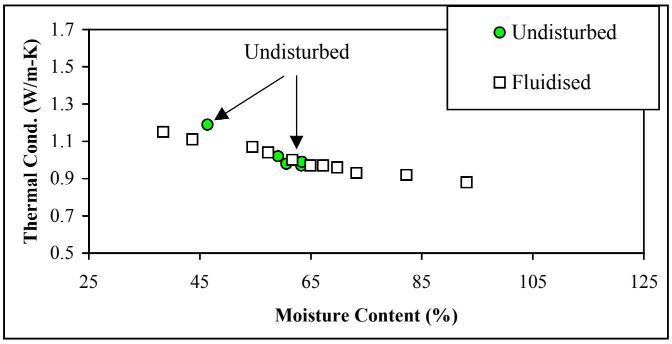

Figure 5: Thermal conductivity of fluidised and undisturbed samples

DISCUSSION

The stress-strain behaviour of the undisturbed and fluidised material seems to be typical of similar onshore silty-clays (Newson and Fahey, 1998). The yield-stress and initial shape of the standard oedometer curves for the intact samples seems to indicate that the material is lightly-overconsolidated. This is also supported by peak undrained shear strength values, which are slightly higher ($c_u/\sigma_v' = 0.5$) than would be expected for a normally consolidated deposit of this material at this depth. The sensitivity (ratio of peak to residual undrained shear strength) of the material was found to be approximately 2 to 3 and thus the material is insensitive with only limited structure other than that due to saline flocculation. The similarity of the fluidised and the undisturbed material compression curves also confirms this finding.

The results of the *in situ* thermal conductivity tests (shown in Fig 5) have been replotted for comparison with further results collected by Stolt Offshore for a wide range of clayey (of intermediate plasticity and above) offshore deposits (shown as triangles) in Fig 6. These values are comparable with results found for similar materials in the North Sea and Gulf of Mexico.

As expected, the thermal conductivity is seen to reduce with increasing moisture content, since this depends on the intimacy of contact of the solid phase (the ratio thermal conductivity of solid to water can be as high as 15:1) the greater percentage of voids at high moisture contents leads to a reduction in thermal conductivity. As the density of the soil increases at lower moisture contents, the number of particle contacts increase, allowing additional heat transfer through these contacts (rather than via the less efficient water) and leads to increases in thermal conductivity. In fact, when the soils are at very high moisture contents, in the absence of convection, the insulating properties of the seawater reduce the thermal conductivity to that approaching seawater alone (0.65 W/m-^{o}K). Whilst the correlation between moisture content and thermal conductivity appears to be quite good, this data covers a range of clay contents and mineralogy, and the data begins to diverge at low moisture contents as the clay content reduces (particularly for low plasticity soils).

A more rigorous approach is to normalise the data by plotting thermal conductivity against *liquidity index* (I_L), which relates the current state of the soil in terms of moisture content to the liquid limit (w_L) and plastic limit (w_P). This plot is shown as Figure 7. Again there is the same general trend of reducing thermal conductivity with increasing liquidity index, although this increases the data scatter slightly. Alternatively, the data can be plotted in terms of void index (I_v), which is defined in equation (2) and is shown in Figure 6.

$$I_v = \frac{e - e^*_{100}}{C_c^*} \quad (2)$$

where e is the current void ratio, e^*_{100} is the intrinsic void ratio corresponding to a stress of 100 kPa and C_c^* the intrinsic compression index.

The void index was introduced by Burland (1990) to describe the *compactness* of a clayey soil and provides a measure of the structure of the soil compared to the intrinsic or sedimented state. Clay soils are typically created by the deposition of the flat plate-like clay particles in water bodies. Within these environments the particles settle and eventually consolidate to form soil strata. A specific particle arrangement develops with a preferred orientation of the clay platelets, which causes a variation of the engineering behaviour of the soil (e.g. compressibility, permeability or strength) in the horizontal and vertical plane.

In geological terms, unless the soil is relatively young, some form of post-depositional process will subsequently change this *sedimented* state, e.g. bioturbation, erosion, wave action, cementation or thixotropy. The structure and behaviour of these soils will differ from that of soils with a purely sedimented structure. Compression curves from these modified materials show greater compressibility and have higher void ratios (for similar stresses) and with remoulding the soil will *destructure* (Leroueil et al., 1985) and the mechanical behaviour will begin to approach that of a sedimented soil.

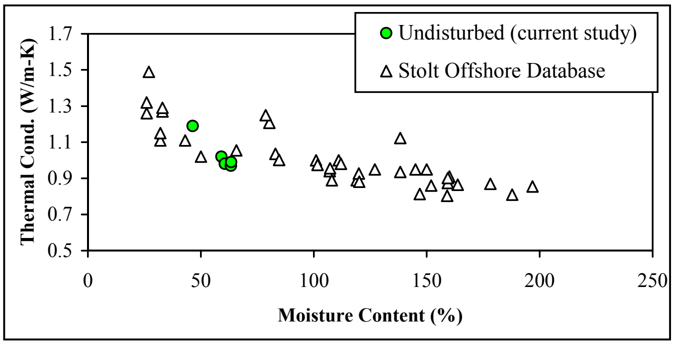

Figure 6: Thermal conductivity v. moisture content for different soils

Whilst the use of the liquidity or void indices in Figures 7 and 8 provides a more rigorous framework to compare thermal conductivity results from different soils there is still some data scatter. This may be due to the use of void ratio (or in the case of liquidity index moisture content), which provides a macroscopic description of soil packing and takes no account of the *distribution* of pore sizes (and thus the possible contacts of the solid phase). With plate-like clay particles it is possible to achieve many different particle-packing arrangements for the same value of void ratio, some of which may favour heat transfer and others that do not. This particle packing is closely related to the structure and sensitivity of clay soils and much of this scatter may be due to the differences in particle arrangements. However, further investigation would be required to confirm this hypothesis.

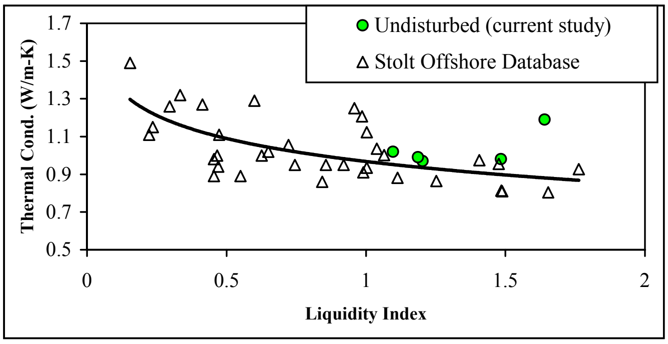

Figure 7: Comparison of thermal conductivity v. liquidity index from different soils

For a soil that has experienced *complete* fluidisation due to jetting, the resulting backfill structure will be very close to the intrinsic or sedimented state. Therefore if this basic framework could be identified for these soils, this would provide a method of determining the thermal conductivity based on simple laboratory tests such as the Atterberg limit tests (i.e. liquid and plastic limit). Alternatively, the relatively straightforward tests proposed within this paper can be used to determine the changes of thermal conductivity with moisture content as self-weight consolidation occurs within an offshore trench following pipe burial.

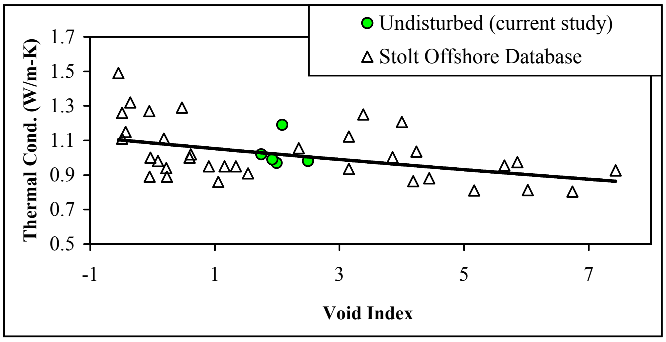

Figure 8: Comparison of thermal conductivity v. void index from different soils

CONCLUSION

A new method for determining the variation of thermal conductivity with moisture content for fluidised clay soil is presented. The undisturbed and fluidised properties and behaviour appear to correlate closely and this suggests that for this soil, the undisturbed structure is very similar to that of a sedimented material, such as the fluidised sample. The values of *in situ* thermal conductivity are comparable with results found for similar materials in the North Sea and Gulf of Mexico, but are lower than values typically assumed in current design approaches. In addition, the method provides data at very low stresses, which are not possible with standard methods such as the oedometer. These results provide extremely useful data on the fundamental thermal conductivity behaviour of deepwater clay offshore sediments. This approach may also be used for prediction of the consolidation behaviour of jetted offshore backfill (e.g. using finite element analysis).

ACKNOWLEDGEMENTS

The work described in this paper was supported by funds from Stolt Offshore Ltd and this support is gratefully acknowledged.

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