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A novel experimental technique to evaluate soil thermal conductivity in a transient state

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As a result of climate change, heat island effects, and an increase in geothermal applications, soil deposits are being subjected to increasingly variable thermal stress, resulting in changes in soil properties and behaviour. Analysing the variations in soil behaviour caused by thermal loads is crucial due to the substantial impact these changes have on the state of soil stress. A critical step towards this goal is to thoroughly understand the heat transmission process in a soil deposit. Thermal loads are transported to the soil primarily by heat conduction and convection. When there is no water seepage, heat transmission is dominated by conduction [1]. The heat conduction is governed by the soil thermal conductivity, *k*, which is affected by the thermal conductivities of the soil components (*i.e.*, air, water, and solid particles) [2], as well as other physical parameters such as moisture content and density [1, 2]. Investigating the thermal conductivity in different soils has resulted in the development of various predictive models, including theoretical, empirical, and mathematical models [4]. Also, two main techniques are typically used to assess thermal conductivity in experimental tests: needle probes and thermal cells [3].

This study introduces a novel approach to understanding the influence of affecting parameters on thermal properties in a transient state of a cylindrical soil sample. The proposed method enables the comprehension of spatio-temporal variability of thermal conductivity in soils subjected to temperature fluctuations. Most studies have relied on steady-state assumptions to measure or estimate thermal conductivity contradicting the variable nature of soil thermal properties. However, the existing transient tools and methods suffer from limitations such as a small sample size and very short testing durations [3]. Consequently, these constraints prevent an accurate capture of the extent to which thermal conductivity would vary due to thermally induced variations in physical properties. As a result, reliable thermo-mechanical analysis of soil subjected to heat sources is hindered. To achieve this goal, a state-of-the-art thermal cell was meticulously designed and constructed at the UNSW Geo-Energy Laboratory. This innovative thermal cell enables the monitoring of thermal and physical properties variations in a cylindrical soil sample with a height of 500 mm and a diameter of 20 mm, facilitating the assessment of temporal and spatial variability in thermal properties. The application of thermal loads to the thermal cell is accomplished by utilising a spiral copper pipe wrapped around the outer walls of the cell. To ensure efficient heat transfer, a layer of graphite sheet is applied to the cylinder wall, promoting uniform heat transmission between the cylinder wall and the pipe. The thermal cell and a schematic representation of the sample set-up are illustrated in Figure 1. When the soil sample is prepared within the thermal cell, the thermal loading mechanism is activated to quickly elevate the temperature of the cylinder's outer wall to a target level. Once the thermal load is applied, the temperature gradient between the soil sample (with an initial temperature of T_0) and the applied temperature (*i.e.*, T_{out}) produces a transient, one-directional radial heat flow in the sample resulting in variations in the soil temperature which begin at the cylinder's wall and progress towards the centre until the system reaches a steady-state condition. The resultant temperature distribution through the sample, however, depends on the soil moisture content, initial void ratio, density, etc., and as the heat transfer is governed by thermal conductivity, it could be concluded that thermal conductivity would change spatially and temporally as a result of variations in the mentioned parameters. Thus, to monitor temperature changes, a series of thermal sensors (8 sensors) are located at different distances from the origin of the cylinder (to observe

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temperature distribution from the source of the thermal load) and also at different elevations (to check the uniformity of the thermal load through the cylinder height). Finally, an analytical solution is employed to analyse the obtained data and estimate the thermal conductivity of the soil, which would be different for various experimental scenarios (*i.e.*, initial void ratios, density, moisture content, etc.). The analytical solution is developed by extending the solution proposed by [5] to capture changes in thermal conductivity in a soil cylinder exposed to temperature increase. Figure 1a shows typical test results in terms of the variations of the temperature through the test which are obtained under the constant applied temperature of 55 C for a dry soil sample with an initial void ratio of 0.4. For a constant initial void ratio and density, when the results of various applied dimensionless temperatures (Θ) are plotted against dimensionless time (Fourier number, F_o) (Figure 1b), it is observed that the temperature profile at a specific radial distance is independent of the applied target temperature and the resultant temperature gradient while the soil density is constant and the soil fully dry.

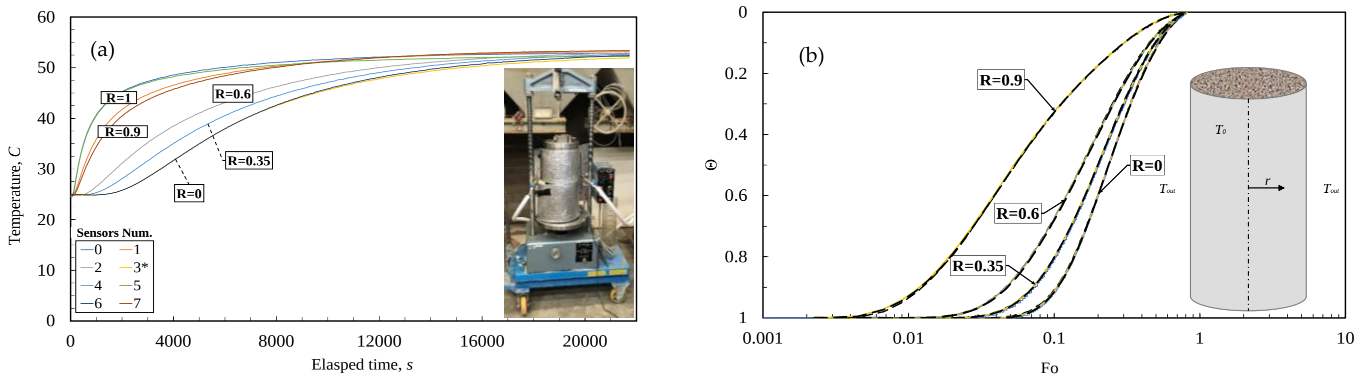

Figure 1: a) Temperature variations against time for different locations and thermal cell apparatus (inset), b) Dimensionless temperature and time at different distances from the origin for all tests and soil cylinder schematic (inset).

Finally, to test the validity of this methodology, the induced temperature variability measured at various depths and radial distances in the soil is compared with the results from a FE heat transfer model, showing good agreement (the comparison is not shown here due to space limitation). It is concluded that the proposed experimental approach is reliable for investigating the spatio-temporal variability of thermal conductivity for a cylindrical soil sample subjected to temperature elevation hence physical parameters variability.

Data Availability Statement

Not applicable.

Contributor statement

Ali Pirjalili: Conceptualization, conducting experiments, data curation and formal analysis, Writing – Original draft, Review & Editing; Asal Bidarmaghz: Conceptualization, Obtaining funding, Writing – Review & Editing; Arman Khoshghalb: Conceptualization, Writing – Review & Editing; Adrian Russell: Conceptualization, Writing – Review & Editing.

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