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Comparison of thermal conductivities of undisturbed field and remolded laboratory specimens

Comparaison des conductivités thermiques de spécimens de laboratoire non remaniés sur le terrain et remoulés

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ABSTRACT: Thermal conductivity is a key parameter governing the performance of shallow thermo-active foundations. In this paper, we present the results from a field and laboratory testing program, where seismic cone penetration tests and conventional undisturbed Shelby tube sampling were performed side by side at the National Geotechnical Experimentation Site in Opelika, Alabama, US. The thermal conductivity of the undisturbed samples as well as remolded samples were measured in the laboratory. The results indicate that in general, the thermal conductivity of the remolded samples is noticeably lower than those of the undisturbed samples. A review of the seismic cone penetration test results indicate that the soils at this particular site typically plot near the boundary of the young, relatively non-structured soils and soils showing significant microstructure effects due to cementation, bonding or aging effects, indicating there may be microstructure effects influencing the thermal soil behavior at this site. Additionally, there may be some variance related to differences in the sensed volume associated with the sensors used for measurement of thermal conductivity.

RÉSUMÉ: La conductivité thermique est un paramètre clé qui gouverne la performance des fondations thermoactives superficielles. Dans cet article, nous présentons les résultats d'un programme d'essais in situ et en laboratoire, dans lequel des tests de pénétration de cônes sismiques et un échantillonnage conventionnel de tubes de Shelby non perturbés ont été réalisés sur le site national d'expérimentation géotechnique d'Opelika, Alabama, aux États-Unis. La conductivité thermique des échantillons non perturbés ainsi que des échantillons remoulés a été mesurée au laboratoire. Les résultats indiquent qu'en général, la conductivité thermique des échantillons remoulés est nettement inférieure à celle des échantillons non perturbés. Un examen des résultats des tests de pénétration au cône sismique indique que les sols de ce site particulier se situent généralement près de la limite des sols jeunes relativement non structurés et présentent des effets de microstructure significatifs dus aux effets de cémentation, de collage ou de vieillissement, indiquant que la microstructure peut influencer le comportement thermique du sol sur ce site. Une variance liée aux différences de volume effectivement mésuré par les senseurs utilisés pour mesurer la conductivité thermique peut existir aussi.

Keywords: Thermal conductivity, residual soils, undisturbed, remolded, thermo-active foundations

1 INTRODUCTION

Shallow thermo-active foundations have emerged as a variation of the traditional foundation system where a conventional foundation is fitted with fluid-circulating tubes to exchange heat energy with the ground, which typically remains at an approximately constant temperature below the upper few (~5 to 10) meters (Loveridge and Powrie 2013, Arson et al. 2013). These foundations can thus be used to extract heat from the ground for heating in the winter and re-injecting heat into the ground for cooling during the summer, in addition to providing structural foundation support.

The ability of thermo-active foundations to exchange heat energy with the surrounding geomaterials is strongly influenced by their thermal properties; namely, their thermal diffusivity, α (m^2/s), which is a function of mass density, ρ (kg/m^3), thermal conductivity, k (W/m-K) and specific heat, c (J/kg-K):

$$\alpha = k/(\rho\, c) \tag{1}$$

Thermal conductivity of the geomaterials surrounding a thermo-active foundation is of particular interest for estimating the heat exchange capacity of these systems. Several previous studies have investigated the factors that influence the thermal conductivity of soils. The factors that influence thermal conductivity can be generally summarized as shown in Table 1 (Kersten 1949; Farouki 1981; Salomone et al. 1984; Brandon and Mitchell 1989; Abu-Hamdeh and Reeder 2000; Cote and Konrad 2005; Yun and Santamarina 2008; Cortes et al. 2009; Nasirian et al. 2015; Wallen et al. 2016). Temperature also has an effect on thermal conductivity (Kersten 1949; Farouki 1981; Nikolaev et al. 2013); however, its impact is often considered negligible in the temperature range within which thermo-active foundations typically operate (Salomone and Marlowe 1989).

As seen in Table 1, soil microstructure can have an impact on thermal conductivity. In this regard, it is well known that aging can improve the mechanical properties of soils (Schmertmann 1991). As a practical geotechnical engineering matter, it has been shown that aged deposits are significantly less susceptible to liquefaction in comparison to recent deposits due to diagenesis (e.g., Andrus et al. 2009). In the case of thermal behavior, bonding and cementation can significantly improve the thermal conductivity of soils. The cementation effect is particularly important when the material is dry, and less important when the material is saturated with water (Farouki 1981). For example, it has been shown that cementation caused by microbially induced calcite precipitation (MICP) can increase the thermal conductivity of sands up to 250 percent under dry conditions and about 25 to 50 percent in the saturation range between 0.2 and 0.8 (Venuloe et al. 2016). The enhancement is attributed primarily to the formation of calcite crystals which act as thermal bridges by increasing the contact area between particles.

Table 1. Factors influencing soil thermal conductivity

Factor	**Generalized Effect**
Saturation	k increases rapidly up to critical moisture content; little increase thereafter
Density/ gradation	k increases with increased density; a small amount of fines can improve k by acting as binder
Mineralogy	k increases with increasing k_{solid}
Effective stress	k increases with increasing effective stress
Pore fluid	k increases as k_{fluid} increases
Particle size/shape	k increases with increasing particle size, and with increasing angularity
Microstructure	k increases with enhanced effective contact area due to bonding, cementation, and creep/diagenesis

The presence of microstructure in soils can be detected based on small-strain wave velocity measurements. In particular, Robertson (2016) has proposed a methodology based on seismic cone penetration test results for identifying soils with microstructure, using the net cone resistance, q_n, normalized cone resistance, Q_{tn}, and modified normalized small-strain rigidity index, $K^*(G)$. $K^*(G)$ is a function of the small-strain stiffness, G_0, which in turn is a function of the measured shear wave velocity, V_s:

$$K^*(G) = (G_0/q_n)(Q_{tn})^{0.75} \quad (2)$$

$$G_0 = \rho\ (V_s)^2 \quad (3)$$

Using this methodology, the line defined by $K^*(G)$ = 330 delineates the soils with significant microstructure from those with little to no microstructure (Robertson 2016).

Additionally, it has been shown that microstructure disturbance due to sample remolding can manifest as reduced small-strain stiffness, when comparing field measurements to remolded laboratory measurements. The disturbance effects are particularly evident for predominantly sandy soils as compared to clayey soils (Rinaldi and Santamarina 2008). With regard to thermal conductivity, Low et al. (2015) showed that laboratory thermal conductivity measurements on undisturbed samples of London clay differed significantly from those calculated from the results of an in-situ thermal response test (TRT). The differences were attributed to effective stress, sample disturbance including potential drying during and after the sampling process, and differences in the sensed volume between the laboratory and field measurements.

In this paper, we present the results from a field and laboratory testing program, where seismic cone penetration tests and undisturbed Shelby tube sampling were performed side by side at the National Geotechnical Experimentation Site (NGES) in Opelika, Alabama, USA. The site is located within the Piedmont physiographic region in the eastern United States, which extends from central Alabama in the south to New Jersey in the north. Several major U.S. cities are located within the region, including Atlanta-GA, Charlotte-NC, Washington-DC, Baltimore-MD and the Philadelphia-PA metropolitan area. The region is characterized by saprolite (residual soils) overlying crystalline rocks. The bedrock typically includes pre-dominances of schist, gneiss, and granite (Mayne et al. 2000). The residual soils were weathered in place due to chemical and mechanical processes, and the subsurface profile is typically characterized by a gradual transition from soil to decomposed rock (often referred to as Partially Weathered Rock) to unweathered rock with depth (Sowers and Richardson 1983). The site has been studied extensively, including geotechnical subsurface characterization using various in-situ and laboratory tests (Mayne et al. 2000; Finke et al. 2001; Mayne and Brown 2003). However, to date, the characterization efforts have primarily focused on the mechanical properties of the residual soils. To the best of the authors' knowledge, no testing has been performed to date to characterize the thermal properties of the residual soils at this site.

2 METHODOLOGY

Field testing at the NGES included the performance of two (2) seismic resistivity piezocone penetration test soundings (SRCPTu-1 and SRCPTu-2), and two (2) soil test borings (B-1 and B-2) adjacent to the sounding locations to obtain Shelby tube samples from several depths. The test locations were approximately 25 m apart, and the ground elevation of the test locations was similar. The SRCPTu soundings were performed using a 15-cm^2 electronic piezocone with a tip net area ratio of 0.80 and with the pore pressure sensor at the shoulder (u_2) position. Shear wave velocity measurements were made in approximately 1-meter intervals. Undisturbed sampling was performed using 7.5 cm outside diameter, 75 cm long Shelby tubes.

The Shelby tube samples were sealed and transported to the Georgia Tech Sustainable Geosystems laboratory for subsequent extraction and laboratory testing. Once the Shelby tubes were in the laboratory, the soil samples were extruded incrementally using a hydraulic extraction device. Prior to extraction of each increment, a 10-cm long, 2.4 mm diameter thermal needle probe (TR-1, manufactured by Decagon Devices) was inserted while the sample was still confined in the Shelby tube in order to measure thermal conductivity. Data logging and analysis of thermal conductivity was performed using a handheld KD2 Pro Thermal Properties Analyzer (also manufactured by Decagon Devices). After measurement of thermal conductivity inside the tube, each sample was extruded, trimmed, the sample dimensions measured, and the sample placed in the oven for determination of unit weight / void ratio and moisture content. These steps were repeated until the samples were fully extracted from the Shelby tubes. In total, forty (40) samples were tested for determination of their unit weight, moisture content, and thermal conductivity.

Thirteen (13) representative samples were then selected for remolding in a custom designed acrylic chamber with an inner diameter of 63.5 mm and a height of 41.5 mm. The specimens were remolded to the desired dry density (to match the field density as closely as possible) via dry tamping in uniform layers. De-aired water was injected through a port located at the bottom of the sample until the target degree of saturation was achieved (to also match the field saturation as closely as possible). The thermal conductivity of the samples was then measured using a 3 cm long, 1.3 mm diameter dual-needle heat-pulse probe (SH-1, manufactured by Decagon Devices). Data logging and analysis of the thermal conductivity tests was performed using the KD2 Pro Thermal Properties Analyzer. The thermal sensors were calibrated regularly during the testing process using the calibration procedures recommended by the device manufacturer.

In addition, index tests (sieve analysis and Atterberg Limits tests) were performed on select samples for evaluation of their grain size distribution and plasticity characteristics. Relevant index properties are summarized in Table 2. The soils can typically be described as silty sands (SM), with a surficial layer of sandy silts of low to high plasticity (ML and MH) at location B-2.

Table 2. Summary of index test results

ID	Location / Depth (m)	FC (%)	LL (%)	PI (%)	USCS
1	B-1 / 4.6-5.2	30	NM	NM	SM
2	B-1 / 6.7- 7.3	30	44	13	SM
3	B-1 / 8.8- 9.4	23	NM	NM	SM
4	B-1 / 12.5-13.1	30	41	12	SM
5	B-1 / 13.7-14.5	21	41	11	SM
6	B-2 / 1.1-1.8	58	48	20	ML
7	B-2 / 2.7-3.5	93	70	29	MH
8	B-2 / 5.2- 6.0	34	NM	NM	SM
9	B-2 / 6.7-7.5	34	43	11	SM
10	B-2 / 8.2-9.0	29	NM	NM	SM
11	B-2 / 9.7-10.5	44	39	7	SM
12	B-2 / 11.3-12.0	24	40	4	SM
13	B-2 / 17.4-18.2	31	NM	NM	SM

FC = Fines Content (passing #200 sieve); LL = Liquid Limit; PI = Plasticity Index; NM = not measured

3 RESULTS

3.1 Subsurface Conditions

The results of the two SCRPTu soundings performed at NGES are shown in Figure 1. The tip stresses have been corrected as per recommended practice, although the correction from q_c to q_t is not significant in these residual soils because of the magnitude of the pore water pressures (Mayne et al. 2000). The cone tip stresses measure about 1 to 5 MPa in the upper 10 m. From 10 to about 18 m, the cone tip stresses measure approximately 4 to 10 MPa. The relatively higher tip resistances and sleeve frictions below 18 m indicate the soundings were most likely terminated in the transitional zone from completely weathered saprolite to the underlying partially weathered rock.

The porewater pressure behavior is somewhat more complex. In the unsaturated zone above the groundwater table, negative, positive and zero-ish pore pressures were observed. This has been attributed to the transient capillary conditions as a result of physical and environmental factors (i.e., varying degree of saturation due to infiltration and prior rainfall activities, etc.) at the time of testing (Mayne et al. 2000). Of particular note are the zones of relatively high positive pore pressure between 1.5 and 3 m in sounding SRCPTu-1, and between 2.5 and 5 m in sounding SRCPTu-2. Below the groundwater table, readings were typically negative and near cavitation (u_2 = -90 kPa). Negative porewater pressures during cone penetration test soundings are typically observed in stiff fissured geomaterials. In Piedmont residuum, this behavior has been attributed to the shoulder location of the u_2 porewater pressure sensor and the resulting shear-induced pore pressures, as well as the remnant discontinuities such as fissures, fractures and jointing of the parent rock (Sowers, 1994; Mayne et al. 2000). The test results suggest the water table depth at the time of testing was approximately 11 m.

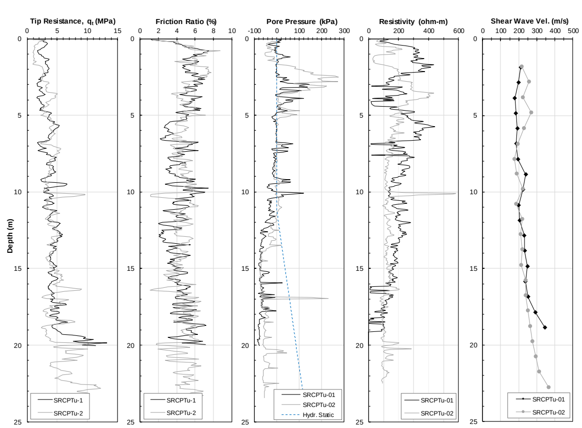

Figure 1. Summary of SCRPTu soundings

Seismic shear wave velocities were measured to be between about 180 and 275 meters per second (m/s) in the upper approximate 10 m. Below this depth, the measured velocities were generally noted to increase with depth, reaching as high as about 345 m/s at a depth of around 19 m in sounding SRCPTu-1, and about 365 m/s at a depth of around 23 m in sounding SRCPTu-2.

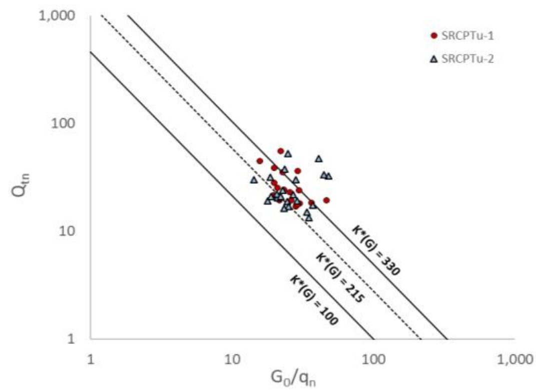

Figure 2. Soil microstructure charts for sounding SRCPTu-1 and SRCPTu-2

Electrical resistivity measurements showed more variance between the two test locations. SRCPTu-1 encountered a zone of relatively higher resistivity in the upper 2.5 m, and seams of lower resistivity from 2.5 to about 5 m. Below 5 m, the resistivity is generally decreasing with depth. Lower resistivity soils were also encountered between about 16 and 17 m, and between about 18 and 19 m. SRCPTu-2 encountered a zone of lower resistivity between about 1 and 2 m, and a zone of higher resistivity from about 2.5 to 4 m. From a depth of 4 to 10 m, the resistivity is generally decreasing with depth. A thin seam of high resistivity soils was encountered just below 10 m, and the resistivity was generally between 100 and 200 ohm-m from 10 to 17 m. Below 17 m, the resistivity was generally around 100 ohm-m.

Figure 2 shows the soil microstructure charts based on Robertson (2016). It can be seen that most of the points plot within the range between K*(G) = 215 and K*(G) = 330 (with a few outliers), though most of the points are closer to the K*(G) = 330 line and some even above. This indicates that there may be microstructure effects present at this site.

3.2 Thermal Conductivity

The results of the thermal conductivity (k) measurements on the Shelby tube samples and the remolded samples are summarized in Table 3, and also shown graphically in Figure 3. In Table 3, the suffixes "-t" and "-r" refer to "tube" and "remolded", respectively. It can be seen from Table 3 and Figure 3 that in general, the thermal conductivity as measured in the undisturbed tube samples is higher than that of the remolded samples. There was only one instance where the thermal conductivity of the tube sample was lower than that of the remolded sample. With the exception of the outlier, the ratio of the thermal conductivity of the tube samples to that of the remolded samples ranged between 1.05 and 1.26, with an average of 1.14 and a standard deviation of 0.07. For the two sandy silt samples, the average ratio was about 1.1, while for the silty sand samples the ratio was approximately 1.15.

Table 3. Summary of measured thermal conductivity

ID	*e*	*S*	***k*-t**	***k*-r**	***k*-t / *k*-r**
1	0.81	0.83	1.718	1.553	1.11
2	0.65	0.70	1.388	1.788	0.78
3	0.75	0.80	2.385	1.943	1.23
4	0.73	0.97	2.086	1.761	1.18
5	0.71	0.89	2.085	1.699	1.23
6	0.73	0.99	2.142	1.950	1.10
7	1.17	0.96	1.328	1.220	1.09
8	0.81	0.79	2.001	1.707	1.17
9	0.68	0.74	1.842	1.752	1.05
10	0.66	0.76	1.750	1.628	1.08
11	0.71	0.89	1.852	1.670	1.11
12	0.70	0.82	2.068	1.639	1.26
13	0.71	0.89	1.864	1.661	1.12

e = void ratio; *S* = degree of saturation

A likely explanation for the difference between the undisturbed tube samples and the remolded samples is the loss of structure upon remolding. As indicated by the seismic cone penetration test results and Figure 2, the soils at this site appear to have some microstructure, most likely due to aging effects. The loss of this microstructure upon remolding may have resulted in lower measured thermal conductivity values.

The findings are also consistent with previous findings (Rinaldi and Santamarina 2008), in that the sandy soils appear to be more susceptible to remolding effects than finer-grained soils, though the sample size for fine grained soils in this study was very small. The other factors listed in Table 1 are not considered to have been a factor, given that both the tube and remolded samples were tested with no confining stress, water was the pore fluid in both tests, and there would have been no change in mineralogy. The rubber tamper used to remold the samples is also not believed to have altered particle size or shape, given that hand pressure alone is not sufficient to result in particle crushing.

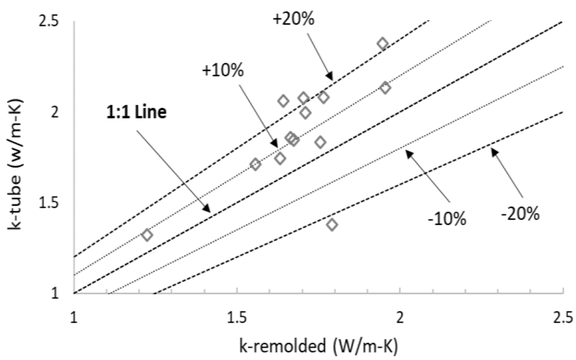

Figure 3. Thermal conductivity of tube vs. remolded samples

Another possible explanation for the difference is the sensed volume associated with the two sensors used for measurement of thermal conductivity. Even though the sensors were calibrated regularly during testing and no issues were observed, the SH-1 sensor used to test the remolded samples has a smaller sensed volume in comparison to the TR-1 sensor. As previously discussed, Low et al. (2015) showed that the back-calculated thermal conductivity from a full-scale thermal response test (TRT) is significantly greater than the thermal conductivity measured in the laboratory. This was attributed to differences in sensed volume, especially due to the heterogeneity which is likely to exist in the field (or in a larger tube sample) but may not exist in a small laboratory specimen, as well as sample disturbance effects, potential drying during and after the sampling process, and effective stress which increases the quality of particle-to-particle contacts in the field. In regard to potential drying during and after sampling, while a lower degree of saturation implies a lower thermal conductivity, drying also induces suction. Suction forces in turn act to improve the quality of the particle-to-particle contacts, and hence may counteract the reduction in thermal conductivity due to loss of moisture.

4 CONCLUSIONS

The thermal conductivity of undisturbed Shelby tube samples and laboratory samples remolded to the same density/void ratio and degree of saturation were measured using needle probe sensors. The results indicate that in general, the thermal conductivity of the remolded samples is noticeably lower than those of the undisturbed samples. A review of the normalized cone resistance and normalized rigidity index based on the seismic cone penetration test results indicate that the soils at this particular site typically plot near the boundary of the young, relatively non-structured soils and soils showing microstructure effects due to cementation, bonding or aging effects. These results suggest there may be microstructure effects influencing the soil thermal behavior at the NGES.

In addition, based on results from literature, it appears that the thermal conductivity of undisturbed samples would be expected to be smaller than those from a full-scale in-situ experiment such as a thermal response test (TRT). In this regard, the present study highligths some of the challenges associated with determination of thermal conductivity from field and laboratory tests. In the laboratory, while samples can be prepared under relatively controlled conditions, variances can still occur due to sample size and preparation, sensor size and accuracy, and other factors. In the field, while a test such as a TRT provides a larger sensed volume (and hence better captures the natural vertical and lateral variation of soil properties), it is also subject to higher costs relative to laboratory testing, as well as differences resulting from models used to interpret the TRT results.

These challenges also have practical implications for design of thermo-active foundations, as the fluid circulation loop length is directly influenced by the thermal conductivity of the geomaterials surrounding the foundation. In this regard, the findings presented herein suggest that using values obtained from remolded samples may be conservative, resulting in longer loop lengths and additional cost. On the other hand, some level of conservatism may be beneficial because the design of the thermal aspect of thermo-active foundations are typically not subject to a relatively large factor of safety, as is commonly used for design of the mechanical aspects of the geotechnical foundations.

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