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Effect of saturation conditions on thermal properties of sands

Effet des conditions de saturation sur les propriétés thermiques des sables

Z. Zhou*, A. Diambra, T. Liu
University of Bristol, Bristol, United Kingdom

**zhixin.zhou@bristol.ac.uk*

ABSTRACT: Soil thermal conductivity, diffusivity and heat capacity are critical parameters that govern the design of specific geotechnical infrastructure including energy piles, high-voltage cables and pipelines. The presence and flow of water are of particular importance as it dominates the conduction and convection hear transferring mechanisms, leading to a global increase in heat conduction ability by replacing air within the multi-phased soil system. This paper presents preliminary results from an experimental programme that aims to characterise the effects of saturation conditions on the thermal properties of a siliceous sand. Thermal conductivities were investigated for samples prepared to varied relative densities and degrees of saturation by two methods: (I) sand-water mixed at specific water contents and moist-tamped in moulds to the target densities; (II) cycles of wetting-draining applied to initially dry specimens through a customised test set-up. Thermal needles were employed that trigger transient heat source and monitor temperature variations. Significant differences were observed in the thermal conductivities between the Method I specimens and the Method II specimens in the first saturation stage. However, the differences diminished in the subsequent infiltration cycles. Overall, the results confirmed strong dependency of sand's thermal conductivity on saturation conditions as the presence of water envelopes and bridges sand particles in heat conduction.

RÉSUMÉ: La conductivité thermique, la diffusivité et la capacité thermique du sol sont des paramètres critiques qui régissent la conception d'infrastructures géotechniques spécifiques, notamment des pieux énergétiques, des câbles haute tension et des pipelines. La présence et le flux d'eau revêtent une importance particulière car ils dominent les mécanismes de transfert de chaleur par conduction et convection, entraînant une augmentation globale de la capacité de conduction de la chaleur en remplaçant l'air au sein du système de sol multi-phasique. Cet article présente les résultats d'un programme expérimental visant à caractériser les effets du degré de saturation sur les propriétés thermiques du sable siliceux. La conductivité thermique a été étudiée sur des échantillons préparés à des densités relatives et des degrés de saturation variés selon deux méthodes: (I) mélange de sable et d'eau à des teneurs en eau spécifiques, tassé humide dans des moules jusqu'aux densités cibles; (II) cycles d'humidification-drainage appliqués à l'aide d'un dispositif d'essai personnalisé. Les conductivités thermiques des échantillons ont été mesurées par des aiguilles thermiques déclenchant une source de chaleur transitoire et surveillant les variations de température. Des différences significatives ont été observées dans les conductivités thermiques des échantillons de la Méthode I par rapport à ceux de la Méthode II lors de la première étape de saturation. Cependant, ces différences se sont atténuées au cours des cycles d'infiltration ultérieurs. Dans l'ensemble, les résultats du programme d'essais préliminaires confirment une forte dépendance de la conductivité thermique du sable aux conditions de saturation et à la présence du film d'eau qui enveloppe et relie les particules de sable dans la conduction de chaleur.

Keywords: Thermal conductivity; saturation condition; high-voltage cables; porous media.

1 INTRODUCTION

Soil thermal properties dictate the storage and movement of heat in soils (De Vries, 1963) and govern heat transfer processes in various applications, including oil and gas pipelines, buried high-voltage (HV) electrical cables, agriculture, shallow geothermal system, thermal energy storage and nuclear waste disposal facilities (Gera et al., 1996; Malek et al., 2021; Nixon et al., 1991; Zhang and Wang, 2017). Thermal conductivity of soils is affected by a range of variables, for examples mineralogy, density, stress level and saturation conditions. The degree of saturation is a also crucial factor as it affects the transition of heat transfer from the solid phase to the liquid phase and the coupled process of heat conduction and moisture movement under various temperature gradients (Farouki, 1981).

Characterising thermal properties of partially saturated soil is crucial for onshore HV cables (Salata et al., 2015) and the landing parts of offshore HV cables, especially in regions where water tables may fluctuate daily or seasonally. Systematic investigation of soil's thermal conductivities in these application scenarios is required. This paper reports preliminary findings from an experimental programme that investigates the impact of sample formation and saturation methods, wetting-draining cycles, and water level fluctuation on the thermal conductivity of granular soils.

2 MATERIAL AND METHODS

2.1 Soil tested

Leighton buzzard fraction B sand was used for this testing programme. It features a mean grain size d_{50} = 0.88 mm, coefficient of curvature C_c = 1, coefficient of soil uniformity C_u = 1.88, specific gravity G_s = 2.65, maximum and minimum void ratios e_{max} = 0.84 and e_{min} = 0.53, respectively (de Leeuw et al., 2021).

2.2 Sample preparation Method I

Method I for sample preparation was based on the conventional moist tamping method. Sand and water were mixed thoroughly at target water contents and filled in five layers into a cylindrical mould with an internal diameter of 50 mm and height of 130 mm. Each layer was tamped to achieve target void ratio and relative density. The adopted sample size followed the recommendation by ASTM (2022) and was compatible with the size of the thermal needle (2.4 mm diameter and 100 mm length) employed in the study (details see Section 2.4).

2.3 Sample preparation/saturation Method II

This method employed moulds of the same size as used in Method I. The specimen was initially prepared by pluviating dry sand to a target void ratio (relative density). Subsequently, water was percolated from the specimen base, and multiple saturation-desaturation cycles were applied through the inflow and outflow reservoirs, as shown in Figure 1. Specimen mass and its variations were measured by a digital balance placed beneath the sample, enabling continuous monitoring of the specimen's global water content and degree of saturation. In contrast to Method I, Method II enabled the application of wetting-draining cycles and simultaneous thermal conductivity measurements.

2.4 Equipment and test programme

The conventional transient thermal needle method was adopted in this study. The thermal unit was consisted of a single thermal needle (TR-3) and the TEMPOS thermal analyser supplied by the METER Group. The equipment allows thermal conductivity measurements in the range of 0.1-4 $W \cdot m^{-1} \cdot K^{-1}$ with an accuracy of ±10%. A 3-D printed top cap was designed to guide the needle's penetration from the centre of the specimen's top surface. Silicon grease was applied to the needle surface to enhance its contact with soil particles and improve the needle's sensitivity in capturing temperature variations (ASTM, 2022). Thermal tests were performed directly on the specimens prepared by Method I. Combinations of four relative densities (0%, 25.8%, 51.6%, 77.4%) and five degrees of saturation (0, 10%, 20%, 50%, 100%) were explored. The specimens prepared by Method II covered the same relative densities as those in Method I but with finer considerations of the degree of saturation.

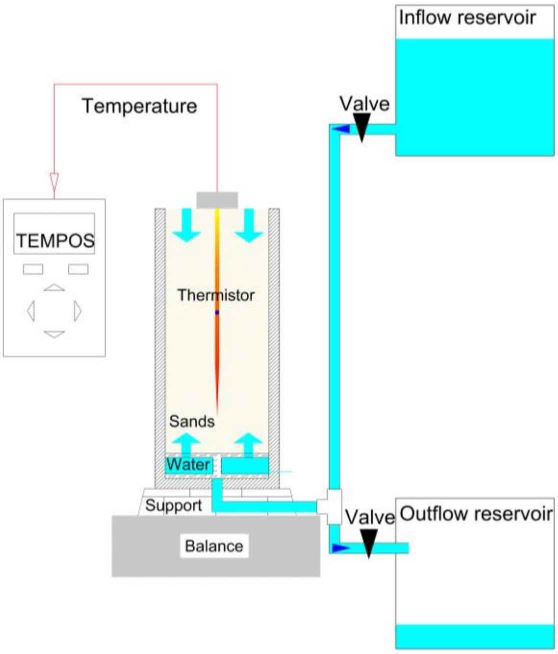

Figure 1. Schematic representation of the Method II set-up.

3 RESULTS AND DISCUSSION

3.1 Results from Method I

Figure 2 shows the variations of thermal conductivity against the degree of saturation (S_r) for the sand specimens prepared with Method I. Nominal trends are indicated with dashed straight lines. Under identical saturation level, specimens prepared at the lowest relative density, D_r = 0% ($e = e_{max}$) manifested lowest thermal conductivities. Higher-density specimens develop greater particle contact areas and therefore greater heat conduction capacity (Abu-Hamdeh, 2003). Sharp increases in thermal conductivity can be observed over the low S_r (<10%) range, followed by gradually increasing trends as S_r increased further.

The observed trends corroborate previous findings by Smits et al. (2010). Water surrounding sand particles enhances heat conduction through connected water channels, which act as a conduit for heat exchange, noting the thermal conductivity of water (≈0.598 W·m^{-1}·K^{-1}) is significantly greater than that of air (≈0.02 W·m^{-1}·K^{-1}) (Aljundi et al., 2024). As the degree of saturation increased further, thermal conductivities rose only modestly as the main substitution processes of air by infilling water were largely completed at this stage.

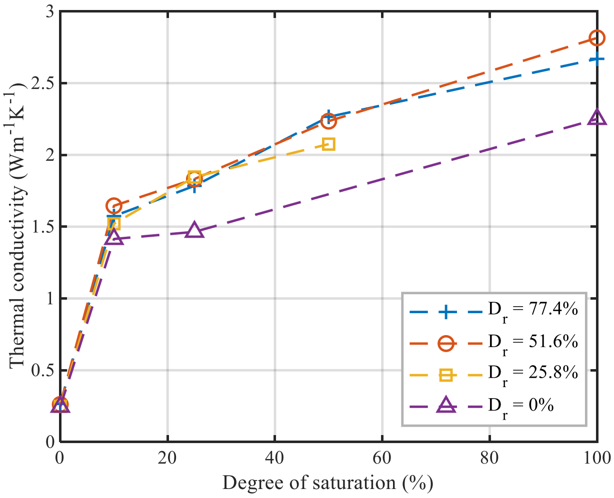

Figure 2. Measured thermal conductivities against degrees of saturation for specimens prepared by Method I.

3.2 Results from Method II

Figure 3 plots thermal conductivities against apparent degrees of saturation (S_r^*) for specimens prepared with Method II. Noting the progressive change in water level during the wetting-draining cycles and the non-uniform nature of the saturation process (especially in the 1st injection stage), apparent degrees of saturation (S_r^*) were computed based on the mass variations measured by the scale to represent the specimens' global saturation states.

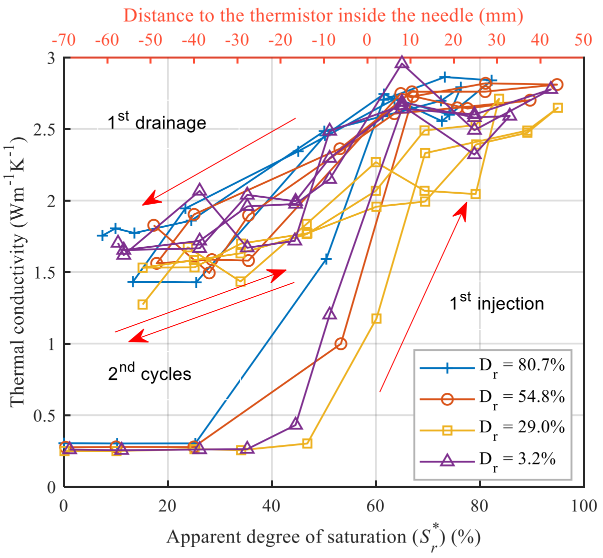

Figure 3. Measured thermal conductivities in two wetting-draining cycles for specimens prepared by Method II.

Figure 3 also plots on the upper x-axis distances between the estimated water levels and the thermistor positioned in the middle of the needle (see Figure 1) during the wetting-draining cycles. Water levels were approximated by assuming full saturation in the wetted zones, neglecting any capillary rise for the relatively coarse-grained uniform (d_{50} = 0.88 mm and C_u = 1.88) sand tested. Much more uniform distributions of water were expected in the subsequent draining-re-wetting cycles.

The measured thermal conductivities in the 1st percolation stage primarily relied on the water level relative to the thermistor. As water percolated into the lower part of the initially dry specimen, the water level remained below the thermistor level. The apparent degree of saturation (S_r^*) remained relatively low (< 30%) and the measured thermal conductivities largely represented those of dry specimens. Marked increases in thermal conductivities occurred as the water level ascended and S_r^* increased further to ≈70%.

Consistent and broadly linear trends can be observed in the subsequent desaturation and re-saturation cycles over the S_r^* range of 10-70%. Thermal conductivities appear to reach plateaux as S_r^* exceeded 70%. It is noted that natural gravity cannot de-saturate the specimens further to S_r^* <10% due to the presence of residual water.

An advanced multi-needle system is being developed at the University of Bristol that captures the distribution and evolution of thermal conductivity in unsaturated sands accurately.

3.3 Comparative analysis

Trends of thermal conductivity for the specimens prepared with Methods I and II are compared in Figure 4 for the first saturation stage and Figure 5 for the subsequent draining-wetting stages. Markedly different patterns are evident under relatively low S_r (or S_r^*) conditions of <60%. The results become more consistent under higher and more uniform saturation conditions in which the needle sensor was sufficiently immersed. Further increases in S_r^* resulted in relatively minimal increases in thermal conductivities, regardless of the specimen preparation method used.

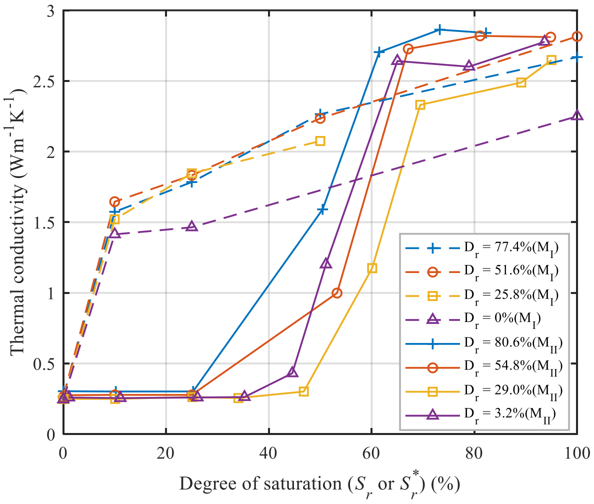

Figure 4. Comparison of measured thermal conductivities in the first saturation stage.

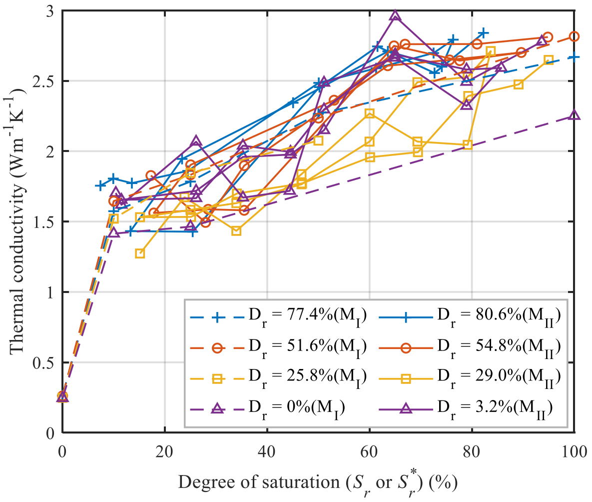

Figure 5. Comparison of measured thermal conductivities in the subsequent wetting-drying stages.

Compatible trends were observed in the subsequent wetting-drying cycles, despite the different specimen formation and saturation procedures employed (Figure 5). Saturating histories appear to yield only minor effects. Sand's thermal conductivity is primarily affected by its degree of saturation, although the water percolation process and any thermal coupling effects may also result in variations in the thermal conductivities of specimens prepared by Method II.

4 SUMMARY AND CONCLUSIONS

This paper presents preliminary results from an experimental programme designed to investigate the effects of saturation conditions on the thermal conductivity of silica sands. Two specimen preparation and saturation methods were employed: (a) a conventional method mixing sand and water at specified water content and tamping to target relative density; and (b) a customised experimental set-up that applied wetting-draining cycles and monitored water inflow and outflow. The measured thermal conductivities for the two methods exhibited significant disparities in the first saturation stage but became much more compatible in the subsequent de-saturation and re-saturation cycles. Further experimental study using an advanced multi-needle system is underway to investigate the potential effects of large number of wetting-draining cycles as well as coupled conduction-convection heat transfer process.

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