Comparison of different methods for measuring thermal properties of soil: review on laboratory, in-situ and numerical modeling methods

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ABSTRACT: Nowadays, development of technology and industry and arising of new engineering application, such as nuclear waste disposal, oil extraction and pipeline, geothermal structures are encouraging the researchers to have a better understanding about the temperature effect in soil up to 100 °C and even more when dealing with the thermal treatment of contaminated soils. A key challenge in problems dealing with temperature is to measure the thermal properties of the soil. Lack of such knowledge might lead to malfunction or non-economical design of structures dealing with temperature change. Different methods can be used for determination of soil thermal properties. Each method has its own positive and negative points comparing to other ones. Laboratory tests is a fast and economical method but meanwhile several aspects cannot be accounted during the test. In-situ measurements is a good way to calculate soil thermal properties with respect to actual site condition and natural environment. However it might be time consuming and expensive for particular locations and high-level technology apparatus might be required. Experimental, empirical and mathematical modeling could a good alternative having no need for small-scale or big-scale tests however; a few models can be utilized for different conditions and type of soils. In addition, some of these numerical models are too complex, need lots of parameters, and can be used for specific occasions. In this paper, different methods for measurement of soil thermal properties are investigated and compared to each other including recently developed methods. Accurate measurement of soil thermal properties could help us to have a sufficient and cost effective design for engineering application dealing with temperature change.

Keywords: soil thermal properties, thermal properties measurement, laboratory methods, in-situ measurement, prediction models

1. Introduction

Temperature change and its potential effect on soil properties and behavior has become an important part of many engineering design and applications. It started at mid-20th century when Gary[1] did the first odometer test at different temperature of 10 and 20 ˚C in 1936. Paswell [2] conducted heating test at constant load using odometer ring in 1967and the first conference with focus on temperature related issues in soils was held in Washington DC USA in 1969. The early studies of other researchers can be found in literature [3–14].

The range of temperature was being investigated back then during early suited was restricted (usually between 10 to 50 °C). The reason of such limitation was related to the researcher’s interest, which was the temperature difference between the laboratory and the field where the samples were being taken. Nowadays, However, development of technology and industry has caused new and more complicated engineering application to arise, such as nuclear waste disposal, oil extraction and pipeline and geothermal structures which are encouraging the researchers to have a better understanding about the temperature effect in soil up to 100 °C and even more when dealing with the thermal treatment of contaminated soils.

Ability of clayey soils like seepage control, pollution prevention, heat insulation and radiation protection could make it an ideal environment for nuclear waste disposal [15, 16]. On the other hand, it can cause the soil to face temperature change up to 100 °C because of chemical reactions of the waste. Thus, the importance of soil behavior toward temperature change made many researchers to work in this field to have better and safe design in long-term function of these disposal areas.

Another engineering application involving temperature change is waste management and design of landfills. Geosynthetic clay liner (GCL) is often used as a mechanical and hydraulic barrier to ensure both safety of the design (e.g. in slopes) and prevention of leakage of chemical and hazardous substances and fluid into environment. GCL is a layer of bentonite captured between layers of geotextiles and sometimes geomemberane is used as the final coverage for the system [17]. Chemical reactions of wastes and temperature fluctuation of climate change can cause the sounding area including GCL to face elevated temperature [18–20] which might cause alternation of mechanical and hydraulical properties of bentonite inside the GCL and even the whole barrier system [21, 22]. for instance rise of temperature up to 50 °C in copper leach pads [23], 70 °C in nickel leach pads [24], 60 °C in municipal wastes [25] and even more than 100 °C in aluminum waste [26] has been reported.

In recent years, pollution and Global warming related issues and the proven effect of fossil energy on that as well as the price in developing or even developed countries, have lead the attention toward finding a renewable

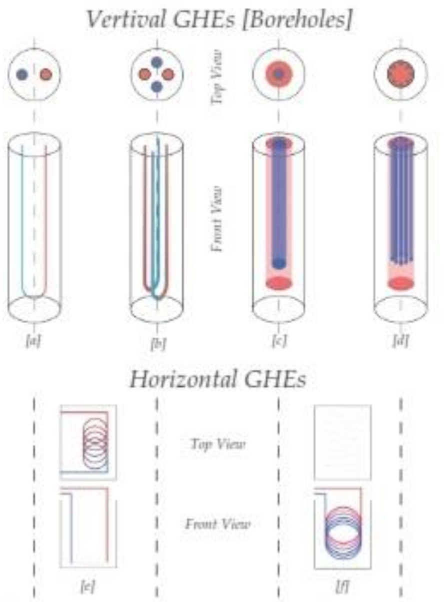


Figure 1. Horizontal and vertical GHE (a) Common vertical GHE designs – single U-tube, (b) double U-tube, (c) simple coaxial, (d) complex coaxial, (e) overlapping slinky loops, (f) vertical spiral loops [29].


Figure 2. Energy pile

and sustainable source of energy such as Geothermal Energy [27–31].

Among different type of the geothermal structures, Ground-source heat pump (GSHP) is the most common type for space heating and cooling [27, 29, 32–36]. GSHPs are connected to a network of buried tubes, called ground heat exchanger (GHE), through which the water is being circulated (Fig.1) [29, 31, 33]. Due to high excavation costs especially for vertical GHEs, another type of heat exchanger has become popular called energy piles. A network of tubes is placed inside the pile foundation to make a both mechanical and geothermal structure (Fig.2) [27, 29, 31, 33, 37].

Because of soil and ground being the source of energy in geothermal structures, it is of high importance to have sufficient knowledge about the ground temperature profile and thermal properties. Therefore several in-situ, laboratory and numerical studies has been done regarding temperature profile and its thermal properties such as thermal conductivity and diffusivity ([34, 35, 38–40]). Heat pump function and circulation of fluid through the soil foundation will cause the temperature fluctuation on pile-soil interface, pile and the sounding soil. the first experiment regarding this issue was done by Morino and Oka [41].

The importance of the temperature and its possible effects on physical and mechanical properties of soil has been highlighted by some example of engineering applications mentioned above. Sufficient knowledge on thermal properties of soil is essential to have better understanding about the effect of temperature change on physical and mechanical behavior of soil. The aim of this paper is to make a detailed review and summarization about the soil thermal properties and different methods of measurement. This information is of high importance and can help us to make sure about the quality and safety of designing the structures dealing with temperature change.

2. *Thermal properties of soil*

Existence of temperature difference between two places will cause heat to transfer from the location with higher temperature toward the lower temperature. Heat can transfer by three method namely conduction, convection and radiation [42]. Heat transfer through geomaterials (soil and rock) is dominated by conduction and the share of other heat transfer methods are negligible. Thus, thermal properties of soil affecting the heat transfer are important to have better idea about temperature and its change on soil behavior [43–45].

2.1. Thermal Conductivity

According to Fourier's law, thermal conductivity is calculated as:

$$k = \frac{q'' L}{\Delta T} \quad (1)$$

where k is thermal conductivity ($W.m^{-1}.K^{-1}$), q'' is heat flux ($W.m^{-2}$), L is the material thickness (m) and ΔT is temperature difference (K or °C) [42]. Thermal conductivity is the most important among other thermal properties in soil and governing heat transfer and temperature distribution [46, 47]. Many external and internal factors can alter the soil thermal conductivity [48–50]. According to [51] these factors are categorized as:

- Compositional factors: soil mineral components, particle size, shape, and gradation.
- Environmental factors: The water content, density and temperature.
- Other factors: properties of soil components, ions, salts, additives, and hysteresis effect.

Regarding soil minerals, Quartz has one of the strong effect on overall soil thermal conductivity because it has the highest thermal conductivity (around 8 $W.m^{-1}.K^{-1}$). Another factor with high impact on soil thermal conductivity is water content, because of its higher thermal conductivity (around 5.7 $W.m^{-1}.K^{-1}$) comparing to solid particles and air.

Zhang et al. [48] investigate the influence of some factors on thermal resistivity, r ($m.K.W^{-1}$), which is inversely related to thermal conductivity. Therefore, lower thermal resistivity means higher thermal conductivity and faster heat transfer through the soil and Vis versa. Fig.3 shows the effect of water content on thermal resistivity. Reduction of thermal resistivity can be noticed by

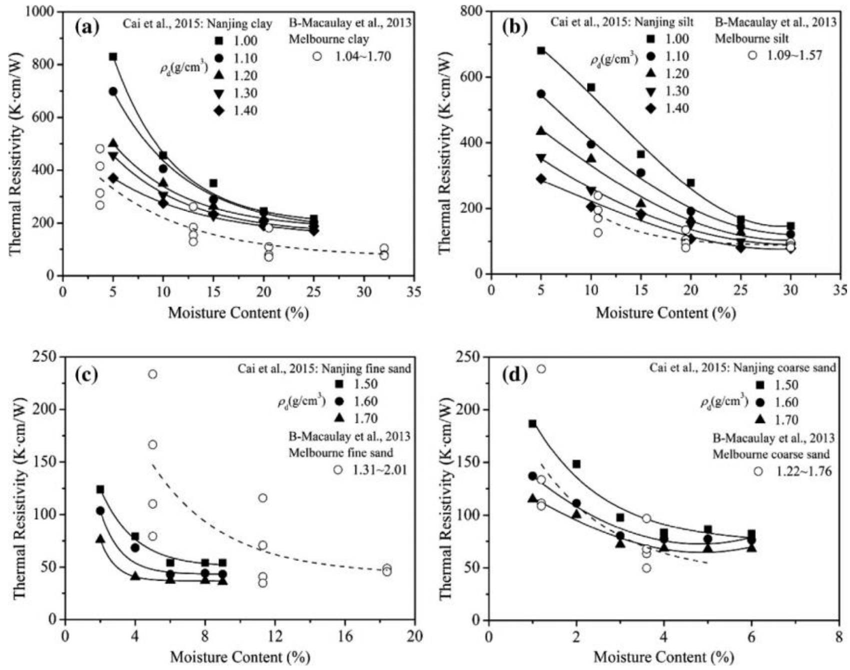


Figure 3. Thermal resistivity versus moisture content at a range of dry density: (a) clay, (b) silt, (c) fine sand, and (d) coarse sand [48, 52, 53]

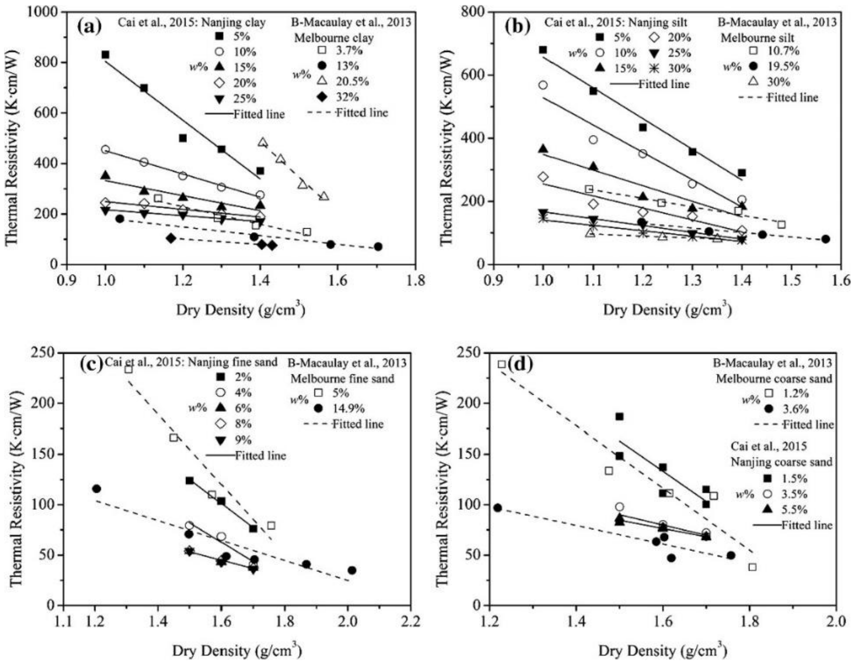


Figure 4. Thermal resistivity versus dry density at a range of moisture content: (a) clay, (b) silt, (c) fine sand, and (d) coarse sand [48, 52, 53]

This behavior was attributed to difference between thermal resistivity of water (about 165 K.cm.W-1) and air (4000 K.cm.W-1) in [48]. When water content increases inside the soil, void areas occupied by air will be replaced by water having rather lower thermal resistivity. Other reason for this result is the physical contact between the soil particles that mostly governs the heat transfer. As water content increases, a water film will be shaped around the particles improving the physical contacts and heat transfers afterwards. Since the particle size and orientation of sand and clay are much different, different behavior of thermal resistivity with water content is observed [48, 52, 53].

Effect of dry density on thermal resistivity is shown in Fig.4 and decrease in thermal resistivity with increase in dry density is observed. Higher dry density will lead to more physical contact between particles and less air in void areas. Effect of saturation increase is displayed in Fig.5 and Fig.6 with reduction in thermal resistivity and increase in thermal conductivity for all type of soils. It can be highlighted that variation of thermal resistivity for clayey soils is much higher comparing to sand. This is because of nature of particle size and orientation as in sandy soils particle physical contact is low and a small amount of water can improve it. On the other hand in clays much more water is needed to fully occupy the contact between particles [48, 52, 54].

Particle size impact on thermal resistivity can be observed in Fig.7. As it is shown, higher particle size will cause lower thermal resistivity. This is also attributed to the physical contact and effect of particle size on that. Moreover the thermal resistivity of rock minerals is lower than clay minerals [48, 55].

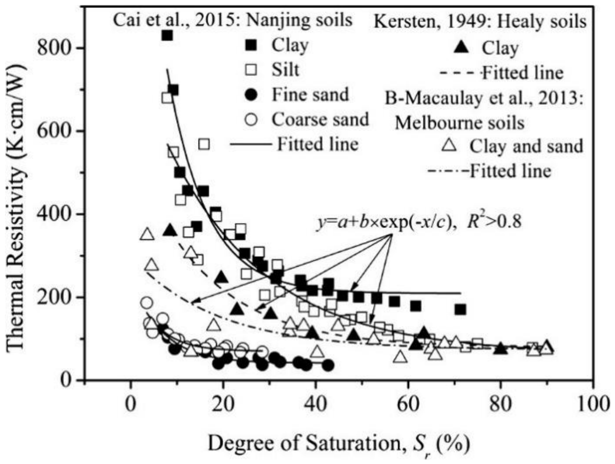


Figure 5. Effect of saturation on thermal resistivity of soil [48, 52, 54]

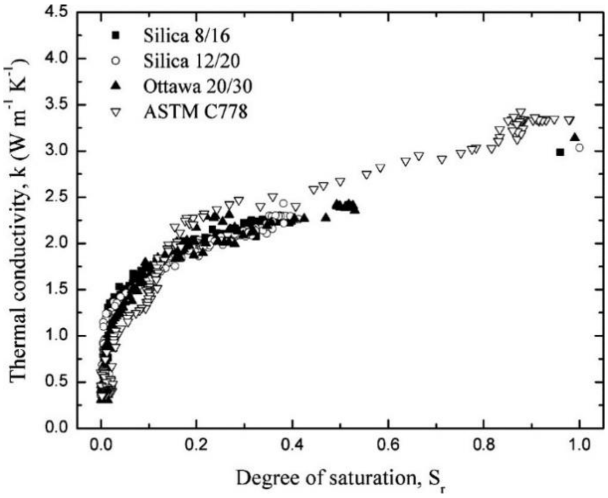


Figure 6. Effect of Saturation on different type of sand thermal conductivity [48, 52, 54]

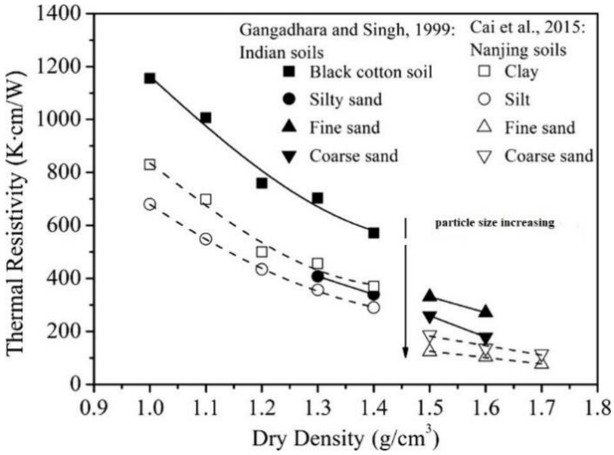


Figure 7. Effect of particle size on thermal resistivity [48, 55]

2.2. Heat capacity

Heat capacity (C, J.K^{-1}) is the amount of thermal energy needed to raise the temperature of a substance by 1 degree. Accordingly specific heat (c_p, J.kg^{-1}.K^{-1}) is the amount of energy needed to raise the temperature of unit mass of substance by 1 degree [42]. Many researchers calculate the specific heat of soil by summing specific capacity of each component [43].

2.3. Thermal diffusivity

In heat transfer analysis, the ratio of the thermal conductivity to the heat capacity is an important property termed the thermal diffusivity (α, m^2.s^{-1}) [42, 43]:

$$\alpha = \frac{k}{\rho c_p} = \frac{k}{C} \tag{2}$$

Where k is the thermal conductivity, ρ is the density, c_p is the specific heat and C is the heat capacity. Higher thermal diffusivity of soil means that it will react faster to thermal change in surrounding area. On the other hand soil with lower thermal diffusivity will react slowly to the temperature change and takes longer time to reach new equilibrium. Thermal diffusivity is sensitive to some soil properties such as water content, soil texture, bulk density, and organic carbon [56–58]. Thermal diffusivity parameter is considered constant during ground temperature profile modeling in [40]. Whereas it is proven in [39] and [38] that thermal diffusivity cannot be taken as a constant parameter and it is increasing with increasing in depth. This is mostly due to change in density and structure of the soil by compaction with depth. Table.1 shows the thermal properties of common components in soils [51, 59].

3. Measurement of soil thermal properties

A key challenge in problems dealing with temperature is to measure the thermal properties of the soil. Previously indicated, thermal conductivity is the most important thermal properties of soils, which dominates heat transfer. With the knowledge of thermal diffusivity and heat capacity, thermal conductivity can be calculated by Eq.2.

Different methods can be used for determination of soil thermal properties as laboratory measurement, insitu measurement and numerical modeling. Each method has its own positive and negative points comparing to other methods. Laboratory tests is a fast and economical way to get an insight of thermal properties of the soil but meanwhile several aspects cannot be accounted during the test such as effect of water movement, climate changes and etc. thermal properties of soil are changing with depth therefore a few samples may not be an accurate represented of the actual location and environment of the soil. Moreover, the effect of the disturbance of the soil during sampling could be another disadvantage. Insitu measurements is a good way to calculate soil thermal properties with respect to actual site condition and natural environment. However it might be time consuming and expensive for particular locations and high-level –technology apparatus might be required. Many researchers nowadays have been trying to calculate thermal properties of soils with experimental, empirical and mathematical modeling. Although with help of this method there is no need for small-scale or big-scale tests, a few models can be utilized for different conditions and type of soils. In addition, some of these numerical models are too complex, need lots parameters, and can be used for specific occasions.

Table 1. Thermal properties of common components in soil [51, 59]

Materials	Density (kg.m^{-3})	Heat capacity (KJ.kg^{-1}.K^{-1})	Thermal conductivity (W.m^{-1}.K^{-1})	Thermal diffusivity (m^2.s^{-1})×10^7
Air (10 °C)	1.25	1.00	0.026	0.21
Water (25 °C)	999.87	4.20	0.59	1.43
Ice (0 °C)	917	2.04	2.25	12
Quartz	2660	0.73	8.4	43.08
Granite	2750	0.89	1.70-4.00	~12
Gypsum	1000	1.09	0.51	4.7
Limestone	2300	0.90	1.26-1.33	~5
Marble	2600	0.81	2.80	13
Mica	2883	0.88	0.75	2.956
Clay	1450	0.88	1.28	10
sandstone	~2270	0.71	1.60-2.10	10-13

3.1. Laboratory tests

Two common type of laboratory test used by researchers are namely steady state methods (divided bar test) and transient method (needle probe test) (Fig.8) [43, 45, 46, 53]. Steady state methods causes a constant temperature gradient through the soil sample and the heat flux reaches a constant level while, in transient methods a radial heat flux is used and the temperature change with time through the soil sample is measured. Each method has its own advantages and simplification. A comparison of these two methods is assessed on soft Bangkok clay in [76] and the thermal conductivity changes with porosity is shown in Fig.9. Heat flux is in one-way direction in steady state method and it can be either horizontal or vertical indicated in Fig.9. As it was discussed before thermal conductivity decrease with increase in porosity and this behavior can be observed in soft Bangkok clay too. Although the needle probe test (Transient methods) shows higher value of thermal conductivity comparing to divided bar test (steady state). This behavior was observed by previous works too and it has been attributed mostly to the sample size and the difference of heat flow between these two methods [60, 61].

Dealing with more coarse materials like gravel, a new laboratory measurement was introduced recently in [62]. As indicated by the authors, previous works on measuring gravel thermal conductivity faced some difficulties regarding to the grain size and minerals variability believed to alter the results [63, 64]. A new apparatus is developed that could overcome the mentioned obstacles because of its large measuring surface and higher capacity. Fig. 10 shows the developed device and the result of measuring thermal conductivity of coarse materials.

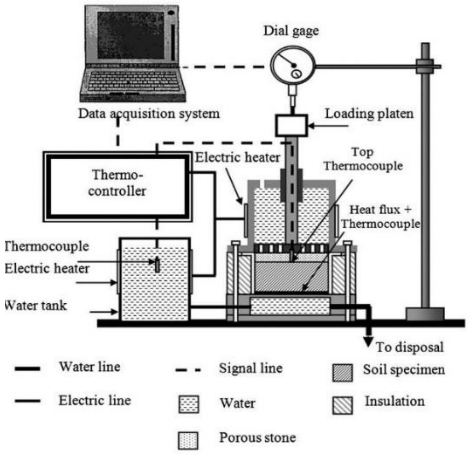
3.2. In-situ measurements

In-situ measurement could be a reliable method to evaluate thermal properties of soil and ground considering the natural environmental without disturbance of soil. Thermal response test (TRT) is one of the most common in-situ methods [30–32, 36, 65]. It was first introduced by Mogensen and was being developed in Europe and USA simultaneously in 90s. [30, 66, 67]. TRT method is based on function of a pilot GHE (ground heat exchanger) and single or double vertical U-Tube is used to circulate fluid through the ground (Fig.11). The circulating fluid is warmed up with constant rate of heating and affect the temperature of borehole and surrounding soil. This experiment is often run for 48 hours and inlet and outlet fluid temperature is being measured continuously. With some correlation methods, the thermal properties of borehole and surrounding soil such as borehole thermal resistance and soil thermal conductivity are calculated. Advantages of TRT is consideration of the natural state of the soil and the geometry of a GHE that makes it a reliable method for designing the GSHPs and geothermal structures. Whereas some limitation and simplification will lead to errors in thermal properties measurement such as water movement, inhomogeneity of soil, error in sensors, voltage fluctuation in heater and climate and air temperature effect. It is suggested that 5-50% error in thermal conductivity estimation can lead to 5-24% change in GHE length and inefficient design of geothermal structure[31, 68–71].

Jensen-Page et al. [31] studied the effect of seasonal temperature change on the TRT performance and alternation of result by seasonal temperature change was observed. They found out that TRT conduction in winter might lead to undersize design of the GHE length and oversize design by summer TRT test. They also suggested to the impact of temperature fluctuation impact on length of GHE to be greater than 10%, the TRT should be done in rather extreme condition and with length of the borehole less than 35m and this impact is important for large projects with many GHEs. On normal weather condition and climate, the impact on GHE length is expected to be less than 5%. Many modifications have been proposed by researchers to overcome the uncertainties of TRT both in the way of apparatus and result analysis.

Thermal response test usually leads to calculate the borehole thermal resistance (R_b) and effective thermal conductivity of the surrounding soil without taking into consideration different thermal properties for each soil layer. With addition of distributed temperature sensing (DTS) system, Hikari et al. [72] proposed the distributed thermal response test (DTRT) to include the change of thermal conductivity for each layer. Zhang et al. [65] studied the thermal properties of ground based on DTRT

a)



b)

Figure 8. Experimental method to measure the thermal conductivity (a) steady state (b) transients [43, 45]

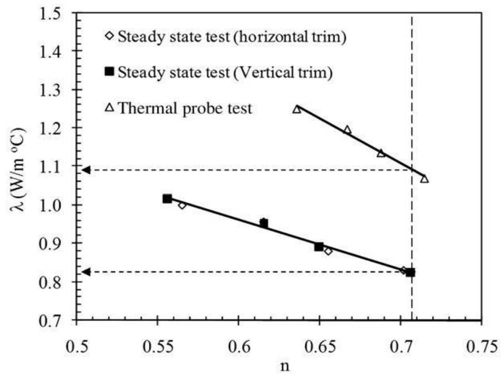
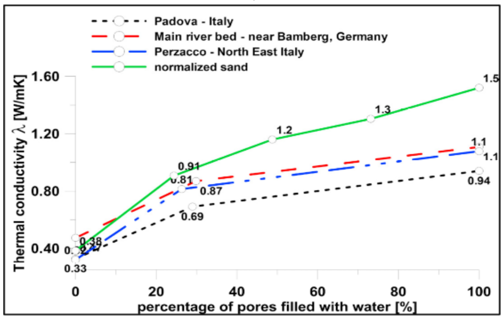


Figure 9. Comparison of thermal conductivity with steady and transient method [43]

and compared it with laboratory measurements. They investigated the differences between in-situ and laboratory result, reason of such difference and proposed a correlation for improving laboratory result. Table.2 shows the discrepancy between laboratory result and in-situ result which was attributed to factors such as water movement and permeability by authors. With proposed correlation on laboratory result, a better agreement with in-situ measurement is reached.

Although DTRT was able to measure the thermal properties of layered ground accurately, it was not able to monitor water movement and seepage. Cao et al. [30] modified the DTRT with actively optical fiber-based technology, developed for in-situ moisture measuring with interpreting the relation between temperature change and moisture, and proposed Active distributed thermal response test (A-DTRT) based on active distributed temperature sensing (A-DTS) systems to investigate the effect of moisture movement on thermal conductivity.

a)



b)

Figure 10. New laboratory test methodology for Gravel and Coarse materials (a) developed apparatus (b) experimental results [62]

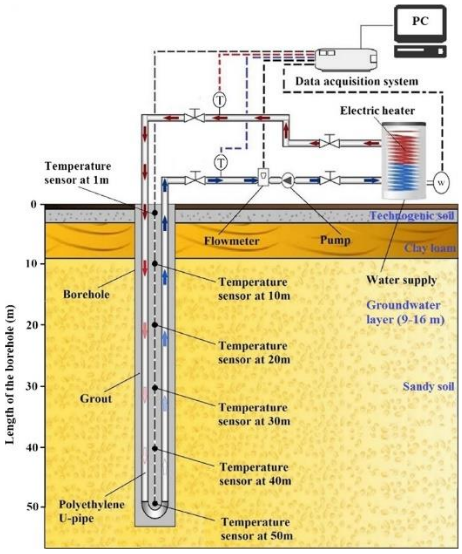


Figure 11. Schematic view of Thermal Response Test [36]

Table 2. Comparison between in-situ and laboratory of thermal conductivity (W.m^{-1}.K^{-1}) [65]

layer	In-situ	Laboratory before modification	Laboratory after modification
Grit	1.906	1.362	1.825
Silty clay	1.397	1.143	1.404
Sandstone	2.854	2.220	2.778
Mudstone	1.520	1.432	1.689

Fig.12 shows distributed thermal conductivity along the borehole length and difference between laboratory and in-situ result support the need for a correlation as proposed before in [65]. It is also observed that laboratory thermal conductivity of soil is lower than in-situ results. However, the thermal conductivity of rocks in laboratory lead to higher value comparing to in-situ results.

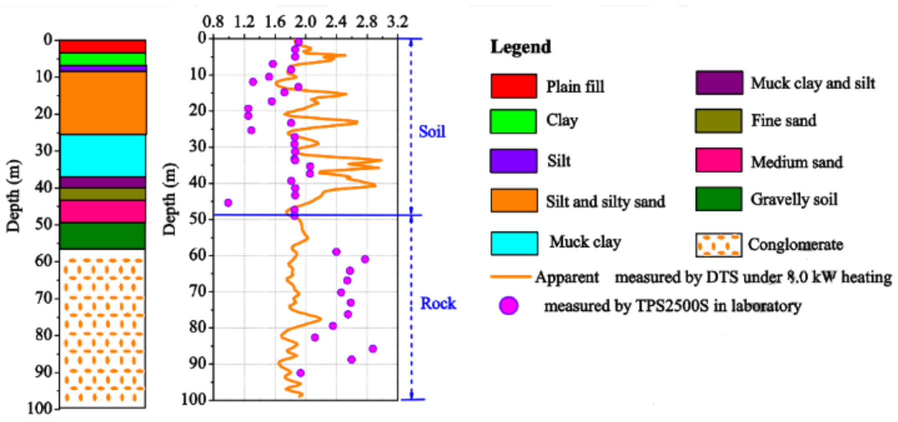


Figure 12. Thermal conductivity of layered ground [30]

Authors believed that water loss and structure change in soil sample and the existence of cracks in field rocks are the reasons for such differ ences. For the effect of moisture on the thermal conductivity result, a critical moisture (β_{cr}) was introduced. For $\beta<\beta_{cr}$ the effect of water movement on TRT results are negligible whereas for $\beta>\beta_{cr}$ the real time monitoring of water movement and possible modification of the test should be considered. Fig.13 shows the effect of seepage velocity on thermal conductivity. Increase in velocity causes the thermal conductivity in ground to increase too and when velocity increases from 0 to 1.6 the thermal conductivity will increase from 2.2 to 14.3 W.m^{-1}.K^{-1}. This suggests that area with higher seepage velocity are preferred for the location of GSHPs and GHEs.

Common models for analysis the recorded temperature with TRT to calculate thermal properties is infinite line source model (ILSM). According to the model, the BHE is considered as an infinitely long line source located in a homogeneous, isotropic and infinite medium, which regression fit to the measured data curve between mean circulating fluid temperatures is further used to determine the effective thermal conductivity of the subsurface. Then thermal diffusivity can be calculated by dividing thermal conductivity into average heat capacity of subsurface layers [36]. More advanced methods has proposed by researchers to drive thermal properties from measure temperature data. Li et al. [46] proposed a least square method based on Finite elements (FELSM) to measure thermal conductivity. They also validates the FELSM results by predicting the temperature and comparing it with laboratory temperature distribution through a sample. Fig.14 shows the high accuracy on the proposed method.

Akhmetov et al. [36] integrated borehole temperature relaxation method (BTR) into conventional TRT. They found out the depth average thermal conductivity based on BTR method is about 0.45 W.m^{-1}.K^{-1} which is almost 3 times lower that thermal conductivity based on LSM (1.56 W.m^{-1}.K^{-1}). This was attributed by the authors to heat convective loss to the ground surface at depth 9-16m that was not considered in LSM method. BTR could also show the depth dependency of thermal conductivity.

Other techniques has also been introduced by researcher for in-situ measurement of thermal properties of the soil. Zhang et al. [49] integrated dual-probe heat pulse (DPHP) device with time domain reflectometry (TDR) technique and proposed thermo-TDR for measuring thermal properties and soil moisture of four different sands at the same time. The compared the result with three model predictions for thermal conductivity and Fig.15 shows the good agreement between models

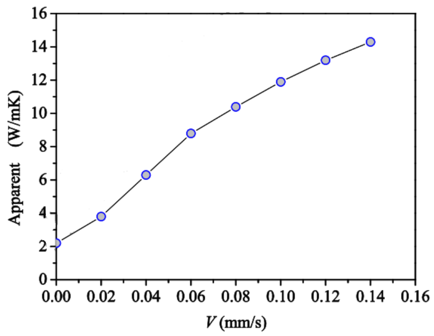


Figure 13. Effect of seepage velocity on apparent thermal conductivity derived by in-situ TRT test [30]

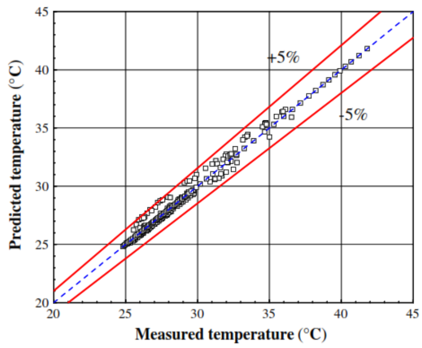


Figure 14. Measured temperature data Vs predicted temperature by FELSM [64]

prediction and in-situ measurements. Schematic view of thermos-TDR is shown in Fig.16.

Lines et al. [32] integrated a soil moisture probe into cone penetration test with pore pressure measurement (CPTu) and proposed a newly-developed thermal cone dissipation test (TCT) to measure soil thermal conductivity of different layers. The function of this test is based on the temperature rise on the cone cause by the friction and measuring the heat dissipation over the time of stopping. They conducted three tests on different kind of soil such as soft clay and stiff sandy clay. It was concluded

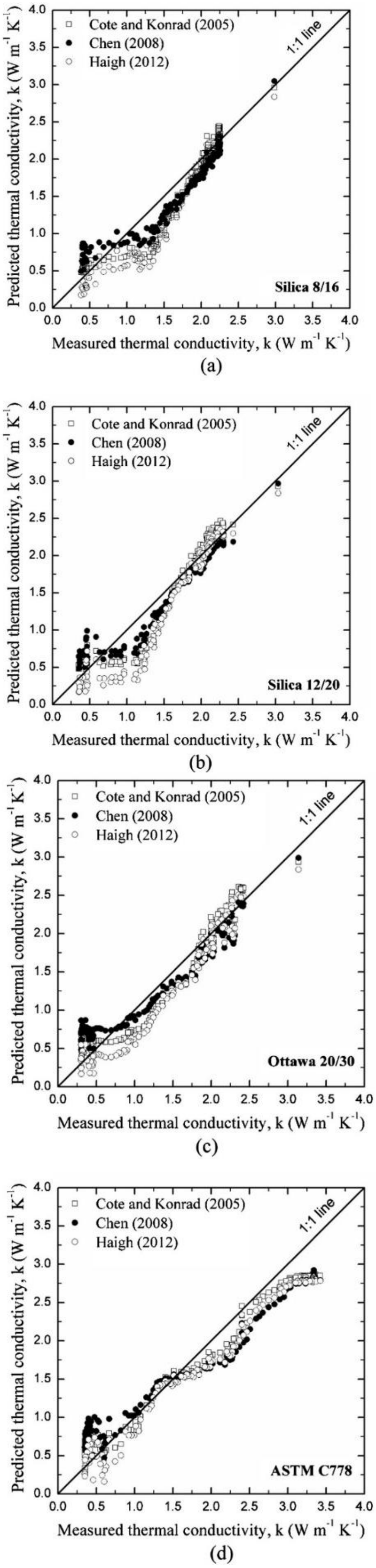


Figure 15. Comparison of thermal conductivity of four different sand by model prediction and thermos-TDR [36]

that TCT is a promising, fast and economical solution to estimate the thermal properties of the soil since CPTu is very common geotechnical test, although there is some limitation with the proposed test like there was not enough temperature rise in soft clay to measure the thermal properties. Authors suggested that further studies were needed to be done to improve the device and test procedure to make it as reliable, fast and economical apparatus.

3.3. Prediction models

Laboratory and in-situ tests might be time consuming, rather expensive in some situation and not applicable in all conditions. Therefore, researchers have been trying to develop theoretical and empirical models based on the in-situ and laboratory measurements to estimate thermal properties of soils. Al Hinti et al. [39] developed a mathematical model to predict the ground temperature profile and thermal diffusivity based on the one-dimensional transient heat conduction equation in a semi-infinite field having constant thermal properties and a sinusoidal temperature prediction model derived by Hillel [73].

$$T(z,t) = T_m + \Delta T_{corr} + A_\circ e^{-\gamma z} sin(he(t-D)) \quad (3)$$

Where T_m is the mean ground surface temperature (C), z is the depth below the ground surface (cm), t is the time (day), P is the duration of one full annual cycle (365 days), A_o is the amplitude of the annual cycle of the ground surface temperature, and D is the phase shift between the ground temperature cycle at a given depth and the ground surface temperature cycle (days). ΔT_{corr} is introduced to allow for the adjustment of the model. By fitting a curve to in-situ measured ground temperature data for different depth, using least square method, Parameters D and γ was obtained (Fig.17). Parameter γ was later used to calculate thermal diffusivity based on the following equation:

$$\gamma = \sqrt{\frac{\pi}{\alpha P}} \quad (4)$$

where P is the period of the oscillation (days) and α is the thermal diffusivity of the soil (cm^2/days). Thermal diffusivity was calculated as 9.7, 11, 9.2, 17, 19, and 22 $cm^2.h^{-1}$ at depth of 50, 100, 200, 500, 800, and 1000 cm respectively. It is concluded from result that thermal diffusivity is depth dependent proving previously mentioned in this paper.

Seward and Prieto [38] used similar method of curve fitting to in-situ measured ground temperature data by the following equation:

$$\theta_z = \theta_0 + \theta_A sin(\phi) \quad (5)$$

An average steady state temperature (θ_0), a maximum temperature variation amplitude (θ_A) and a time delay phase (ϕ) is determined at different depths. These results are used to calculate the apparent thermal diffusivity using differences in the phase (ϕ) and amplitude (θ_A) at different depths:

$$\alpha_\phi = \left(\frac{\omega}{2}\right)(z_2 - z_1)^2 \left(\frac{1}{(\phi(z_1) - \phi(z_2))}\right)^2 \quad (6)$$

$$\alpha_A = \left(\frac{\omega}{2}\right)\left(\frac{z_2 - z_1}{ln\left(\frac{|\theta_A(\omega,z_1)|}{|\theta_A(\omega,z_2)|}\right)}\right)^2 \quad (7)$$

where z_1 and z_2 are the selected depths, ω is the angular frequency given by $2\pi/T$ and T=365.25 days. Table.3 shows the result for modeled apparent and experimental measurement of thermal diffusivity. As it can be seen the calculated thermal diffusivity is in good agreement with the experimental data but the apparent thermal diffusivity

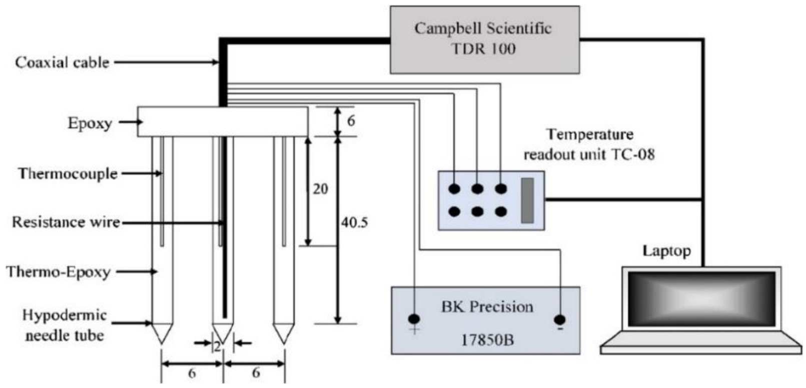


Figure 16. Thermo-TDR device [49]

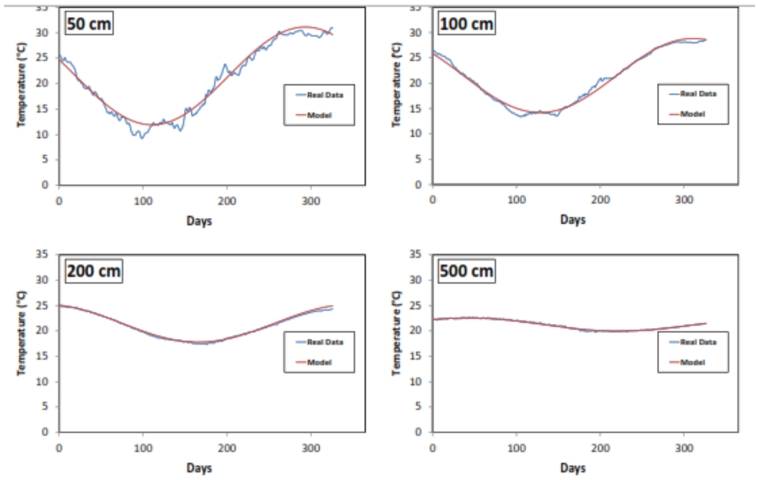


Figure 17. Comparison between prediction model and in-situ measurement of ground temperature at different depth [39]

Table 3. Experimental and predicted thermal diffusivity [38]

Depth(m)	Soil type	Thermal diffusivity ($\times 10^{-7}$ m²/s)		
		In-situ(α_A)	In-situ(α_ϕ)	lab
0.1-1.0	Top soil/clay	3.39	4.41	3.78
1.0-3.0	Sand-grit clay	6.75	6.31	4.10
3.0-6.0	Clay with sand and pebbles	7.78	5.82	6.67
6.0-9.0	Clay with large stones	9.92	10.6	7.95

calculated based on the maximum temperature amplitude are closer to the experimental data and it was related by authors to the bigger effect of inhomogeneity in the soil on phase lag over depth than temperatures. Thermal diffusivities increased with depth, as it was observed in previous mentioned study, suggesting that the ground at depth has a greater capability for rapid changes in temperature. Authors believed this is likely due to increased saturation levels and compaction of material at depth, allowing heat to be transferred quickly. As it was discussed in section 3.2, one the limitation of in-situ measurement techniques such as TRT is no considering the effect of different layers which was proven in [38, 39] that neglecting this issue can alter the results significantly.

Many researchers have been trying to develop mathematical models to predict thermal properties of soil during past years. Wiener [74] theoretically proposed upper and lower limit of thermal conductivity. Maximum and minimum values of thermal conductivity occurs when the heat flow is parallel and perpendicular to components respectively. These values are also called Wiener boundary and calculated as follow:

$$k = k_w^L = \left[\sum \frac{\emptyset_\alpha}{k_\alpha}\right]^{-1} \quad \text{(Lower limit)} \qquad (8)$$

$$k = k_w^U = \sum \emptyset_\alpha k_\alpha \quad \text{(Upper limit)} \qquad (9)$$

Where ϕ_α and k_α are the volume fraction and thermal conductivity of each phase (solid, liquid and gas), respectively. De Vires [75] introduced another theoretical formula for thermal conductivity based on uniform distribution of solid particles in continuous porous medium as follow :

$$k = \frac{\sum_{i=0}^{N} K_i \chi_i k_i}{\sum_{i=0}^{N} K_i \chi_i} \qquad (10)$$

Where k_i is the thermal conductivity of each soil constituent, χ_i is the volume fraction of each component and K_i is the ratio of average thermal gradient of each component to that of continuous medium in soils. De Vires proposed following equation for K_i considering particle size and shape:

$$K_i = \frac{1}{3} \sum_{a,b,c} \left[1 + \left(\frac{k_i}{k_0} - 1\right) g_a\right]^{-1} \qquad (11)$$

Where g_a, g_b and g_c are the grain shape coefficients, and usually taken as 1/3 for spherical soil particles and k_i/k_0 is the ratio of thermal conductivity of one soil constituent to that of continuous medium in soils. Disadvantages of de Vires model is that determination of parameter K_i is somewhat difficult since it is affected by many factors. This model consider the air and water distributed uniformly through the medium that might affect the result too. Some modification based on these early studied have also been published. Tong et al. [76] proposed a new model to predict thermal conductivity of soil based on Wiener model [74]. Advantage of this model is that many influencing factors such as water content, porosity, degree of saturation, temperature and pressure are considered:

$$k = \eta_1(1-\phi)k_s + (1-\eta_2)[1-\eta_2(1-\phi)]^2 \times \left[\frac{(1-\emptyset)(1-\eta_1)}{k_s} + \frac{\phi S_r}{k_w} + \frac{\phi(1-S_r)}{k_g}\right]^{-1} \times \eta_2\left[(1-\phi)(1-\eta_1)k_s + \phi S_r k_w + \phi(1-S_r)k_g\right] \quad (12)$$

Where k_s, k_w and k_g are the thermal conductivities of solid, water and gas, respectively, ϕ is the porosity; η_1 is the parameter related to porosity, $0 < \eta_1(\phi) < 1$; η_2 is parameter related to porosity, degree of saturation and temperature, $0 < \eta_2(\phi,S_r,T) < 1$. As it was discussed in section 3.2, simplification and alternation in soil structure and environment could cause some discrepancy between laboratory test and in-situ measurement for soil thermal properties. So it is beneficial to consider influencing factors as much as it is possible. Beside the advantages of this model, it is more complex comparing to previous model and determination of parameters η_1 and η_2 should be attended carefully. A recent theoretical model for sand is proposed by Haigh [77] which consider the interaction between the solid, liquid and gas during the heat conduction and gives much better result comparing to previous models. The formulation is as follow:

$$\frac{k}{k_s} = 2(1+\xi)^2\left\{\frac{\alpha_w}{(1-\alpha_w)^2} ln\left[\frac{(1+\xi)+(\alpha_w-1)\chi}{\xi+\alpha_w}\right] + \frac{\alpha_a}{(1-\alpha_a)^2} ln\left[\frac{(1+\xi}{(1+\xi)+(\alpha_a-1)\chi}\right]\right\} + \frac{2(1+\xi)}{(1-\alpha_w)(1-\alpha_a)}[(\alpha_w - \alpha_a)\chi - (1-\alpha_a)\alpha_w] \quad (13)$$

where k and k_s are the thermal conductivities of soil and solid, $\alpha_w=k_w/k_s$ is the ratio of thermal conductivity of water to thermal conductivity of soils, $\alpha_a=k_a/k_s$ is the ratio of thermal conductivity of gas to thermal conductivity of soils, ξ and χ are parameters related to the water film and degree of saturation respectively. Complexity of determination for parameter ξ and χ is disadvantages of this model comparing to the early simpler ones. These models are based on theoretical assumption of porous medium however empirical fit to experimental measurements are quite common methods to develop models to predict thermal properties of soil. Kersten [78] proposed and early simple model for soil thermal conductivity considering water content and dry density with experimental measurement on 19 samples including gravels and sands, sandy soils and clayey soils, mineral soils and crushed stones and organic soil :

$$k = 0.1442[0.9\log w - 0.2] \times 10^{0.6243\gamma_d} \quad (14)$$

(Silt and clay)

$$k = 0.1442[0.7\log w + 0.4] \times 10^{0.6243\gamma_d} \quad (15)$$

(Sandy soils)

where k is the thermal conductivity of soils, W.m^{-1}.K^{-1}; w is the moisture content of soils, %; and γ_d is the dry density of soils, lb/ft^3. Johansen [79] developed kersten model [78] and introduced normalized thermal conductivity for the first time as follow :

$$k_r = \frac{k-k_{dry}}{k_{sat}-k_{dry}} \quad (16)$$

Where k_{sat} and k_{dry} are the soil thermal conductivities under fully saturation and dry condition respectively. Thermal conductivity of soil can be calculated by knowing k_{sat} and k_{dry} with the help of new k_r, which is also called Kersten number. For determination of k_{sat} , Sass et al. [80] proposed a simple formula which is widely being used by researchers :

$$k_{sat} = k_s^{1-n}k_w^n \quad (17)$$

Where k_{sat}, k_s *and* k_w are saturated, solid particles and water thermal conductivity respectively. Porosity, n, can be calculated as follow:

$$n = 1 - \frac{\rho_d}{d_s\rho_w} \quad (18)$$

Where ρ_d and ρ_w are soil dry density and density of water respectively and d_s is relative density of solids particles. k_w is about 0.6 W.m^{-1}.K^{-1} at room temperature. If the mineral component of soil are, know the thermal conductivity of solid particles can be calculated as follow:

$$k_s = \prod_j k_{m_j}^{\chi_j}$$
$$\sum_j \chi_j = 1 \quad (19)$$

Soils are often consist of several types of minerals that might make it difficult to calculate the thermal conductivity of solid particles. As it was discussed previously in this paper, Quartz has the most important effect on thermal conductivity among other minerals. Therefore Johansen [79] proposed a simplified model to calculate k_s based on the Quartz content of soil :

$$k_s = k_q^q k_0^{1-q} \quad (20)$$

Where k_q, k_0 and q are thermal conductivity of Quartz, average thermal conductivity of other minerals and volume fraction of quartz respectively. Eq.20 also could be simplified as follow:

$$k_s = \begin{cases} 2^{1-q} \times 7.7^q, & q > 0.2 \\ 3^{1-q} \times 7.7^q, & q \leq 0.2 \end{cases} \quad (21)$$

Johansen [79] also modified de Vires model [75] to calculate thermal conductivity of dry soil :

$$k_{dry} = \frac{0.137\rho_d+64.7}{2650-0.947\rho_d} \quad (22)$$

After determination of k_{sat} and k_{dry} the only remaining parameter is k_r. by fitting experimental data Johansen [79] also proposed some equation to calculate normalized thermal conductivity (Kersten number) based on degree of saturation (S_r) :

$$k_r = \begin{cases} 0.7\log(s_r) + 1 & for\ median\ and\ fine\ sand \\ \log(s_r) + 1 & for\ fine\ soils \\ 0.54s_r^2 + 0.46s_r & for\ peat \end{cases} \quad (23)$$

Comparing to Kersten model [78] which was very simple rather low in accuracy, Johansen model [79] gave a better result and it has been the base for many other models afterwards. Cote and Konrad [81] proposed a new relationship for k_r considering the effect of soil type by using parameter κ :

$$k_r = \frac{\kappa S_r}{1+(\kappa-1)S_r} \quad (24)$$

A new equation for thermal conductivity of dry soil was proposed based on the porosity:

$$k_{dry} = \chi 10^{-\eta n} \quad (25)$$

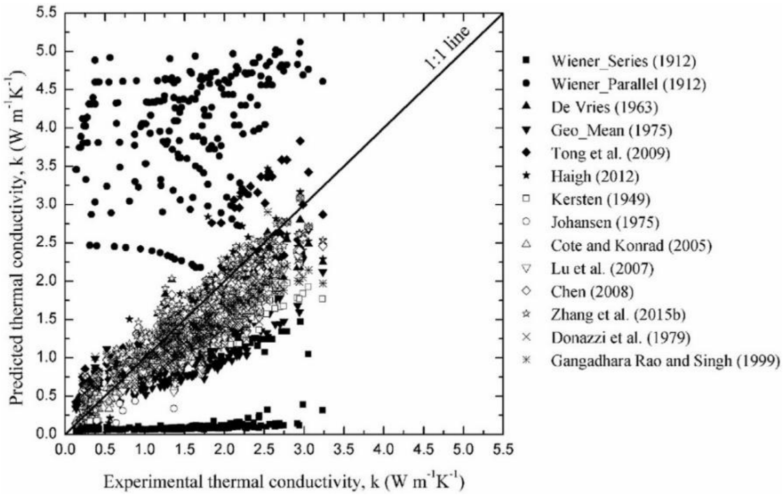


Figure 18. Performance of thermal conductivity prediction model and experimental data [51]

Where χ and η are parameter related to effect of soil type and grain shape respectively. Table 4 shows the value of parameter κ, χ and η for different type of soils.

Another modification of Johansen model [79] is done by Balland and Arp [82]. They proposed a new equation for thermal conductivity of solids considering the effect of organic matter:

$$k_s = k_{om}^{V_{om}} k_q^q k_0^{1-q-V_{om}} \tag{26}$$

Where k_{om} and V_{om} are thermal conductivity and volume fraction of organic matter respectively. They also proposed following equation for the dry and normalized thermal conductivity:

$$k_{dry} = \frac{(ak_s - k_a)\rho_d + k_a G_s}{G_s - (1-a)\rho_d} \tag{27}$$

$$k_r = S_r^{0.5(1+V_{om}-\alpha V_{sand}-V_s}\left[\left(\frac{1}{1+\exp(-\beta S_r}\right)^3 - \left(\frac{1-S_r}{2}\right)^3\right]^{1-V_{om}}$$

Where k_a is thermal conductivity of air, a is constant (~0.053), G_s is specific density, α and β are coordination coefficient and V_{sand} and V_c are volume fraction of sand and coarse material respectively. Lu et al. [83] Conducted laboratory test using Thermo-TDR probe and proposed following equation by empirical fit to the data:

$$k = [k_w^n k_s^{1-n} - (b - an)] \times [\alpha(1 - S_r^{\alpha-1.33})] \tag{28}$$

a and b are parameter considering the thermal conductivity of dry soil and α is parameter accounting for effect of soil type on normalized conductivity. a and b are suggested to be taken as 0.56 and 0.51 respectively. For parameter α, 0.96 and 0.27 are suggested for coarse and fine materials.

Chen et al. [84] proposed simple equation to estimate thermal conductivity of quartz sand using thermal probe in laboratory :

$$k = k_w^n k_s^{1-n}[(1-b)S_r + b]^{cn} \tag{29}$$

Where b and c are fitting parameter and value of 0.0022 and 0.78 are suggested for quartz sand respectively. The accuracy of model is high for sand since it is based on empirical fit to laboratory tests on quartz sand. Most recently Zhang et al. [49] measured thermal conductivity of sands using Thermo-TDR probe and modified the Cote and Conrad model [81]. The model is simple similar to Chen et al model [84] however the accuracy is even higher. The comparison of modified Cote and Conrad model performance with measured experimental data and Chen et al [84] and Haigh [77] is shown in Fig.15.

Table 4. Value of cote and Conrad parameters [81]

Soil type	parameter		
	κ	χ	η
Well-graded gravels and coarse sands	4.60	1.70	1.80
Medium and fine sands	3.55	1.70	1.80
Silts and clays	1.90	0.75	1.20
Peat	0.60	0.3	0.87

Table 5. Suggested value for *b* [55]

Soil type	Parameter b
Silt	-0.54
Silty sand	0.12
Fine sand	0.70
Coarse sand	0.73

Mixed model using both empirical and theoretical approaches are proposed as well. Donazzi et al. [85] proposed following equation for thermal conductivity prediction:

$$k = k_w^n k_s^{1-n}\, exp[-3.08n(1-S_r)^2] \tag{30}$$

Midttomme [86] developed another model considering the effect of particle size (d_m) as follow :

$$k = 0.215 \times \log(d_m) + 1.93 \tag{31}$$

Gangadhara Rao and Singh [55] proposed a model considering dry density and moisture content using needle probe test in laboratory :

$$k = 10^{0.01\gamma_d - 1}(1.07 \log w + b) \tag{32}$$

Parameter b is to consider soil type and table.5 shows the suggested values proposed by the authors.

Comparison between different prediction models and experimental data in literature on thermal conductivity of sand is studied in [51]. As it can be observed in Fig.18 most of the model predicted values are less than experimental measurement because they do not usually take into account the effect of quartz. Table.6 also show a comparison between different model [51]. Most of the prediction model could give good result in sand and coarse material and usually underestimate the thermal

Table 6. Comparison between different prediction model for thermal conductivity [51]

model	Advantage	disadvantage	Applica-bility
wiener	Quantification of two limit thermal conductivity	Not applicable to soils	Porous
De Vires	High prediction accuracy	Complex formula, difficult to determine parameters	All
Tong et al.	Considering many influence factors comprehensively	Complex formula, difficult to determine parameters	Porous medium
Haigh	Simple formula and high prediction accuracy	Limited applicability	sands
Kersten	Simple formula	Neglect of quartz content effect	All
Johansen	Normalized thermal conductivity concept and relatively high prediction accuracy	Unknown effect of soil type on k_r-S_r relationship	All
Cote and Conrad	Considering effect of soil type on k_r-S_r relationship	Unknown sensitivity of κ to soil type	All
Balland and Arp	Considering effect of organic content	Neglect of quartz content in solid phase	All
Lu et al.	Simple formula	Unknown effect of soil type on thermal conductivity of dry soils	All
Chen	High prediction accuracy for sands with relatively high quartz content	Not applicable to other soil types	sands
Zhang et al.	Very high prediction accuracy for quartz sands	Not applicable to other soil types	Quartz sands
Donazzi et al.	Simple formula	Low prediction accuracy at low saturation	All
Gangadhara and singh	Simple formula	Low prediction accuracy at high saturation	All
Midttomme et al.	Simple formula	Only considering particle size effect	Quartz sands

conductivity in fine materials. This well proved in study of T.Zhang et al. [48]. A review on thermal conductivity calculation procedure is proposed based on the normalized thermal conductivity (k_r) concept (Fig.19). the result of proposed method is evaluated against prediction model in two location Ninjang, China [52] and India [55]. As Fig.21 shows, there is good agreement between calculated and predicted results for coarse materials however; the models underestimate the thermal conductivity for fine-grained soils. These behaviors was attributed to unknown mineralogy of fine soils, which is usually required complex experiments. On the other hand a good linear relationship between predicted and calculated result for fine grained soil is seen therefore a correlation coefficient for empirical parameters was proposed by the authors as 1.736 and 2.415 for Ninjang and India areas respectively. Fig.23 shows the comparison of result after modification of empirical parameters for fine materials and a good agreement is established. This method can help geotechnical engineers to estimate thermal conductivity of soils and avoid mineralogy tests.

4. Conclusion

The importance of temperature change and its effect on soil properties and behavior were brought up earlier in this paper followed by some examples of geotechnical application dealing with temperature change. Thus, it is of high importance to have clear understanding about temperature change and its possible effects on different aspects of geotechnical designs. In order to do so, the first important step is to measure and interpret the thermal properties of soils which is believed to have great effect on response of the soil to temperature change.

Different factors influencing thermal properties of the soil were investigated by authors. It can be concluded that water content and volume fraction of Quartz are the most important and dominating ones. Quartz has the highest thermal conductivity among other common soil minerals and water has the higher thermal conductivity comparing to other phases in soils (solid particles and air). Therefore, they have great effect on the overall thermal conductivity of the soil. Since the heat transfer in soil is governed by conduction, physical contact between particles can affect the thermal conductivity too.

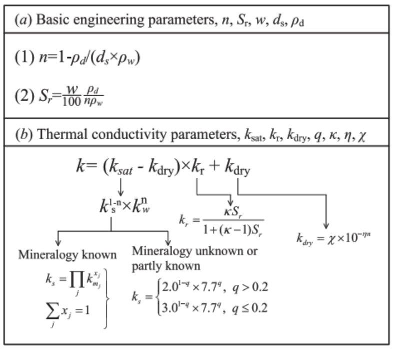


Figure 19. steps methods proposed in [48]

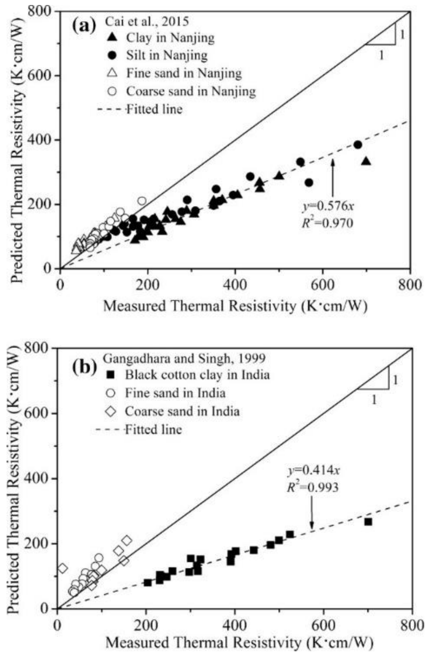


Figure 20. Comparison of calculated and predicted thermal conductivity before modification [48]

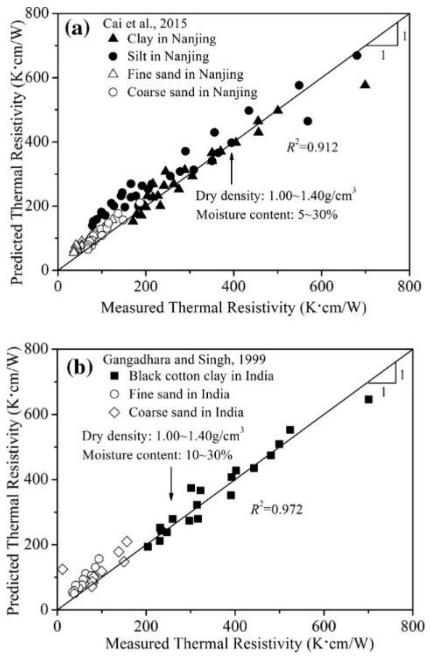


Figure 21. Comparison of calculated and predicted thermal conductivity after modification [48]

Increase in properties like density, compaction and particle size can increase the thermal conductivity by increasing the physical contact between the particles. Increase in water content and degree of saturation can increase the physical contact between particles too, especially in fine grain soils, by creating a water layer around the solid particles (e.g. double layer in clayey soils). It is essential to pay closer attention to water content during measurement of thermal conductivity since its variation can greatly alter the thermal conductivity in different ways.

Various methods have been used by researchers to measure the thermal properties of the soil as laboratory test, in-situ measurement and prediction models. Advantages and disadvantages of these methods were investigated and the following worth to be mentioned. Laboratory tests offers quick, easy to perform and somewhat economical options to measure thermal conductivity. However they are usually consider some simplifying assumptions and therefore might not represent the actual condition. Disturbance of the samples and removal from the site might alter the structure of the soil and hence lead to different results. As it was mentioned previously in the paper, thermal properties could not be considered as a constant parameters and could vary especially through the depth because of the inhomogeneity in the ground and small scale laboratory sample might not be a very good represented of the actual ground. It is suggested to pay attention to water content change during laboratory test carefully as well as inhomogeneity of the soil to have a closer result to real conditions. Therefore for future research, for example focusing on some correlation parameters on experimental results to take these variations in water content and layers of the soil into consideration could be a good method to overcome the disadvantages of laboratory tests.

On the other hand, in-situ measurements offer reliable method in terms of considering the actual site condition and the effect of surrounding environment on the results. TRT is a known and popular in-situ test to measure thermal properties of the soil which works on the basis of simulating a real sized GHE function. Important obstacles in this test were again lack of attention toward water content and movement as well as considering the properties of different layers since the TRT test gives an average value of thermal conductivity of the measured depth of the ground. Nevertheless, noticeable improvement have been done to overcome these mentioned obstacles and disadvantages with modification of TRT apparatus with some new technology to measure the water movement effect on the results and thermal properties for different layers.

Several prediction models based on mathematical, empirical and theoretical basis have been proposed by researchers during past years and modification of early models are still being done by new studies. Early models usually are applicable for various conditions and material although the accuracy is rather low. The new models are showing considerable improvement in accuracy but they are usually not generally applicable and are suitable for one or two specific kind of soils and conditions. Most of the predictions models show good accuracy for sandy soils since the early studies and models were mainly based on sands and Quartz while as it was discussed in paper, a discrepancy is observed between the experimental results and predicted ones by proposed models for fine grained soils. This discrepancy in results is suggested to be attributed to the more complex structure of clayey soils and the role of the water content in forming the bonds between particles which could greatly influence the thermal properties. This mentioned role of water content is less visible in coarse material therefore a better agreement between experimental results and predicted ones are seen for sandy soils. For future research, concentrating on the microstructure of clayey soils seems essential to be able to modify the existing models or proposing new models to improve the accuracy.

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