UC San Diego

UC San Diego Previously Published Works

Title

Shear Behavior of Silty Soil and Soil-Structure Interface under Temperature Effects

Permalink

<https://escholarship.org/uc/item/1pb9583w>

Authors

Xiao, Suguang
Suleiman, Muhannad T
McCartney, John S

Publication Date

2014-02-24

DOI

10.1061/9780784413272.399

Peer reviewed

Shear Behavior of Silty Soil and Soil-Structure Interface under Thermal Loading

S. Xiao¹, M. T. Suleiman², Ph.D., M. ASCE and J. S. McCartney³, Ph.D., P.E. M.
ASCE

¹Graduate Student, Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, PA 18015 (email: sux211@lehigh.edu)

²P. C. Rossin Assistant Professor, Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, PA 18015 (email: mts210@lehigh.edu)

³Associate Professor, Department of Civil, Environmental and Architectural Engineering, University of Colorado at Boulder, Boulder, CO 80309 (email: john.mccartney@colorado.edu)

ABSTRACT: Geothermal structures, such as energy piles, are subjected to cyclic changes of temperature that affect the properties of soil-structure (or pile) interface surrounding soil. To evaluate the effects of thermal loading (i.e., change of temperature) of the soil and soil-pile interface, a series of direct shear tests with controlled temperature were conducted. To characterize the soil properties, the direct shear device was placed in a temperature controlled chamber and the temperature of the soil was monitored. The soil tests were conducted at temperatures of 4, 21, 30, and 38°C. Furthermore, the effect of cyclic temperature change was investigated using a small number of cycles (maximum of four cycles in this paper). The effects of thermal loading were also characterized using a modified direct shear test device where the bottom half of the soil box was replaced by a concrete plate. The soil-pile interface properties were measured at the same temperatures and normal stresses as the soil tests. Finally the results of the soil and soil-pile interface were compared.

INTRODUCTION

In addition to supporting structural loads, geothermal deep foundations (or energy piles), which incorporate embedded closed-loop primary pipes circulating a liquid (water or antifreeze), function as a heating and cooling system by providing access to the steady temperature of the subsurface soil (Brandl 2006). The operation of the heat exchange system is of cyclic nature because the heat pump runs for some time and then stops before it runs again, which induces thermal cycles at the soil-pile interface and on the surrounding soil. The temperature at the soil-pile interface of energy piles vary between 1°C to 31°C (Brandl 2006; Hamada et al. 2007; Wood et al. 2009; Abdelaziz et al. 2011; and Shang et al. 2011). The change of temperature results in expansion and contraction of the pile altering the normal pressure at the soil-pile interface and leading to changes of the soil-pile interface shear (i.e., shaft resistance). However, the effects of temperature change and temperature cycles on the soil-pile interface have not been investigated. The heat exchange between the pile and surrounding soil also influence the mechanical properties of the surrounding soil. A great number of tests have been developed by different researchers to investigate the

soil behavior under thermal loads (e.g., Laguros 1969; Noble and Demirel 1969; Houston et al. 1985; Kuntiwattanakul et al. 1995). The studies show that undrained heating induce excess pore pressure which reduce the strength of soil. On the other hand, for drained heating, results indicate that as temperature increases the strength of the soil increases. In this paper, a modified direct shear test device was utilized to evaluate the effect of temperature change and cyclic thermal loading on soil and soil-pile interface mechanical properties.

TESTING APPARATUS

The conventional direct shear testing device was used to measure the soil shear strength of the soil. To control the temperature during the test, the direct shear testing device was placed in a temperature-controlled chamber. Two thermocouples were installed through the drainage holes to measure the temperature of the soil (Figure 1).

Figure 1. Direct shear test apparatus setup

In order to test the soil-concrete interface shear response at different temperatures, the direct shear device was modified. In the modified direct shear apparatus, the lower shear box is replaced by a concrete plate with embedded tubes. The top half of the shear box incorporates the soil specimen. The dimension of the concrete plate is 101.6 mm (4.0 in.) by 127.0 mm (5.0 in.) by 21.6 mm (0.85 in.). Two smooth steel plates were embedded on the top surface of the concrete plate to minimize the friction between adjustment screws of the upper half shear box and the concrete plate (Figures 2(a), 2(b), and 3). Silicone rubber tubes of 6.4 mm (0.25 in.) diameter were embedded in the concrete plate as shown in Figure 3. Fluid from a heat pump was circulated through the tubing to control the heating and cooling of the concrete. One thermocouple was placed on the concrete surface to measure the temperature of soil-concrete interface.

Figure 2. Direct shear test apparatus setup for soil-structure interface with thermal loading

Figure 3. Layout of the heating/cooling tubing in the concrete plate

MATERIALS

Soil obtained from the Bonny dam near the Colorado-Kansas border was used in this study. The soil had a plasticity index of 4, a specific gravity of 2.6, and a fines content of 84%. The soil was classified as ML (inorganic silt) according to the Unified Soil Classification System (USCS). The maximum dry unit weight of the soil is 17.7 kN/m³ and the optimum water content is 13.6%, both corresponding to the maximum standard Proctor compaction effort. Additional information and properties of soil can be found in Stewart and McCartney (2012).

The specimens were compacted in the shear box to achieve a dry unit weight of 1451 kg/m³ and a target moisture content of 13% during the shearing stage, which required few trials due to temperature change and the time needed to achieve the

target temperature. The measured water contents of soil specimens at the end of shearing were ranging from 12.6 to 14.6%.

TEST PROCEDURES

Soil tests

The dimensions of the soil specimen were 63.5 mm (2.5 in.) in diameter and with a thickness of 22.75 mm (0.97 in.). According to ASTM D3080, the rate of shearing was determined to be 0.20 mm/min to reach to the shearing rate requirements for all the specimens. Before the consolidation stage, thermocouples were set in the soil through the drainage holes in the shear box to measure the temperatures. The shearing stage was performed when the soil reached the target temperature. Soil tests were conducted under a normal stress of 93 kPa at temperatures of 4, 21, 30, and 38°C, respectively. Tests were also performed at the normal stress of 93 kPa after subjecting the soil to cyclic thermal loading. Two soil specimens were tested; one subjected to a thermal cycle with temperature change from 21 to 38°C to 21°C before shearing and the other subjected four thermal cycle between 21 and 38°C; were used to evaluate the effect of temperature cycles. Furthermore, two-cycle thermal loads (21 - 38°C) were also applied on a soil specimen at 62 kPa normal stress.

Soil-structure interface tests

The soil-structure interface shearing tests were conducted in the lab at a room temperature of 21°C, and the heat pump was utilized for heating and cooling as shown in Figure 3. The concrete plate was placed under the top soil shear box. The soil specimen in the upper shear box has a thickness of 13.8 mm (0.55 in.) and a diameter of 63.5 mm (2.5 in.). After the consolidation stage, the heat pump was started to apply heating or cooling to the concrete plate. The target temperatures at the soil-structure interface were 6 and 21°C. During the shear stage, the temperature of the soil-structure interface was maintained at the target. The temperature of concrete top surface was recorded during the whole test.

RESULTS AND DISCUSSION

Soil tests were performed at different temperatures with the same normal stress of 93 kPa in the temperature-controlled chamber. Figure 4 presents the shear stress-horizontal displacement curves at different target temperatures (4°C, 15°C, 26°C, and 38°C). The results in Figure 5 illustrate the peak shear strength of silt as function of temperature. The peak shear strength at 38°C is 15.1% larger than that at 4°C. These results are comparable to those reported by Noble and Demirel (1969) where a clay soil presented an increment of strength of 18.5% between 2°C and 40°C. The results of the one cycle test show minimal change of stress-strain response when compared to the test at 38°C. After four-cycles of thermal loading between 26°C and 38°C, approximately 7% increases of the peak shear strength was observed when compared to the response at 38°C. It was also observed that after four cycles of heating between 26°C and 38°C at 93 kPa normal stress, minimal change of soil specimen thickness was observed (i.e., 0.04 mm).

Figure 4. Soil mechanical response at different temperatures with a normal stress of 93 kPa

Figure 5. Peak shear strength of silt with different thermal loading patterns (monotonic heating or temperature cycles) at a normal stress of 93 kPa

The shear stress versus displacement curves for soil specimens subjected to different normal stresses (31, 62, and 93 kPa) at 6°C and 21°C are shown in Figure 6. Soil specimens tested at 21°C demonstrates greater shear strengths than that at 6°C. Moreover, two-cycle thermal loading in the range of 21 to 38°C were applied on the soil specimen, the peak shear strength increased by 2.6% comparing to that at 21°C under the same normal stress. The failure envelopes of 6 and 21°C were plotted in Figure 7. The cohesion of soil at 6 and 21°C were 37.9 and 35.5 kPa, respectively.

Figure 6. Shear stress versus displacement of soil under different normal stresses at 6°C and 21°C

Figure 7. Failure envelopes for soil at 6°C and 21°C

A comparison of the shear stress-strain curves of the soil and soil-concrete interface is shown in Figure 8. The shear strength of the soil is 30 to 90% larger than the soil-concrete interface at the same normal stress. The failure envelopes for the soil and soil-concrete interface are shown in Figure 9. The intercept of shear envelopes for

the soil- concrete interface is smaller than that of the soil (7.5 vs. 35.5 kPa), and the interface friction angle is only slightly smaller than that of the soil.

Figure 8. Comparison of the shear strength of soil and soil-structure interface at different normal stresses in room temperature (21°C)

Figure 9. Failure envelopes for soil and soil-structure interface at 21°C

In Figure 10, the peak shear strengths of the soil-structure interface at 21°C are 5-16% larger than that at 6°C. However, all the water contents of the soil specimen at 6°C were around 0.6% higher than the specimens at 21°C. More studies will be conducted to investigate on the temperature effects on the soil-structure interface with

different water contents. The shear strength parameters of soil and soil-interface at 6 °C as well as 21 °C are tabulated in Table 1.

Figure 10. Shear strength of soil-structure interface at different temperature

Table.1 Shear strength parameters of soil and soil-concrete interface

Test description	Effective angle of friction, °	Cohesion or Adhesion, kPa
6°C, soil	29	37.9
21°C, soil	25	35.5
6 °C, soil-concrete interface	32	3.1
21°C, soil-concrete interface	32	7.5

SUMMARY AND CONCLUSIONS

The mechanical properties of compacted silt under the temperature variation were explored. In addition, the direct shear device was modified to evaluate shear behavior of soil-structure interface under the thermal loading. The results from the testing lead to the following provisional conclusions:

1. The shear strength of silt is proportional to the temperature. The cyclic thermal loads increase the shear strength of the silt. The unsaturated silty soil presented thermal-strengthening behavior under the cyclic thermal loading.
2. The peak shear strengths of the silt are 30-90% larger than the soil-structure interface at the same normal stresses and water contents.
3. The shearing behavior of soil-pile interface has the same trend as the soil where the soil-pile interface strength increases as the temperature increases.

Future tests will be conducted to explore the effects of temperature change on friction angles and cohesions for soil and soil-concrete interface.

ACKNOWLEDGMENT

This project was financed (in part) by a grant from the Commonwealth of Pennsylvania, Department of Community and Economic Development, through the Pennsylvania Infrastructure Technology Alliance (PITA).

REFERENCES

- Abdelaziz, S.L., Olgun, C.G. and Martin II, J.R. 2011. Design and Operational Considerations of Geothermal Energy Piles. *Proceedings of GeoFrontiers 2011*, Dallas, Texas, CD-ROM.
- Amatya, B. L., Soga, K., Bourne-Webb, P. J., Amis, T. and Laloui, L. 2012. Thermo-mechanical behaviour of energy piles. *Géotechnique*, 62 (6), pp. 503-519.
- Amis, A., Bourne-Webb, P., Amatya, B., Soga, K. & Davidson, C. 2008. The effects of heating and cooling energy piles under working load at Lambeth College. *Proceedings 33rd Annual and 11th International DFI Conference*, New York, article no. 1620.
- ASTM International. *Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions*. Vol. 04.08, in *Annual Book of ASTM Standards*. 2004.
- Bourne-Webb, P. J., Amatya, B., Soga, K., Amis, T., Davidson, C. and Payne, P. 2009. Energy Pile Test at Lambeth College, London: Geotechnical and Thermodynamic Aspects of Pile Response to Heat Cycles. *Géotechnique*, 59 (3), pp. 237-248.
- Brandl, H. 2006. Energy Foundations and other Geothermal Ground Structures. *Géotechnique*, 56 (2), pp 81-122.
- Hamada, Y., Nakamura, M., Kubota, H. 2007. Field Measurements and Analyses for a Hybrid System for Snow Storage/Melting and Air Conditioning by Using Renewable Energy. *Applied Energy*, 84 (2), pp. 117-134.
- Houston, S. L., W. N. Houston, and Williams, N. D. 1985. Thermo-Mechanical Behavior of Seafloor Sediments. *Journal of Geotechnical Engineering*, Vol. 111 (11), pp. 1249-1263,
- Kuntiwattanakul, P., Towhata, I., Ohishi, K., & Seko, I. 1995. Temperature Effects on Undrained Shear Characteristics of Clay. *Soils and Foundation*, 35(1), pp. 147-162.
- Laloui, L., Nuth, M., and Vulliet, L. 2006. Experimental and Numerical Investigations of the Behavior of a Heat Exchanger Pile. *International Journal for Numerical and Analytical Methods in Geomechanics*, 30 (8), pp. 763-781.
- Laguros J.G. 1969. Effect of temperature on some engineering properties of clay soils. *Highway Research Board, Special Report 103*, National Research Council, Washington, D.C., pp. 186-193.

- Murayama, S. 1969. Effects of temperature on elasticity of clays. *Highway Research Board, Special Report 103*, National Research Council, Washington, D.C., pp. 194–203.
- Noble, C. A. and Demirel, T. 1969. Effect of temperature on strength behavior of cohesive soil. *Highway Research Board, Special Report 103*, National Research Council, Washington, D.C., pp. 204-219.
- Shang, Y., Li. S. 2011. Analysis of Geo-temperature Recovery under Intermittent Operation of Ground-source Heat Pump. *Energy and Buildings*, 43 (4), pp. 935-943.
- Sherif, M.A., and Burrows, C.M. 1969. Temperature effects on the unconfined shear strength of saturated cohesive soil. *Highway Research Board, Special Report 103*, National Research Council, Washington, D.C., pp. 267–272.
- Stewart, M.A. and McCartney, J.S. 2012. Strain distributions in centrifuge model energy foundations. *Geo-Congress 2012*. Oakland, CA. March 28-30th, ASCE. 10 pg.
- Stewart, M. A. and McCartney, J. S. 2013. Centrifuge modeling of soil-structure interaction in energy foundations. In review.
- Wood, C. J., Liu, H. and Riffat, S. B. 2009. Use of Energy Piles in a Residential Building, and Effects on Ground Temperature and Heat Pump Efficiency. *Géotechnique*, 59 (3), pp. 287-290.