Laboratory Method for Determining Thermal Resistivity of a Coarse Aggregate Mixture

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ABSTRACT
As energy demands continue to rise, the development of renewable energy infrastructure is becoming more important. Sources, such as wind or solar farms, have large areal footprints and require extensive networks of buried cable to transport the energy produced to the consumer. Heat generated by energy flow through cables can cause cable overheating and failure if the heat is not quickly dissipated. Therefore, accurate measurement of the thermal properties of the material surrounding the cable is critical for project design. The low thermal resistivity of sand makes it an ideal backfill material. However, depending on the local geology, this material may need to be imported which can increase project costs. While the use of local materials can be cost efficient, the soil thermal properties must be evaluated for project suitability. Because of the high variability of thermal resistivities between soil materials, including air and water, problems arise when a heterogeneous soil contains significant portions of coarse aggregates and large pores, making a representative measurement difficult to obtain using a thermal needle probe. An alternative to the needle method was developed at our GHD Geotechnical Laboratory to accurately measure the bulk thermal resistivity of coarse-grained soils. The initial results are presented.

RÉSUMÉ
Vu la croissance continue des demandes d'énergie, le développement des sources d'énergie renouvelables devient de plus en plus important. Ces sources, telles que les parcs éoliens ou solaires, peuvent avoir une grande empreinte aérienne, nécessitant l'utilisation généralisée de câbles enterrés pour transporter l'énergie produite. La chaleur générée par le flux d'énergie traversant les câbles peut devenir problématique en entraînant éventuellement une surchauffe et une défaillance des câbles dans le cas où elle n'est pas rapidement dissipée. Par conséquent, une mesure précise des propriétés thermiques du matériau entourant le câble est essentielle pour la conception du projet. La faible résistivité thermique du sable en fait un matériau de remblai idéal. Toutefois, en fonction de la géologie locale, il peut être nécessaire d'importer ce matériau ce qui peut augmenter les coûts du projet. Bien que l'utilisation de matériaux locaux puisse être rentable, les propriétés thermiques du sol doivent être évaluées pour déterminer si le projet convient. En raison de la grande variabilité des résistivités thermiques entre les matériaux du sol, y compris l'air et l'eau, des problèmes se posent lorsqu'un sol hétérogène contient des portions importantes d'agrégats grossiers rendant difficile l'obtention d'une mesure représentative à l'aide d'une sonde à aiguille thermique. Notre laboratoire géotechnique à GHD a développé une alternative à la méthode de la sonde à aiguille thermique pour mesurer avec précision la résistivité thermique globale des sols à grains grossiers. Cet article présente les premiers résultats.

1 INTRODUCTION

In response to current environmental challenges, renewable energy demands have been steadily increasing. Renewable resources such as solar, wind, and hydro, supply 17% of Canada's energy demands according to Natural Resources Canada (2016). Energy generated by these sources is transported to the consumer through cables. These cables are buried in trenches to ensure protection of the cables and provide minimal disruption to societal infrastructure. However, the electricity that flows through cables emits heat. These cables become susceptible to overheating if the surrounding soil environment is resistant to the heat produced, shortening the lifespan of the cables (Campbell et al. 2019). To maximize heat dissipation, soils with low thermal resistivity (high thermal conductivity), such as quartz sands, make ideal trench backfill materials. These materials are often imported, but depending on the transport distance, importation can significantly increase project costs. While more cost-effective options include the use of local materials exclusively, or in combination with imported materials, this requires an accurate assessment of the thermal properties of the materials proposed for use (Campbell et al. 2019).

The conventional method for both laboratory and on-site measurement of soil thermal properties is the needle method (ASTM 2000; IEEE 1996). This transient line heat source method consists of a thermal needle that contains a heating wire and a temperature sensor. A small amount of heat is supplied to the wire for a short duration. To avoid moisture migration along the thermal gradient, the heating and measurement periods are as short as possible. The temperature of the probe is monitored for a time during heating (t_h), and again during cooling once the heat supply has ceased for a time equal to t_h. Thermal conductivity, k, is derived from a set of algorithms that are applied to the temperature readings. Temperature during heating, T_h, is calculated by:

$$T_h = m_0 + m_2 + m_3 \ln t \quad [1]$$

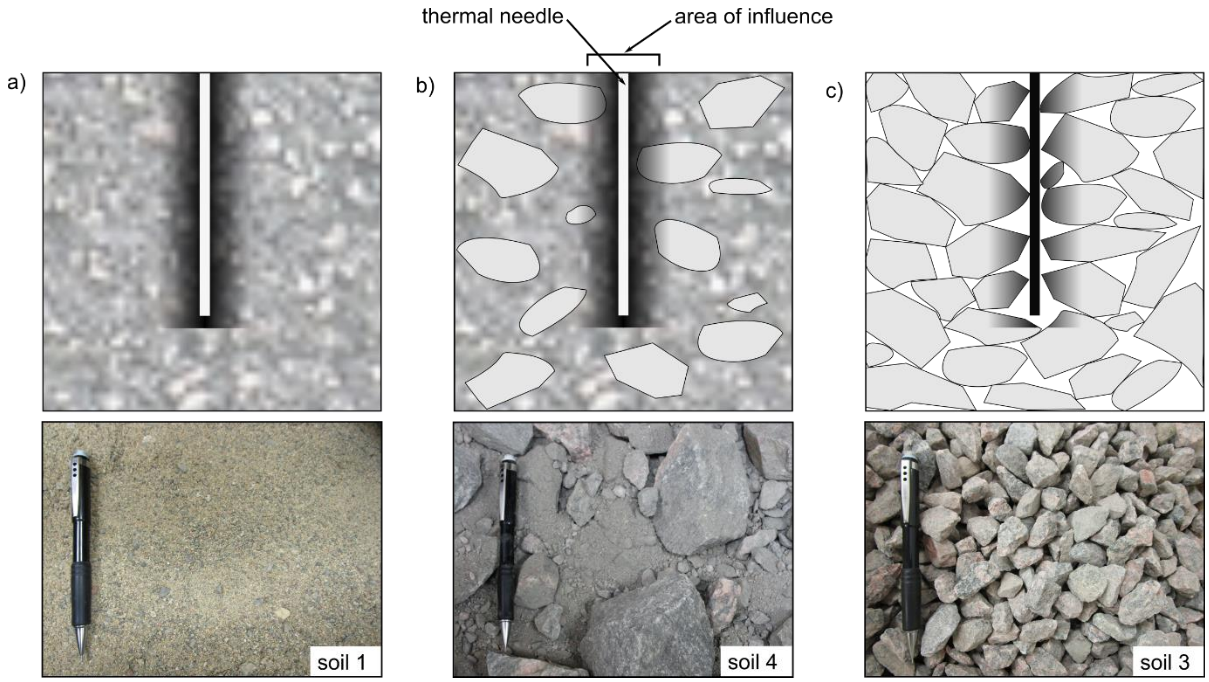

Figure 1. Schematics of needle method implementation showing the area of influence (shaded area) around the thermal needle, and the effect of adjacent materials (grain size and pore space) on the output of the needle readings in soils with various particle sizes. Soils analyzed in this study include a) homogeneous, fine-grained standard sand, b) mineral soil with large aggregates, and c) crushed granitic gravel (Table 1, soils 1, 4, and 3).

where m_0 is the ambient temperature during heating, m_2 is the rate of background temperature drift, m_3 is the slope of a line relating temperature rise to the logarithm of temperature, and t is time (Decagon Devices Inc. 2011). Temperature during cooling, T_c, is determined by:

$$T_c = m_1 + m_2 + m_3 \, ln\left[\frac{t}{(t - t_c)}\right] \qquad [2]$$

where m_1 is the ambient temperature during cooling. Thermal conductivity (k, W m^{-1} K^{-1}), is calculated as:

$$k = \frac{q}{4\pi m_3} \qquad [3]$$

where q is the heat input per unit length (W m^{-1}). This method supplies a transient heat source and provides an indirect measurement of thermal resistivity, ρ, based on a series of calculations. Results obtained using the needle method are predominantly influenced by the materials (including air space) in closest proximity to the needle, as illustrated in Figure 1. Though this method is simple and efficient, it is most appropriate for use in homogeneous, fine-grained soils where pore diameters are small and uniform, and good contact between the needle and the soil particles can be achieved (IEEE 1996). Where large aggregates make up a significant portion of the soil matrix by volume, such as across the Canadian Shield, air and water held within larger pore spaces, and poor contact between the needle and large aggregates leads to biased measurements that erroneously characterize the thermal properties of the bulk soil by disproportionately representing air- or water-filled pore spaces, or soil fines where present (IEEE 1996). Therefore, using this method for measurements of thermal properties of such soils produces unreliable and potentially inaccurate results.

Other methods used to determine the thermal properties of soils include direct measurements and numerical modeling. The most common direct methods include the divided bar and the guarded hot plate (GHP) techniques (Dalla Santa et al. 2017; Altrimi et al. 2016; Blazquez et al. 2017; Zhao et al. 2016). The divided bar (or comparative) method utilizes a material with a known thermal conductivity to determine that of an unknown sample. The guarded hot plate (GHP) method requires that a sample be placed between a heat source with a known and carefully controlled power output applied to the sample, and heat sink (or cold plate). In each system, the thermal energy flux through the soil is monitored by thermocouples. Once the system reaches steady state conditions, thermal conductivity of the material of interest can be determined. Numerical models developed for the prediction of soil thermal properties are based on varying proportions of the soil components (Altrimi et al. 2016; Blazquez et al. 2017; Zhang et al. 2017). Use of these models require significant background data on the soils being assessed, and necessitate laboratory analyses of soil physical properties including porosity, moisture content, mineralogy, and grain size, shape and packing. Because making these laboratory measurements for all soils of interest is impractical, and negate the efficiency of using a model, especially in field settings, many assumptions must be made (Zhang et al. 2017). For example, the De Vries model assumes all soil particles have ellipsoidal shapes and that there is no contact between soil particles, while the Johansen model assumes a particle density of 2700 kg m^{-3}, regardless of mineralogy. The Chen model is based on a high sample size of needle-probe measurements, making this method unreliable in many soil types for the reasons discussed above. In conditions where significant soil heterogeneities exist, and in situations where laboratory analysis is not feasible, employment of these models may produce results that are not representative of the soil as a whole, resulting in limitations to their use.

The rising demand for renewable energy, and the consequent expansion of wind farms across rural regions, call for simple, reliable methods for measuring the thermal resistivity of bulk soil materials that can accommodate soils containing large aggregates while eliminating preferential measurement of pore spaces and soil fines. While numerical models may provide more accurate ρ values, knowledge of the physical properties of the soil are required to drive these models, such as grain size and shape, porosity, pore diameter, moisture content and mineralogy. The technology proposed in this paper 1) evaluates the reliability of the needle method for determining thermal resistivity, ρ, for various soil types, 2) offers a simple and versatile direct measurement method for assessing the thermal resistivity of a wide variety of soil materials, including those that contain large aggregates and heterogeneous mineralogical makeup, and 3) eliminates the need to make assumptions and conduct additional laboratory testing in order to utilize models.

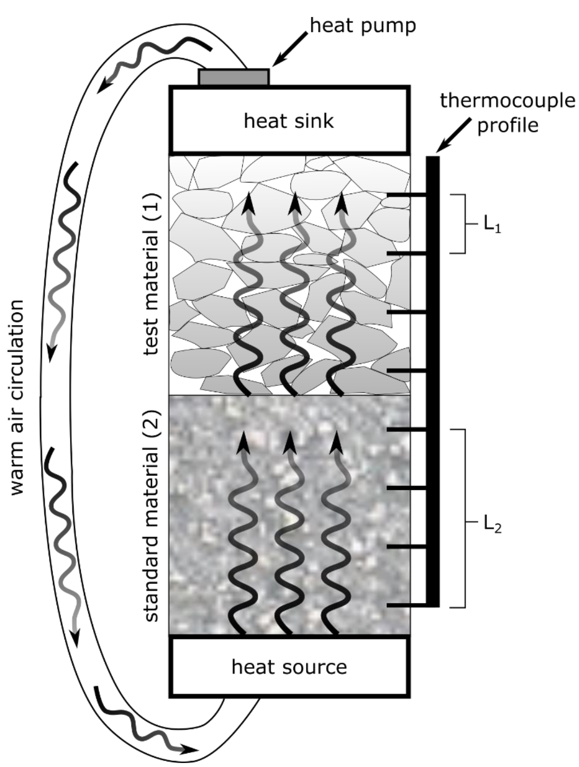

Figure 2. Schematic of proposed top-down cooling cell technology showing test design, direction of heat flow, and thermocouple placement.

2 METHODS AND MATERIALS

In the GHD Geotechnical Laboratory, a testing procedure was developed for direct measurement of the thermal resistivity, ρ, of a bulk soil containing, or wholly composed of, coarse grained (< 9 cm) aggregates, where the needle method would be insufficient. The method proposed in this paper is based on Fourier's Law that states:

$$q = -kA\frac{\Delta T}{L} \quad [4]$$

where q is the heat flux density (W m^{-2}), k is the thermal conductivity of the material (W m^{-1} $°C^{-1}$), A is the cross-sectional area perpendicular to the direction of heat flow (m^2), ΔT is the temperature difference between temperature sensors (°C) and L is the distance between sensors (m). Since the amount of heat flow through the standard material with known k equals the heat flow through the test material (Zhao et al. 2016), k_1 of the test material can be calculated by:

$$k_1 = k_2\frac{A_2\Delta T_2 L_1}{A_1\Delta T_1 L_2} \quad [5]$$

where subscripts 1 and *2* are associated with the test material and standard sand, respectively. Since thermal resistivity, ρ (°C cm W^{-1}), is more commonly used in geotechnical engineering, ρ is obtained by taking the reciprocal of k:

$$\rho_1 = 1/k_1 \quad [6]$$

A "top-down cooling cell", hereafter termed cooling cell, uses a modified divided-bar technique (Figure 2). The cooling cell consists of an insulated chamber (Figure 3) with the cooling element (heat sink) and cold air circulation fan at the top (Figure 3a), while the heat generated by the cooling element on the exterior of the chamber is routed through a heating duct to a compartment below the chamber (Figure 3b), creating a heat source. To reduce convective thermal transfer induced at the surface by the cooling element fan, as well as moisture condensation

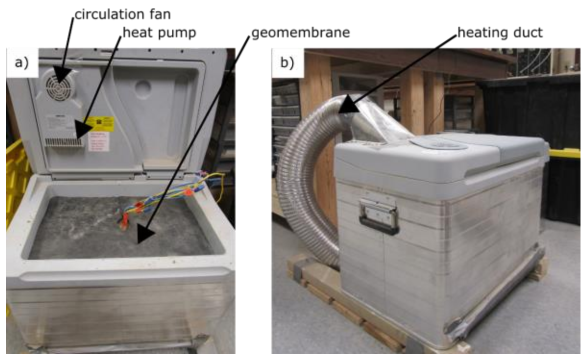

Figure 3. Proposed cooling cell showing a) external warm air return and b) internal cooling element, circulation fan and geomembrane cover to minimize convective thermal transport.

around the element, a piece of thin geo-membrane was fitted to the areal dimensions of the chamber interior (Figure 3a). This "closed loop" system results in a constant one-dimensional heat flux through the soil materials contained within the chamber, and reaches steady-state conditions after an equilibration period of two to four days, illustrated in Figure 4.

The chamber volume was divided in half vertically (see Figure 2) and two materials (standard and test) were placed inside the chamber between the heat source and sink. The bottom portion was filled with the fine-grained standard material (dry sand) for which the conductivity values obtained using the thermal needle method are widely considered reliable. Thermal conductivity, k_2, of the standard material was measured using the needle method and verified by the literature. This provided a standard material of known k. The top portion of the chamber was filled with the test material of unknown k_1, separated from the standard by a layer of muslin cloth to avoid soil mixing and contamination of the standard. A thermocouple profile was constructed using eight type-T thermocouple sensors with a vertical spacing of 3 cm, providing four sensors within each soil layer. HOBO Single Channel Thermocouple Data Loggers (UX100-014M) recorded temperature at each depth at ten-minute intervals during the equilibration period. Once steady-state conditions were observed for 24 hours, k_1 of the test sample was determined using Equation 5, then was converted to thermal resistivity, ρ, using Equation 6.

Materials tested include limestone screenings, crushed granitic gravel, fine-grained mineral soil with large aggregates (primarily composed of schist), and coarse sand with large aggregates of varied mineralogy (Figures 1 and 5, Table 1). A needle probe (KD2-PRO) was used to measure thermal conductivity of both materials (standard and test) before and after each cooling cycle. Using Equation 5, the average of the thermal conductivity readings of the standard sand (k_2) were used to derive k_1 for all test samples. Values of k_1 for the limestone screenings measured using the thermal needle were compared to the k_1 obtained by the cooling cell test to validate the accuracy of the cooling cell. Once reliability of the cooling cell was determined using fine-grained homogeneous material, k_1 of the large-grained and heterogeneous materials obtained from the cooling cell method were compared to the corresponding needle readings to assess consistency, or inconsistency, between the two methods.

The results of the top-down cooling cell were validated against an ideal material composed of fine-grained, uniform particles whose k is typically measured using the thermal needle method, in this case a fine-grained quartz sand (Figure 1a). This sand was designated as the standard material in which k for all other test materials would be compared. Because both soils have the same cross-sectional area, Equation 5 can be simplified to:

$$k_1 = k_2 \frac{\Delta T_2}{\Delta T_1} \quad [7]$$

Using $k_2 = 0.37$ W m^{-1} K^{-1} for the standard material, and the temperature difference (ΔT_1) between probes in the test material, k_1 of a test material was calculated for each 3 cm

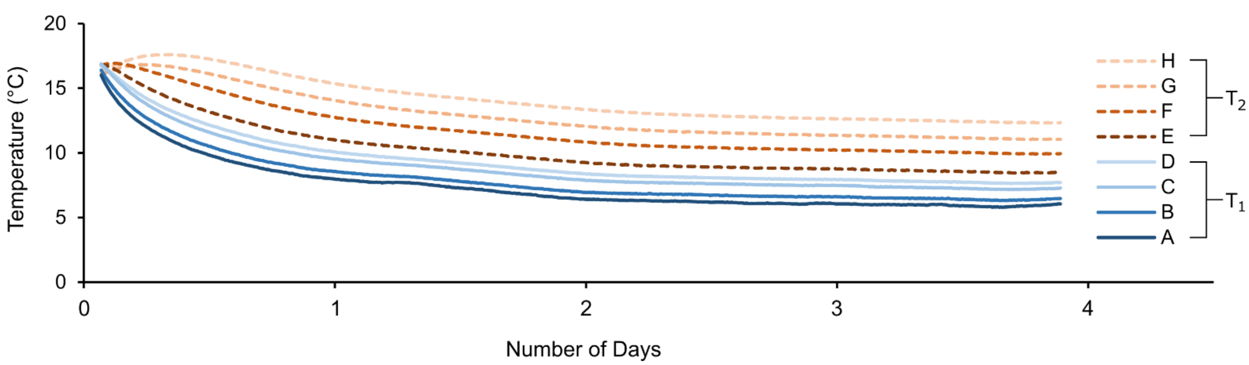

Figure 4. An example of the temperature profiles in the cooling cell during the equilibration period showing coarse sand containing large aggregates at 2% moisture content. Subscripts 1 and 2 indicate the test and standard materials, respectively.

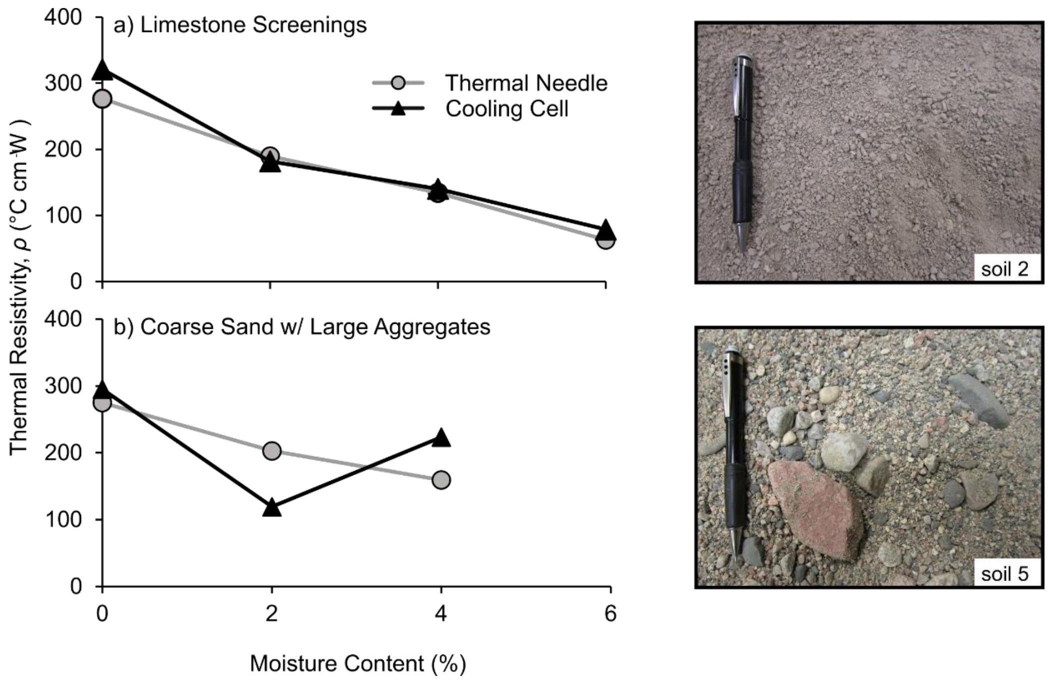

Figure 5. Comparison of thermal resistivity measured using the needle method and the cooling cell for a) homogeneous, limestone screenings and b) a coarse-grained sand containing large aggregates (pit-run), and corresponding photographs of the materials tested (Table 1, soils 2 and 5).

interval (L_1 = 3 cm) over the full profile of the standard material (L_2 = 9 cm). All three between-sensor k_1 values were averaged, then compared to the bulk soil k_1 value obtained from the upper- and lower-most thermocouple sensors (data not shown).

3 RESULTS AND DISCUSSION

Since the thermocouple profiles had a uniform spacing of 3 cm throughout both materials, uniformity of the temperature gradients (ΔT) throughout each profile was assessed. As shown in Figure 4, ΔT within the standard material was similar between sensors (sensors E-H), but inconsistent within the test material (sensors A-D; coarse sand), which was composed of more heterogeneous mineralogy and greater particle size distribution. In this sandy soil with large aggregates (Figure 5b), the presence of a large particle between sensors would results in a very different ΔT compared to a portion of the same soil where the soil fines are dominant. For example, k_2 of the coarse aggregate is controlled by the mineralogy of the single particle and the influence of air and water is negligible. Comparatively, while the soil fines may or may not exhibit a different mineralogical composition than the aggregates, the smaller particulates and greater relative volume of pore space within soil fines containing either air, water, or both, and the degree of contact between particles, strongly influence thermal conductivity. As illustrated in Figure 4, ΔT can vary dramatically within one soil, depending on the portion of soil being assessed, and whether or not that portion is representative of the bulk soil.

To assess the efficacy of the cooling cell, resistivity measurements of the limestone screenings at moisture contents of 0, 2, 4, and 6% were compared using both methods (Figure 5a). Values obtained by the cooling cell show good agreement with results from the needle method, indicating that the proposed cooling cell method is reliable, and increases confidence in the values obtained for other more heterogeneous soil materials.

A second set of tests was run on a coarse-grained sand containing large (100 mm) aggregates (pit-run; illustrated in Figure 1b, data shown in Figure 5b), with moisture contents of 0, 2, and 4%. The results show ρ values obtained using the needle were inconsistent with those measured by the cooling cell, particularly when moisture content was greater than 0%. In dry conditions (0% moisture), the two methods show good agreement. Because interparticle porewater was absent, this indicates that ρ was controlled by particle size and mineralogy, and that the soil fines (sand) had good particle contact. The observed linear decrease in ρ with increasing moisture content, measured using the needle method, was controlled by increasing moisture held between finer particles where the needle was inserted. Comparatively, as moisture increased, irregularities in ρ were observed using the cooling cell.

As expected, the increase in moisture content from 0% to 2% resulted in decreased ρ due to the low resistivity of water held within pore spaces. However, an increase in ρ was observed between 2% and 4%. Possible explanations for this include an unequal distribution of coarse aggregates, and the randomization and varying mineralogy of aggregates in closest proximity to the thermocouple profile. Furthermore, where coarse aggregates are located between the temperature sensors, the influence of soil solids would be dominant and changes in soil moisture conditions would have minimal impact on ρ, These results indicate that the needle readings are strongly influenced by moisture held within pore spaces between the finer particles and that the cooling cell may more accurately represent the whole soil, including coarse aggregates where pore space (and therefore porewater) is virtually non-existent. Comparison of the values obtained by both methods with the published values shown in Table 1 indicates that the needle method may be sufficient for this material in dry conditions. However, once water is incorporated into the sand matrix, the resistivity-moisture relationship is inconsistent and becomes dependent on the chemical and physical properties of the soil being assessed.

To further assess the results of the cooling cell, the thermal resistivity of two additional materials with distinct grain size distributions were measured using both methods, and compared. These materials include a fine-grained mineral soil with large aggregates (illustrated by Figure 1b), and a crushed granitic gravel (Figure 1c) composed of homogeneous particle sizes and large air-filled pore spaces. Assessment of the mineral soil with large aggregates (Figure 1b; Table 1) indicates that ρ measured using the cooling cell (192 °C cm W^{-1}) may be two to four times lower than that measured using the needle (378-616 °C cm W^{-1}). In this case, we believe the influence of the large aggregates (composed of negligible pore space) on the needle readings was nonexistent, and the soil fines and interparticle pores solely dictated the ρ measurements. Furthermore, the variation in ρ measured using the cooling cell suggests that the presence and volume of coarse aggregates have a substantial impact on thermal transfer through the soil. The granitic gravel (Figure 1c; Table 1) exhibited ρ = 1727 °C cm W^{-1} using the needle method, compared to 189°C cm W^{-1} using the cooling cell. Since ρ = 4000 °C cm W^{-1} for air and 40 °C cm W^{-1} for granite, this indicates that the values obtained using the needle method are strongly influenced by the air-filled pore space surrounding the needle due to poor needle-particle contact (Campbell et al. 2016; IEEE 1992), with lesser influence from the granite particles. However, lower ρ measured using the cooling cell suggests that the thermal transfer through and between grains is significantly greater than indicated using the traditional needle method.

Comparison of ρ acquired via the needle method and GHD's top-down cooling cell are shown in Table 1, and compared to ρ of common soil and trench backfill (Hydro One 2000) components. Results suggest that the needle method is insufficient for measuring the thermal properties of some soils, particularly those composed of fine soil particulates mixed with coarse aggregates, and those wholly composed of coarse aggregates.

4 CONCLUSIONS

This research shows that if resistivity values for a soil of interest are accepted strictly based on the traditional needle method, materials may be deemed unsuitable for a particular use when indeed they are suitable, resulting in unjustified increases in project costs. In response, an alternative method for measuring thermal resistivity of a wide variety of soils has been developed.

Table 1. Comparison of thermal resistivity, ρ, values for the test soils (moisture content = 0%) using the thermal needle and the cooling cell, and that of common soil materials from the literature. Soils 1-5 are test samples (see Figures 1 and 5).

Soil Material	thermal resistivity, ρ (°C cm W^{-1}) needle	cell
1 standard sand	270	247
2 limestone screenings	277	321
3 crushed granitic gravel	1727	377
4 mineral soil, large agg.	378 - 616	192
5 coarse sand, large agg.	275	295
water	169	
air	4000	
organics	500	
sand	333	
granite (solid)	40	
limestone	77	

The results of this study show that measurements of the thermal properties of a soil using the needle method may be representative of the whole soil, depending in the soil moisture conditions, physical properties, and the method used for assessment. In soils containing or wholly composed of large aggregates, the thermal properties of a bulk soil may not be accurately characterized by the standard, traditional thermal needle method. This research shows that the resistivity measured using the thermal needle is artificially high in such soils due to poor contact between the needle and soil grains, and may be artificially low if the soil material is composed of a significant portion of large aggregates. Readings may be disproportionately influenced by air held within pore spaces in gravel soils, or by the thermal properties of soil fines in well-graded soils.

Unlike the needle method, GHD's cooling cell method appears suitable for all soil types, including those composed of coarse aggregates. Though the proposed technology requires 24 to 48 hours to reach thermal equilibrium, it provides a portable, versatile and reliable method for determining the thermal resistivity of any soil. Furthermore, this method eliminates the need for additional laboratory analyses of the soil physical characteristics required for the determination of thermal properties by numerical modelling.

While initial results from the cooling cell seem promising, methodological improvements will be pursued. The thermocouple profile provided important information about the consistency of thermal properties throughout a soil and increased our confidence in the results, application of this test requires temperature sensors only at the top and bottom of each layer. For this reason, the next steps include increasing the number of profiles and decreasing the number of sensors within each profile. Furthermore, numerical models will be employed to cross-validate the results from this method.

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