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Effect of ground mineralogy on energy pile performance in dense sand

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Abstract. Geothermal energy piles have emerged as a cost effective and efficient solution for heating and cooling buildings through renewable energy. Although significant research effort has been dedicated to investigating the performance of these systems, the effect of ground mineralogy has received little attention. This study examines the likely performance of energy piles in dense sand with varying mineralogy. A 3D thermal discrete element model is used to determine the dry thermal conductivity of quartz, feldspar and mica rich sand. This is then used in a 2D finite element analysis to estimate the dissipation/extraction capacity of the soil surrounding a typical energy pile. A 35% increase in quartz content is predicted to result in 51% improvement in the thermal performance of a pile.

Introduction

Geothermal energy piles serve a dual purpose, transferring the load of a superstructure to the substrate beneath whilst also exchanging heat with this medium as part of a ground source/coupled heat pump (GSHP/GCHP). Energy piles are typically constructed using reinforced concrete or steel which may be driven, bored or augered. Energy piles exploit shallow depth solar energy flux [1] and the near consistent subterranean temperature found at depths of 15-100m. When linked to an air-handling system highly efficient and cost effective space cooling and heating is possible [2,3].

In light of this, a number of field studies have examined the performance of steel pile configurations [4-6] and concrete pile configurations [7,8] while analytical studies have examined the effect of ground water flows [9] and pile configuration [10] on performance. Numerical studies have also considered the effects of thermo-mechanical coupling [11], ground water [2] and cyclic thermal fluctuations [12] on energy pile performance. These studies have each considered a fixed substrate composition and morphology, with limited effort to extend results to varying ground composition.

This paper examines the effect of ground mineralogy on energy pile performance. A discrete element model is used to evaluate the thermal conductivity of dry sand composed of quartz, feldspar and mica with varying constituent volume fractions. The simulation is based on a radial implementation of the divided bar method for thermal conductivity measurement. The conductivity values are then used to estimate the minimum dissipation/extraction capacity of the soil surrounding an energy pile using a thermal finite element analysis.

Methodology

Physical characteristics of sand substrate: The dense sand substrate considered in this study is modelled on that found in many coastal regions of Australia and is composed of the three principle components, quartz, feldspar and mica particles. The physical parameters of the selected materials, obtained from [13] and used in this study, are present in Table 1. The mean properties of the feldspar and mica mineralogical groups have been adopted. A uniform particle size distribution with range of 0.5-1.5mm and a target void ratio of 0.365 is used.

Table 1 Physical properties of minerals in dense sand

Mineral	Density (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio	Coefficient of Friction	Specific Heat Capacity (J/kg^{o}C)	Thermal Conductivity (W/m^{o}C)
Quartz	2650	95	0.2	0.55	830	7.7
Feldspar	2560	40	0.3	0.68	750	2.5
Mica	2970	180	0.2	0.55	770	2.1

Thermal conductivity evaluation: The thermal conductivity of the sand with varying composition is evaluated using a 3D thermal discrete element model. Quartz content is varied over a range of 55-90% (vol.) while maintaining feldspar and mica in equal proportions. The Cundall & Strack (1979) contact formulation as described and implemented in [14,15] respectively, is used with a damping coefficient of 0.2. Inter-particle heat transfer is prescribed as in [16] with the harmonic mean of particle thermal conductivities used at contacts. The time scale employed corresponds to the thermal time defined in Eq. 1 and in which the minimum particle diameter d, mass m, bulk material specific heat capacity c and thermal conductivity k_b is used.

$$t_{th} = \frac{mc}{dk_s} \quad (1)$$

The macroscopic thermal conductivity of the sand is measured through a radial implementation of the divided bar method. Unlike the typical approach in which the specimen is sandwiched between two flat plates, the sand is placed between two ring shaped boundaries to form an annulus, as shown in Fig 1a, in which the inner and outer ring diameters are D_{in} and D_{out} respectively. The inner and outer boundary temperatures are fixed with a temperature differential ΔT of 10^{o}C, comparable to that between an operating energy pile and ambient ground temperature.

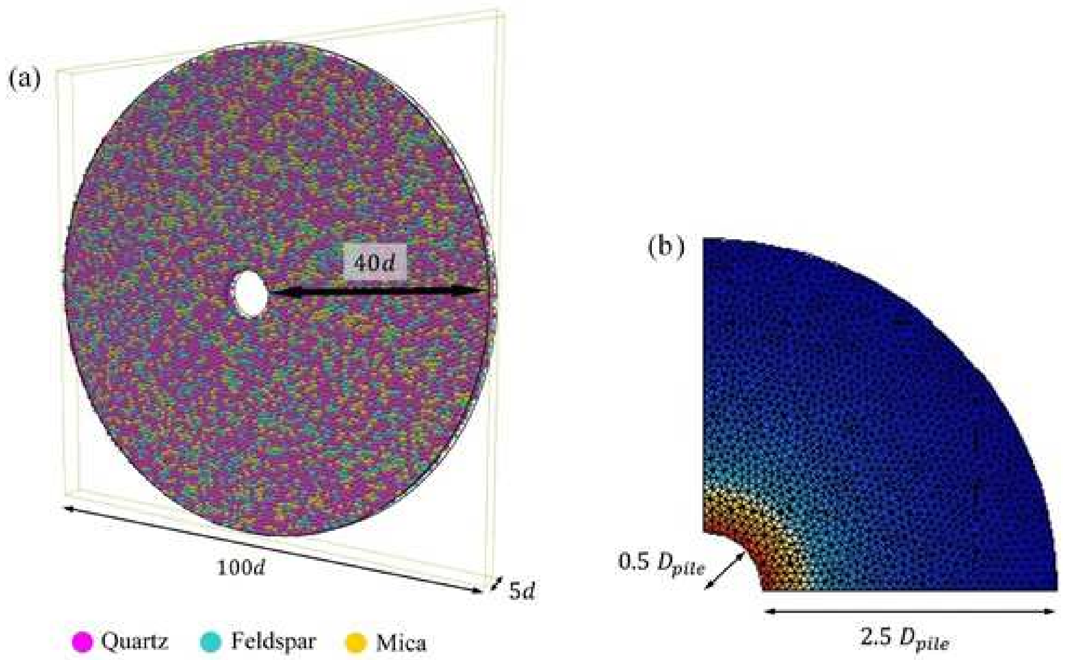

Fig. 1 Model illustrations: (a) discrete element model for the determination of sand thermal conductivity using a radial divided bar approach, in which d represents the minimum particle diameter; (b) finite element model for the determination of dissipation/extraction capacity of the soil surrounding an energy pile, in which D_{pile} represents the pile diameter.

Isostatic compaction of the initially loosely packed sand particles is used to achieve the target packing ratio. The final annulus thickness achieved is approximately 40 times the minimum particle diameter. The out of plane depth h is set to 5 times the minimum particle diameter with periodic boundary conditions applied in this direction. By tracking the steady state heat flux across the annulus Q the thermal conductivity of the sand k_s is determined using the steady-state radial heat conduction solution to Fourier's law as defined below:

$$k_s = \frac{Q \ln(D_{out}/D_{in})}{2\pi h \Delta T} \quad (2)$$

Energy pile capacity estimation: The dissipation/extraction capacity of the soil surrounding an energy pile is determined using 2D thermal finite element analysis. A model based on the field study conducted at Lambeth College, London [17] is constructed using the framework in [18]. The soil surrounding a pile is represented by an axisymmetric quarter annulus, as shown in Fig. 1b, with a thickness equivalent to 2.5 times the pile diameter D_{pile}, the distance at which the temperature change in the soil reached a negligible value in the said study. Constant temperature boundary conditions were employed at the inner and outer edges of the annulus, corresponding to the previously mentioned temperature differential. The steady state heat flux density at the pile-soil interface was then determined using the sand bulk thermal conductivity. The former represents the rate at which heat may be dissipated/extracted per unit of pile surface area under constant thermal load.

Results and Discussion

Transient thermal response: The transient temperature distributions obtained during the radial divided bar simulation display a consistent reciprocal logarithmic profile across the thickness of the sand specimen as shown in Fig. 2. Temperature T', time t' and distance r' have been normalized with respect to the temperature differential, thermal time calculated in accordance with Eq. 1 using volume weighted parameters and specimen thickness, respectively, to provide a set of master curves. It should be noted that the profiles rapidly converge towards the steady state temperature distribution.

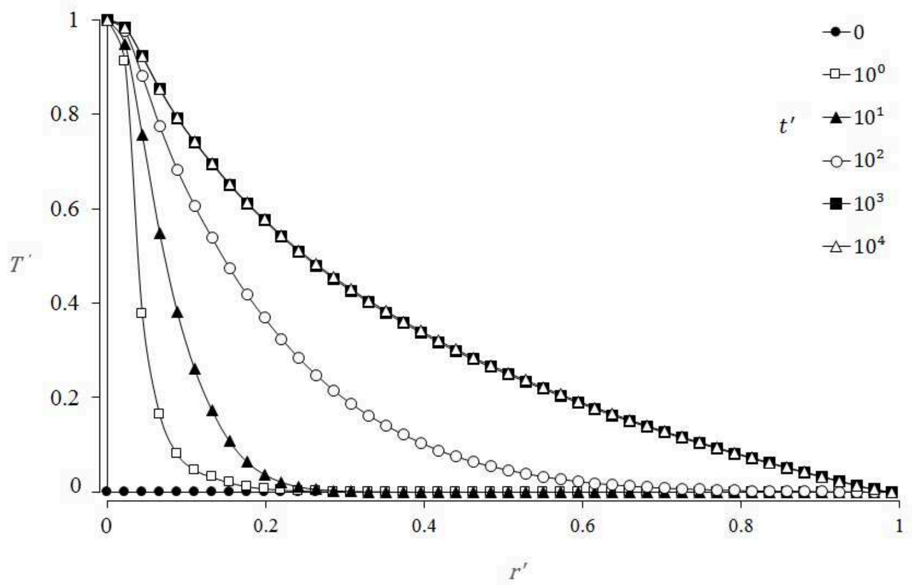

Fig. 2 Transient temperature distribution across thickness of the sand specimen. Temperature T', time t' and distance r' have been normalized with respect to the temperature differential, mean thermal time and specimen thickness, respectively.

The distributions resemble the temperature profiles for radial heat flow in continuous media predicted by continuum thermodynamics. This provides support for the use of the discrete element and radial divided bar approaches for the accurate estimation of macroscopic conductivity in granular media. Furthermore the results highlight the ability of the thermal discrete element model to link contact scale thermal phenomena with macroscopic behavior.

Thermal conductivity: Thermal conductivity is found to be strongly influenced by the mineralogy of the dense sand, and specifically the quartz content. The thermal conductivity of the sand displays a linear dependence upon the quartz volume fraction, as shown in Fig. 3.

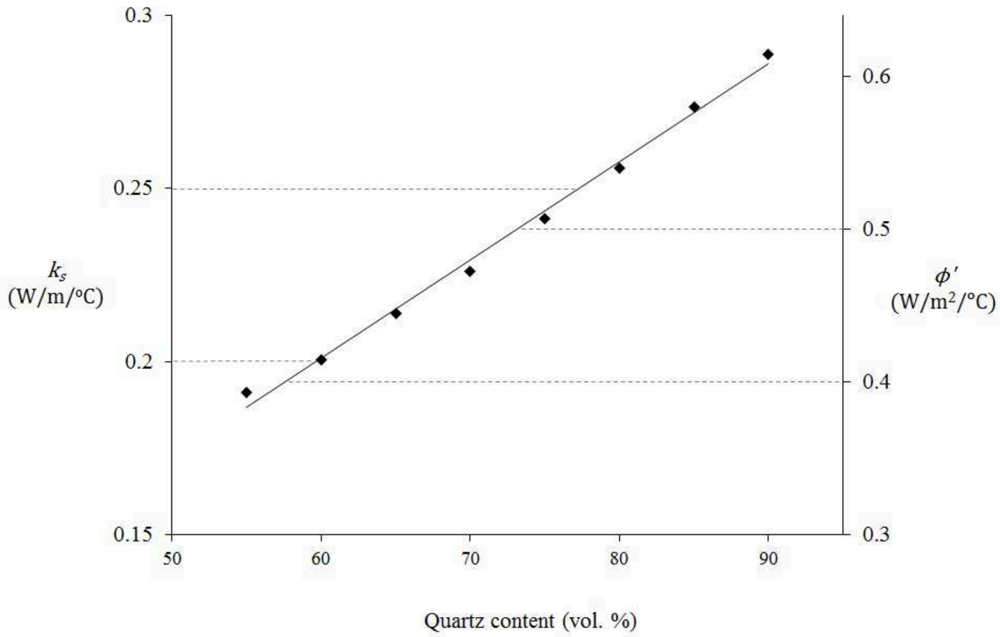

Fig. 3 Thermal conductivity of dense sand k_s and heat flux ϕ' at the pile-soil interface normalised with respect to the pile-ground temperature differential, for varying quartz content with feldspar and mica maintained in equal proportions.

The trend is consistent with the predictions of mixture theory and lies within the range of empirically determined values of sand conductivity [19] for similar sands. A 51% increase in thermal conductivity is observed over the 35% range in quartz volume fractions tested. The associated reduction in mica, which is almost twice as stiff as quartz and feldspar, is assumed to increase inter-particle contact areas (during the isostatic compression stage) and hence results in a disproportionate increase in overall thermal conductivity.

Energy pile capacity: The heat flux density ϕ' at the pile-soil interface, normalized with respect to the pile-ground temperature differential, is also shown in Fig. 3. This quantity is taken to be a lower estimate of the performance of an energy pile system.

Clearly the quartz content in dense sand plays a critical role in determining the effectiveness of an energy pile. The pile-soil interface heat flux density presents an equivalent improvement to that of thermal conductivity for an increasing quartz content. It should be noted that this measure does not consider the thermal storage capacity of the soil and pile material, which greatly increases the short term heat dissipation/extraction capacity, but is rather an indicator of the long term performance under sustained thermal load.

Conclusion

This study has investigated the effect of varying ground mineralogy on the likely performance of geothermal energy piles in dense sand. A 3D thermal discrete element model of a radial implementation of the divided bar method for thermal conductivity assessment has been developed.

The model is used to determine the thermal conductivity of densely packed coarse sand with varying quartz content. This value is then used in a 2D thermal finite element analysis to estimate the nominal steady state heat flux density at a pile-soil interface, providing a lower bound estimate for the dissipation/extraction capacity of the soil surrounding a pile.

The discrete element model yielded temperature profiles resembling those predicted by continuum thermodynamics for radial heat flow, which quickly converged to a steady state. Increasing the quartz content resulted in a disproportionately greater increase in thermal conductivity, which translated into an equivalent improvement in the finite element predicted dissipation/extraction capacity.

This paper represents a first order investigation intended to motivate further research into the effects of soil mineralogy on thermal pile performance. In particular the determination of thermal conductivity of dense sand is rudimentary, considering a highly simplistic three-phase system and neglecting the presence of an inter-pore fluid. Further to this, the estimation of the dissipation/extraction capacity of the soil surrounding an energy pile is crude and limited in its applicability to realistic installations. Nevertheless, this investigation has sought to highlight an overlooked phenomenon in an attempt to promote further numerical and empirical study within this area.

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