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An improved steady-state apparatus for measuring thermal conductivity of soils

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ABSTRACT

The thermal conductivity of soil is among the most critical parameters required to design ground heat exchangers, which are widely used as a renewable technology for providing heating and cooling for buildings. This paper describes the development of new test apparatus that can be used for soil specimens obtained from routine site investigation as well as reconstituted specimens. The design of the apparatus is based on the application of Fourier's law where one directional uniform heat flux is generated through two identical specimens, producing a measurable temperature gradient that is used to calculate the thermal conductivity of the specimen. A new concept of minimizing the radial heat losses using a thermal jacket as a heat insulation barrier was examined. It was found that the no-radial heat losses condition can be achieved with thermal jacket temperature approximately equal to the average value of the ambient temperature and average specimen temperature. All parameters that can affect the measurements have been tested and the results showed a good performance with margin of error upto 5%. An application of the new test procedures involved conducting several experimental tests on undisturbed and reconstituted soil samples highlighted the simplicity of this apparatus in measuring thermal conductivity of soil under different conditions.

1. Introduction

Increasing demand for energy and the requirement to reduce emissions of CO_2 to fight global warming has led to great emphasis on energy conservation. Recently, a major development in geothermal energy has been the use of the heat stored in ground as a source of heat power. Heat flow through soils and related materials, including underground construction materials such as grouts, is of great interest in many engineering applications which involve thermal effects, such as energy foundations, vertical and horizontal ground heat exchangers, oil and gas piping, ground improvement, and radioactive waste repositories [1–3]. Ground-coupled heating–cooling systems (GCHCs) make use of the ground as a heat source in winter and a heat sink in summer, to provide heating and cooling for buildings. These systems have been recognized as being among the most energy efficient and sustainable systems for space heating and cooling in residential and commercial buildings [4,5]. This technology has started to spread worldwide, as it is clean and renewable, with annual growth of 7.5% [6]. The efficiency of the system depends entirely on the thermal properties of the soils consisting the ground layers. Thermal conductivity is considered as the most important character in controlling the heat flow through the soils [7]. The thermal conductivity of the underground is often estimated by performing a thermal response test (TRT) which has become more popular in measuring in situ thermal properties [8]. In addition of high cost and long duration, the thermal response test can only provide the average values of the thermal properties of the underground soil profile.

No standard steady state laboratory tests to measure thermal conductivity of soils have been proposed previously [9,10] though a few standard tests exist to determine this property for building materials, such as those in construction standards [11–15]. Laboratory techniques used to measure thermal conductivity of soils can be classified into two main categories. The first includes steady state methods in which the heat flow through the soil specimen reaches a constant level. The second includes unsteady methods which measure the thermal conductivity during a transient state. It should be noted that transient state procedures are simpler, but the steady state methods are considered more accurate. Among several steady state methods, the guarded hot plate (GHP) is considered as the most accurate and precise technique for thermal conductivity measurements [16]. The needle probe equipment is

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the only standardized transient method in measuring thermal conductivity of soils [17]. It should be noted that, different results has been obtained using steady and unsteady state methods when they are used to measure the thermal conductivity of soils. The mechanism of the heat transfer through the sample and the anisotropic structure of soil grains, which is generally observed for fine-grained sediments, might be the main sources of the observed discrepancies. In some studies, the deviation reached 50% between the needle probe and divided bar method although the average discrepancy between the two methods is in the range 10–20% [2,9,18]. Furthermore, when some national measurement organizations carried out a measurement program of some available reference materials to be used internationally, the results show that there is laboratory-to-laboratory difference for each material [19]. Therefore, the performance of any apparatus used to estimate the thermal conductivity of soils under steady state methods can be evaluated by the accuracy of controlling the boundary conditions to ensure that the parameters used in calculations are realistic. For this reasons any results obtained using steady state methods is likely to have different values when compared with documented results. In all methods, measurements of the temperature drop across the specimen and the heat flux are required to determine the thermal conductivity [20]. Existing test methods originally were developed for structural and insulation materials where large, homogenous, specimens can be used, and these are difficult to obtain from routine soil investigations. Consequently, various configurations of equipment have been established to measure the thermal conductivity of different soils at different conditions [21–24]. The efficiency of each apparatus is entirely dependent on the accurate estimation of the heat flux passing through the specimen, and is mainly limited by the amount of the radial losses along the specimen length. Ambient temperature interference (ATI) is the main factor that has a significant influence on the laboratory studies aimed at one-dimensional heat flow [25]. Zhou et al. [26] have used a buffer of the same soil material to develop a soil cell with limited radial loses. The most recent device was designed by Hamuda [10] in which the two identical specimens are sandwiched between a central heater and two sink discs. However, the radial heat loss was not adequately controlled, due to high radiative loss through the vacuum insulation and due to relatively large contact area between the heater disc and the ambient temperature. This paper describes the development of a new thermal conductivity measurement apparatus that can offer a high level of control of boundary conditions and that can be used for testing of undisturbed and reconstituted soil specimens of different types of soil [27].

2. The new thermal cell

The function of the new thermal cell is to measure the thermal conductivity of laboratory prepared soil specimens as well as samples obtained from routine ground investigations (typically U_{100} samples). Also, the cell is designed to be able to operate over a temperature range that covers the natural ground temperature, using a simple procedure that can cover a wide range of soil types under different conditions.

2.1. Basic design principals

The design is based on the application of Fourier's law of one-dimensional heat conduction under steady state condition. From the definition of the one dimensional steady state, it is assumed that the heat flow is considered to be in one direction, which means that no lateral heat transfer occurs within the specimen. Practically, it is difficult to achieve this condition because of the ambient temperature interference (ATI) which produces additional radial temperature distribution to the desired axial temperature gradient [26]. It is essential to consider the effect of the ambient temperature on longitudinal and radial heat flow. The common method to minimize the effect of ambient temperature is to use an insulation layer, keeping the ambient temperature constant and controlling the temperature of sink disk. There are three options for the sink temperature. The first is to keep the sink temperature higher than the ambient temperature, which will produce a contrived heat flow from the sink into the specimen. The second option is to keep the sink temperature below the ambient temperature. This will make the outer portion of the specimen cooler which may give more chance of heat to inject radially into the specimen. The third (and the best) option is to keep the sink temperature near the ambient temperature; however the radial loses will be linked to the efficiency of the insulation. In fact, to establish unidirectional heat flow, it is required to have a mechanism that separates and controls the two kinds of the heat flow (longitudinal and radial heat flow). In order to minimize the effect of ATI and to maximise heat flow in one direction, our apparatus is designed to control the radial heat flow by constructing a new layer with adjustable temperature (thermal jacket) and to keep the temperature of the sink disc near ambient temperature. The level of the thermal jacket temperature will control the amount and the direction of the radial heat flow along the specimen length. As the temperature of the thermal jacket is kept below the minimum specimen temperature, heat will flow from the specimen to the ambient. The amount of this heat depends on the difference in temperature between the specimen and the ambient. On the other hand, heat will flow from the thermal jacket into the specimen as the thermal jacket temperature is kept higher than a certain level of temperature. This means that there is a place where there is no radial flow. Since the ambient temperature is lower than the thermal jacket temperature, the heat generated by the thermal jacket will flow from the jacket to the ambient not into the specimen. The idea is just to keep the temperature of the thermal jacket at the desired level and so that it loses its heat to the ambient. Another source of heat leakage that in some designs can negatively contribute to the measurement is the base heat loss. To eliminate the effect of the base heat loss, in the equipment reported here the heater is inserted between two identical specimens. Consequently, the input power used in the calculations is divided by two. However, in this case the symmetry of the specimens and the apparatus itself are influential. Also, the heat flux, which is defined as the amount of the heat that passes through a unit cross-sectional area, should be uniform across the specimen. To achieve this, the heater and sink discs must be as flat as possible and made of highly conducting and emissive material. It is important at this point to highlight the effect of the contact resistance which is defined as the resistance to heat transfer at an interface between adjoining objects of different shapes or roughness due to poor physical contact, on the estimation of heat flux using heat flux meters. The poor contact between the soil and heat flux meters, in some thermal cell configurations, can cause an underestimate of the heat flux by a significant value. For example, if there is an air gap of 5% of the thickness of the plate, this would lead to an underestimate of the heat flux of upto 54% [28]. In the new thermal cell, the heat flux is directly determined from the heat power input and all temperatures used in the calculation of the thermal conductivity are measured within the length of the specimen, which means that any concern of the contact thermal resistance is not relevant. The number, positions and the directions of the measuring thermocouples are also very important, because the thermal conductivity of the thermocouple material is very high compared with the soil. This may cause unpredictable heat flow through the thermocouples if not appropriately considered. Finally, as the diameter of