Determination of Thermal Conductivity of Coarse and Fine Sand Soils

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ABSTRACT

Energy piles are technologies that tap into the thermal energy present in the ground and then utilize it for heating and/or cooling buildings. Heat is transmitted into/from the soil by conduction or convection due to the thermal gradients within the soil mass. The main thermal characteristics of soil are the thermal conductivity and thermal capacity.

Soil thermal conductivity measurements describe the soil properties which govern the flow of heat through the soil.

This paper describes a determination of thermal conductivity of sands at steady state and cooling stage conditions. Determination of thermal conductivity of sands (dry coarse sand, saturated coarse sand, dry fine sand, and saturated fine sand) at cooling stage conditions gives similar results to the generic published values.

1. INTRODUCTION

Energy piles is one of geothermal ground storage technology where the foundation bearing piles were used not just to physically support the building, but also as a key aspect of the building energy design. These are technologies that tap into the thermal energy present in the ground and then utilize it for heating and/or cooling buildings. This is a cost-effective way to include the underlying soil in the heat management of a building.

Bored piles, driven piles, piled retaining walls and diaphragm walls can adapted for use in ground storage systems for heating or cooling purposes. An example of a bored pile reinforce cage with pipe circuit. These piling techniques all have potential, but the impacts on constructability of our local ground conditions would have to be investigated for any project.

The pipes in the pile contain a heat carrying fluid, such as a water/glycol mixture. In winter the relatively warm fluid is fed to the evaporator side of a heat pump, where it is cooled. The heat extracted from it is used to warm the building via the central heating system. In summer the fluid takes up excess heat from the building, also via the central heating system. The pipes allow the glycol mixture to exchange heat with the soil. In a well dimensioned pile, the extra resistance to heat flow due to the presence of a concrete layer around the heat carrying pipe is negligibly small compared to the total heat resistance.

The rate of heat or cold extraction of a single energy pile depends primarily on the temperature of the heat carrying fluid and the heat conductivity of the soil surrounding the pile. The higher the heat conductivity, the easier the heat extracted from the soil in the immediate surroundings of the pile can be replaced by heat flowing inwards from layers of soil further from the pile. Figure 1 showing typical system of heating and cooling using energy piles.

Heat is transmitted into/from the soil by conduction or convection due to the thermal gradients within the soil mass. The main thermal characteristics of soil are the thermal conductivity and thermal capacity. Soil thermal conductivity measurements describe the soil properties which govern the flow of heat through the soil. The thermal conductivity is defined as the quantity of heat that flows through a unit area in a unit time under a unit temperature gradient.

A soil’s thermal conductivity is significantly influenced by its saturation and dry density. Saturation describes the amount of moisture contained in a soil, while dry density refers to the mass of soil particles per unit volume. An increase in either the saturation or dry density of a soil will result in an increase in its thermal conductivity. Other factors that have a secondary effect upon soil thermal conductivity include mineral composition, temperature, texture, and time.


Figure 1: Typical system of heating and cooling using energy piles.
Table 1: Summary of values of thermal conductivity and specific heat capacity of various soils

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Water Content (%)</th>
<th>Bulk Density (Mg/m³)</th>
<th>Dry Density (Mg/m³)</th>
<th>Thermal Conductivity (W/m K)</th>
<th>Specific Heat Capacity (J/kg K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH C13 88</td>
<td>21.3</td>
<td>1920</td>
<td>1583</td>
<td>2.89</td>
<td>1520</td>
</tr>
<tr>
<td>China CLAY (D)(sat.)</td>
<td>46.2</td>
<td>1730</td>
<td>1183</td>
<td>1.52</td>
<td>2362</td>
</tr>
<tr>
<td>China CLAY (D)(dry)</td>
<td>0</td>
<td>1390</td>
<td>1390</td>
<td>0.25</td>
<td>800</td>
</tr>
<tr>
<td>Sandy CLAY</td>
<td>26.5</td>
<td>1890</td>
<td>1494</td>
<td>1.61</td>
<td>1696</td>
</tr>
<tr>
<td>Sandy CLAY</td>
<td>19.5</td>
<td>2100</td>
<td>1757</td>
<td>2.45</td>
<td>1459</td>
</tr>
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<td>Soft dark grey sandy gravelly CLAY</td>
<td>28.5</td>
<td>1912</td>
<td>1488</td>
<td>3.57</td>
<td>1764</td>
</tr>
<tr>
<td>Soft grey fine sandy CLAY</td>
<td>54.6</td>
<td>1650</td>
<td>1067</td>
<td>4.20</td>
<td>2646</td>
</tr>
<tr>
<td>Soft grey fine sandy CLAY</td>
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<td>1741</td>
<td>1231</td>
<td>3.03</td>
<td>2200</td>
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<td>Stiff dark grey sandy gravelly CLAY</td>
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<td>2299</td>
<td>2088</td>
<td>3.69</td>
<td>1141</td>
</tr>
<tr>
<td>Stiff grey sandy gravelly CLAY</td>
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<td>2369</td>
<td>2161</td>
<td>3.28</td>
<td>1125</td>
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<tr>
<td>Stiff grey brown sandy gravelly CLAY</td>
<td>9</td>
<td>2352</td>
<td>2158</td>
<td>3.20</td>
<td>1104</td>
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<tr>
<td>Very soft grey fine sandy CLAY</td>
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<td>1711</td>
<td>1170</td>
<td>3.51</td>
<td>2362</td>
</tr>
<tr>
<td>Grey slightly silty sandy GRAVEL</td>
<td>11.1</td>
<td>1983</td>
<td>1785</td>
<td>4.44</td>
<td>1175</td>
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<tr>
<td>Grout</td>
<td>166</td>
<td>1250</td>
<td>470</td>
<td>0.64</td>
<td>6412</td>
</tr>
<tr>
<td>Grey limestone (very hard)</td>
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<td>2690</td>
<td>2687</td>
<td>2.54</td>
<td>803</td>
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<tr>
<td>Course SAND (dry)</td>
<td>0</td>
<td>1800</td>
<td>1800</td>
<td>0.25</td>
<td>800</td>
</tr>
<tr>
<td>Course SAND (sat.)</td>
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<td>2080</td>
<td>1730</td>
<td>3.72</td>
<td>1483</td>
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<tr>
<td>Dark grey clayey fine sand/silt</td>
<td>28</td>
<td>1848</td>
<td>1444</td>
<td>4.26</td>
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<tr>
<td>Fine SAND (dry)</td>
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<td>1600</td>
<td>0.15</td>
<td>800</td>
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<td>Fine SAND (sat.)</td>
<td>24.6</td>
<td>2010</td>
<td>1613</td>
<td>2.75</td>
<td>1632</td>
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<td>Made ground (Silty gravelly sand)</td>
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<td>2182</td>
<td>1916</td>
<td>3.03</td>
<td>1270</td>
</tr>
<tr>
<td>Medium SAND (dry)</td>
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<td>1700</td>
<td>1700</td>
<td>0.27</td>
<td>800</td>
</tr>
<tr>
<td>Medium SAND (sat.)</td>
<td>20.2</td>
<td>2080</td>
<td>1730</td>
<td>3.34</td>
<td>1483</td>
</tr>
</tbody>
</table>

Table 1 showing summary of values of thermal conductivity and specific heat capacity of various soils. There are many methods used to measure the thermal conductivity of soils. This paper is for a test to directly measure the thermal conductivity of soils obtained from routine investigations.

2. THERMAL CONDUCTIVITY MEASUREMENT

In this research, the method to determine thermal conductivity of soil is using one dimensional conduction test. Tests to determine thermal conductivity are either based on measuring the power needed to create a constant temperature difference, or a constant power is applied and the resulting temperature difference is measured or the temperature is monitored as the temperature changes.

Main equipments that using to determine thermal conductivity (Figure 2).

- Thermal cell.
- Temperature control unit.
- Pico logger and Personal Computer (PC).
- Temperature sensors (type K thermocouples).

The test is designed to use cylindrical specimen. The ends of a specimen are maintained at different temperatures and heat allowed to flow axially through the sample. A cylindrical specimen of soil is surrounded by a jacket of insulating material (for axial flow) and is positioned between two platens. The platens contain heating elements but also seal the specimen preventing any changes in water content. The temperatures within the bottom platen, at the base of the specimen, at the top of the specimen and in the air above the top platen, together with the power consumption are measured throughout a test.
2.1 Procedure of Measurement

In a one-dimensional conduction test the temperature of the top and bottom of the specimen are controlled using heat cartridges and thermocouple feedback. In the standard test in a constant temperature laboratory the temperature gradient across the specimen is generated by heating the base of the specimen allowing the heat to dissipate to air from the top of the specimen. This means that air currents have to be minimised to ensure free convection.

There are three distinct stages to the test. The first stage was to bring the temperature gradient to constant. The second was to maintain the temperature gradient until steady state is reached. The final stage was the cooling stage after the heater was switched off.

The procedure of thermal conductivity measurement:

1) All equipment including the specimen was placed in a constant temperature room and allowed to reach the temperature equilibrium.

2) Applying constant heat to the base of cylindrical specimen of soil and keeping it’s a temperature room.

3) Monitoring and recording the temperature at the top and bottom of specimen at 5 minutes interval until the temperature gradient across specimen is constant. Temperature control unit using a cartridge heater and a thermocouple feedback are used to control the temperature at the base of specimen.

4) Checking the temperature at thermocouple within the specimen and at the top of specimen regularly to establish the steady state condition.

5) Switch off the power when temperature at the thermocouples within specimen and temperature at the top of specimen reach the steady condition.

6) The specimen allowing to cooling stage. Monitoring and recording the temperature at the top and bottom of the specimen and within the specimen at 5 minutes interval. Subsection headings should be capitalized on the first letter.

2.2 Specimen Data

In this research, the specimens that have been tested are four samples of sand. They are dry course sand, saturated coarse sand, dry fine sand, and saturated fine sand. Figure 3 and 4 showing sieve analysis result of two kinds of sand that used in this research.

Soil parameter of first specimen (saturated coarse sand) is \( \gamma_{\text{bulk}} = 17.58 \text{ kN/m}^3 \) and \( \gamma_{\text{dry}} = 20.70 \text{ kN/m}^3 \). The second one (dry coarse sand) is \( \gamma_{\text{bulk}} = 15.33 \text{ kN/m}^3 \). The third specimen (saturated fine sand) have soil parameter: \( \gamma_{\text{bulk}} = 18.41 \text{ kN/m}^3 \) and \( \gamma_{\text{dry}} = 21.37 \text{ kN/m}^3 \) and the last sample (dry fine sand): \( \gamma_{\text{bulk}} = 15.13 \text{ kN/m}^3 \).

![Figure 3: Plot of percent finer vs. grain size (coarse sand).](image)

![Figure 4: Plot of percent finer vs. grain size (fine sand).](image)
3. THERMAL CONDUCTIVITY ANALYSIS

The thermal conductivity is defined as:

\[ k_t = \frac{Q}{A \frac{\Delta T}{\Delta L}} \]  

(1)

where \( Q \) is the amount of heat passing through a cross section, \( A \), and causing a temperature difference, \( \Delta T \), over a distance of \( \Delta L \). \( Q/A \) is known as the heat flux which is causing the thermal gradient, \( \Delta T/\Delta L \). Once steady state conditions are achieved Equation (1) can be used if the power is measured directly.

If it is not possible to make accurate measurements of the heat flux then it is possible to use the temperature decay curve to determine the heat transfer coefficient and use the fact that during steady state conditions the energy transmitted through a specimen is equal to the energy dissipated from the top of the specimen.

A theoretical decay curve shows that the temperature variation with time is:

\[ T = T_w + (T_o - T_w) e^{-\frac{h_L}{m_c_p}} \]  

(2)

where \( m \) is the mass of dry soil, \( T_o \) is the temperature at the top of the specimen and \( c_p \) is the specific soil capacity. The capacity of a partially saturated or saturated soil can be found from:

\[ \Sigma m_c_p = (m_{p,soil} + m_{p,water} \]  

(3)

where \( (m_{p,soil}) \) is the mass multiplied by the unit specific heat capacity. Dry sand soil has the unit specific heat capacity is about 800 J/kg K and saturated sand soil is about 1632 J/kg K (See Table 1).

This is based on the assumption that the temperature difference across the specimen is small. Experimental evidence has shown that this is the case some time after the specimen starts to cool. The heat transfer coefficient \( h \), is calculated by adjusting the cooling curve until it matches the experimental curve.

So, the thermal conductivity is given by

\[ k_t = L \cdot h(T_{top} - T_o)/(T_{base} - T_o) \]  

(4)

where \( T_{top} \) is the temperature at the top of the specimen at the start of the cooling curve, \( T_{base} \) the temperature at the base of the specimen and \( L \) is the length of sample.

Figure from 5 to 12 show the results of tests on a variety of sand. The average result of thermal conductivity of dry coarse sand at steady state condition is 2.05 W/m/oC and at cooling stage condition is 0.36 W/m/oC. In saturated condition of that specimen, give result at steady state condition is 7 W/m/oC and at cooling stage condition is 3.40 W/m/oC.
Figure 7: The variation of temperature with time for a test on saturated coarse sand.

![Temperature variation graph](image)

Figure 8: The fit of the theoretical curve to the cooling curve for a test on saturated coarse sand.

![Temperature fit graph](image)

Figure 9: The variation of temperature with time for a test on dry fine sand.

![Temperature variation graph](image)
Figure 10: The fit of the theoretical curve to the cooling curve for a test on dry fine sand.

Figure 11: The variation of temperature with time for a test on saturated fine sand.

Figure 12: The fit of the theoretical curve to the cooling curve for a test on saturated fine sand.
The average result of thermal conductivity of dry fine sand at steady state condition is 1.76 W/m°C and at cooling stage condition is 0.16 W/m°C. In saturated condition of that specimen, give result at steady state condition is 5.69 W/m°C and at cooling stage condition is 3.55 W/m°C.

From all the result above, analysis of thermal conductivity at cooling stage give similar results to the generic published values (see Table 1).

4. CONCLUSIONS
The tests have confirmed that the thermal conductivity varies with material condition. The tests give different results between steady state condition and cooling stage condition. Thermal conductivity analysis at cooling stage gives similar results to the generic published values.

REFERENCES