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Temperature Effects on Lateral Earth Pressure

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ABSTRACT

This study aims to assess the effects of temperature on lateral earth pressure exerted on energy geostructures. The experiments performed in this study utilize a fully instrumented retaining wall facility, with pressure cells and strain gauges, at Virginia Tech. Compacted well-graded sand with silt is used as the backfill soil. Thermal loads are applied to the retaining wall and backfill soil through geothermal piping, and both the vertical and lateral earth pressures and strains are monitored during thermal cycling. A thermal cycle is applied to determine the evolution of the lateral earth pressure with temperature. The results regarding changes in the lateral earth pressure versus temperature are reported.

Keywords: Geothermal, Lateral Earth Pressure, Geo-structures, Foundations, Temperature

1 INTRODUCTION

Energy geostructures act as heat exchangers that utilize shallow geothermal energy for space heating and cooling (Olgun, 2015; McCartney, 2016). While it is well-established that temperature variations impact soil strength and deformation, both at the microscale (Darari et al., 2017; Jaradat et al., 2017) and macroscale (Zeinali & Abdelaziz, 2021), current design methods for energy geostructures assume temperature-independent soil behavior. For example, temperature-dependent load-displacement curves for shaft and toe resistances of heat exchanged piles still need to be reached. Quantifying temperature impact on vertical and horizontal earth pressure facilitates the development of temperature-dependent lateral earth pressure and load-displacement curves. For retaining structures, Coulomb (1776) and Rankine (1857) lateral earth pressure theories for active and passive conditions, as well as at-rest conditions, from Jaky's (1948), are temperature-independent (Filz, 1992). At the micro level, the chemical composition, size, and shape of sand grains influence the thermal expansion of the soil skeleton (Svidró et al., 2020). Numerical analyses have been done to simulate the thermal-hydro-mechanical (THM) behavior in the soil at varying temperatures and its effects on the lateral earth pressure of structures. However, they have not been supported by field scale analyses (Sailer, 2019; Thota, 2020). Accordingly, this study aims to determine the temperature effect on lateral earth pressures

applied on energy geostructures at the field scale. A fully instrumented retaining wall facility is utilized for this purpose. The experimental setup, testing program, and preliminary test results are presented and discussed in the next sections.

2 EXPERIMENTAL SETUP AND PROGRAM

Experiments were performed at the retaining wall facility at the Prices Fork Lab of Virginia Tech. The retaining wall facility consists of an area of backfill soil contained by two rigid walls and an actively moving retaining wall. The backfill soil was instrumented with pressure and strain gauges to measure the horizontal and vertical pressure and strains within the ground, respectively. Pressure gauges were also placed vertically along the retaining wall to obtain lateral earth pressure. Two levels of geothermal piping that circulate thermal silicon fluid were embedded in the backfill. The geothermal pipings were connected to a temperature control unit to induce the desired temperature changes. A heating-cooling cycle was applied to observe changes in soil response and lateral earth pressure evolution with temperature. The pressure and strain gauges were connected to a data logger and multiplexers for recording and storing the experimental results.

2.1 Retaining Wall Facility

Sehn and Duncan (1990) developed the retaining wall facility at the Prices Fork's lab at Virginia Tech for their experimental study of compaction-induced earth pressure. The retaining wall facility is 7x10x6 ft, as demonstrated in Figure 1, with an access ramp built to facilitate access for compaction and backfilling. The wall on the right side has four instrumented panels, each 7 ft high by 2.5 ft wide. These panels are permitted to move horizontally. The walls opposing the access ramp and panels are fixed. The backfill height is 6.5 ft and was instrumented at two levels at 2 and 5 ft from the concrete floor, respectively, as shown in Figure 2.



Figure 1. *Virginia Tech instrumented retaining wall facility*

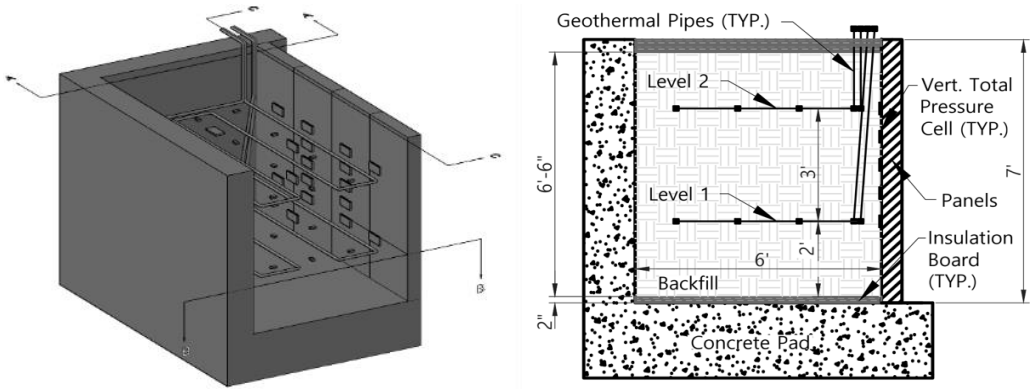


Figure 2. *Retaining wall facility with updated instrumentation (left). Cross section A-A of retaining wall facility from the ramp (right).*

2.2 Instrumentation and Equipment

To induce temperature changes and monitor soil pressure and movement during thermal cycling, the backfill area was instrumented with 22 pressure gauges, 24 strain gauges (SG) with built-in thermistors, and geothermal piping. The instrumentation spacing and configuration for the two geothermal piping levels were identical, as shown in Figure 3. The used pressure gauges were vibrating wire total pressure cells (PCs) from RocTest with a capacity of 2000 kPa. PC calibration factors for mechanical (C_f) and thermal (C_T) from Roctest were used for each PC. The strain gauges used were the EM-5 embedded strain gauges (SGs) developed by RocTest with a range of 3000 με. The pressure and strain gauges were oriented horizontally and vertically to record vertical and horizontal readings, respectively, with 4 PCs and 12 SGs installed near each level of the geothermal piping. Additionally, 18 PCs were placed along the retaining wall to measure lateral earth pressure applied right on the retaining wall, as shown in Figures 2 and 3. All sensors were connected to a RocTest RT-MUX 6/32 multiplexers, and the data was recorded by a Campbell Scientific CR6 datalogger.

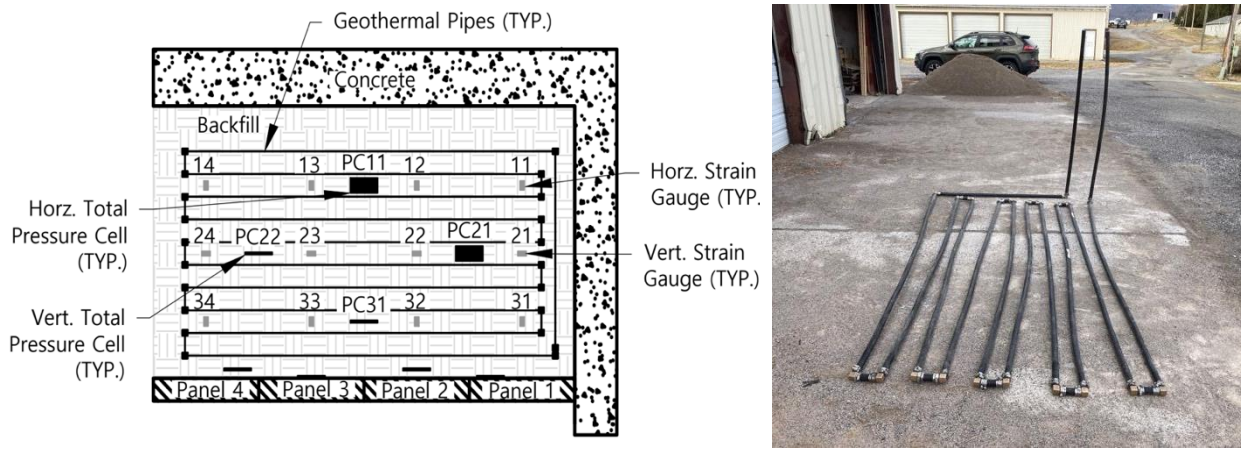


Figure 3. *Plan view B-B of level 1 of retaining wall facility (left). Level 1 geothermal pipe assembly (right)*

The geothermal piping used to induce temperature changes were 1 inch in diameter, 250 psi NSF high-density polyethylene (HDPE) flexible tubes. The pipes were cut down to lengths and connected using bronze fittings, secured with stainless steel clamps (Figure 3). The pipes were spaced 6 inches center-to-center based on a finite element model developed in COMSOL Multiphysics, to estimate the zone of influence of the HDPE pipes. The geothermal piping at the lower and upper levels of the backfill were connected in parallel to form one continuous closed system, which was then connected to a temperature control unit (TCU). The TCU chosen for this project was the Julabo PRESTO A45t with a fluid temperature range of -45 to 250 ˚C. The TCU circulates thermal p60 fluid, Julabo's thermal silicone fluid. The TCU also records the backfill soil temperature through an external pt100 sensor placed 3.5 ft from the bottom of the backfill soil.

A 2-inch-thick FOAMULAR extruded polystyrene (XPS 1000) rigid foam insulation boards were used as an insulation barrier to minimize heat losses during thermal cycling. With a compressive strength of 100 psi, XPS 1000 was selected to eliminate the effect of the board deformations under the applied loads and temperatures from the experimental results. One board thickness of insulation was placed on the concrete floor within the backfill area, and two board thicknesses were placed on the top of the backfill and soil ramp (Figure 1).

3 TESTING PROGRAM

3.1 Materials

The backfill soil used for this project was a cohesionless fill purchased locally from Acco Stone quarry in Blacksburg, Virginia. This fill classifies as well-graded sand with silt (SW-SM), following the Unified

Soil Classification System, USCS (ASTM, 2020). Figure 4 below provides the gradation curve of the backfill soil .

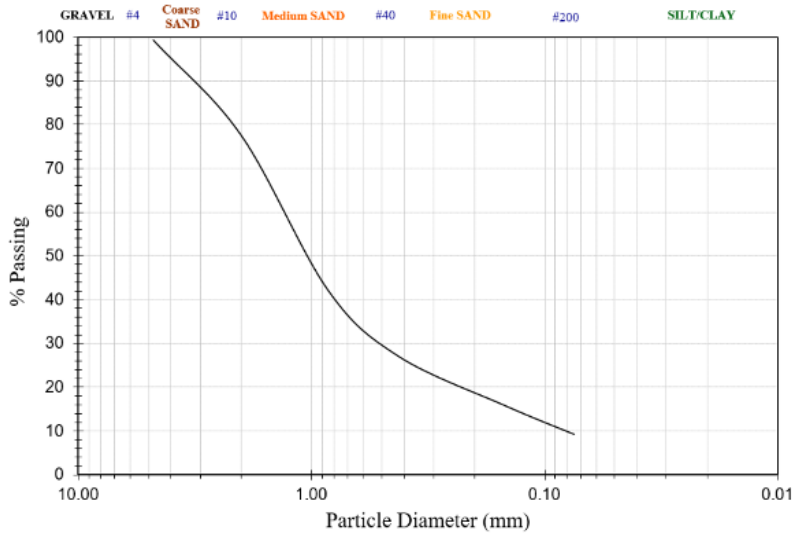


Figure 4. *Gradation curve of Acco stone sand used in the experiments for this study.*

Compaction characteristics for this sand were obtained using a standard proctor test, following ASTM D698. The maximum dry density ($\gamma_{dry,\,max}$) and optimum moisture content (w_{opt}) for this sand were 131.5 pcf and 9.3%, respectively, as shown in Figure 5.

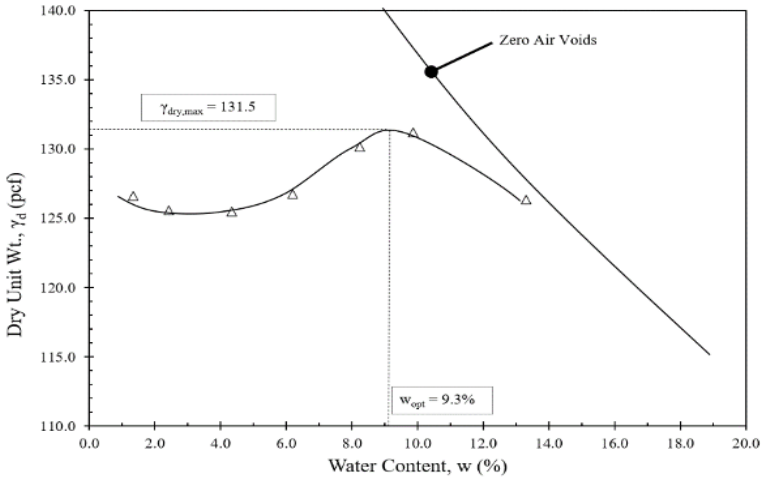


Figure 5. *Standard proctor compaction test curve for the Acco stone sand used in this study.*

3.2 Compaction method

A method of placing and compacting the backfill into the testing area was developed to increase efficiency and ensure quality control. The sand was placed in a hopper using a bobcat, and the weight of the hopper was recorded using a crane weight scale and an overhead crane. The hopper was then transported by the overhead crane over the backfill area, and the sand was deposited. After that, the sand was smoothed and leveled by hand, and a plate compactor was used over the lift for a selected number of passes to achieve relative compaction (RC) of 90% or more, as discussed further below.

To determine the number of passes of the plate compactor needed to achieve the desired RC, the lift height was measured from the top of the concrete walls to the lift surface at nine points. Three points

were taken 1.5 ft, 3 ft, and 4.5 ft from the center of panel 1, between panels 2 and 3, and the center of panel 4 (9 total points). Based on the height of the wall and thickness of the underlying lifts, the height of the lift at each point was backcalculated. The backfill area was divided into three zones based on the width of the ramp and length of panel 1 (zone 1), panels 2 and 3 (zone 2), and panel 4 (zone 3). Based on the weight and dimensions of the lift, the moist unit weight (γ_m) of the lift at each point was determined.

Four samples were taken from each compacted lift for moisture content measurement, equidistant from each of the nine points. An average moisture content was taken for each point based on the point's proximity to the moisture content sample. The average moisture content for each point was used to determine the dry unit weight (γ_{dry}) at each point. The average γ_{dry} was taken in each zone, and a weighted average of the lift's γ_{dry}, or $\gamma_{dry,\ total}$ was found based on the three zones. The $\gamma_{dry,\ total,}$ and $\gamma_{dry,\ max}$ were used to determine RC. This procedure was repeated for the uncompacted lift, and after each compactor pass for a total of 6 passes. Figure 6 shows the relationship between RC and the number of passes of the plate compactor. It is shown in this figure that a minimum of 2 passes per lift is sufficient to achieve the desired 90% minimum relative compaction for 6 and 9-inch lift thicknesses.

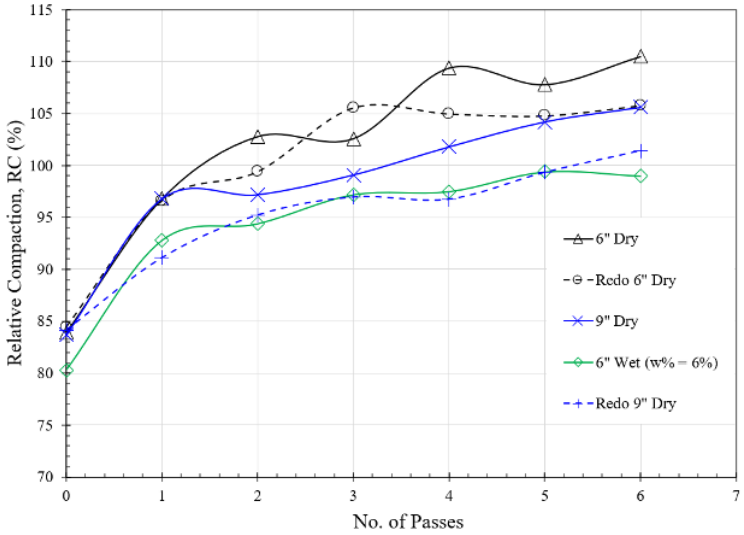


Figure 6. *Relative Compaction curves of soil layer per number of passes of a plate compactor*

3.3 Experimental steps

Before heating or cooling was applied to the backfill soil, reference pressures and strains within the backfill soil and lateral earth pressures applied to the wall were recorded. These temperature-independent measurements established a baseline for comparison before thermal loads were applied to the soil. These measurements and the following experiments were done under dry backfill conditions (moisture content, *w%*, less than 0.5%). Due to low atmospheric temperatures (-5 to 15˚C) during the experimental time, the backfill soil was continuously heated to 20˚C through the lower level of the geothermal pipes for two weeks. The temperature of the internal fluid within the temperature control unit and the temperature-dependent strain and pressure in the soil were recorded. The SGs and PCs recorded the temperature of the soil. Only the first level of instrumentation with a load of 27 inches (1.5 ft) of backfill soil was utilized due to construction delays during these two weeks. Then, the remaining backfill soil was placed with a total height of 54 inches (4.5 ft) of backfill soil on top of the lower level of instrumentation. The additional backfill was under dry conditions (*w%*, less than 1.9%). The temperature of the lower level of the geothermal pipes was held constant at 20˚C for 24 hours and then increased to 70˚C for six days.

4 EXPERIMENTAL RESULTS

The increase in temperature of the backfill soil showed additional tensile strains in the SGs (Figures 7a and 7b) and compression applied to the PCs (Figures 8a and 8b). For sign convention, negative and

positive strains indicate tension and compression, respectively, and positive pressure indicates compression.

Level 2 instrumentation results are not shown because these instrumentations experienced minimal temperature change since the backfill was heated using the lower-level geothermal pipe only for this manuscript. Lateral earth pressures recorded by the PCs along the panel walls are also not shown because they record lower pressures than the PCs within the backfill; further analysis is undergoing to understand this phenomenon. SG 23 is not shown in Figures 7a and 7b because the instrument stopped recording strain and may have been damaged during backfill compaction. SG 34 is not shown in Figure 7b because SG was an outlier and gave positive (compression) strain values.

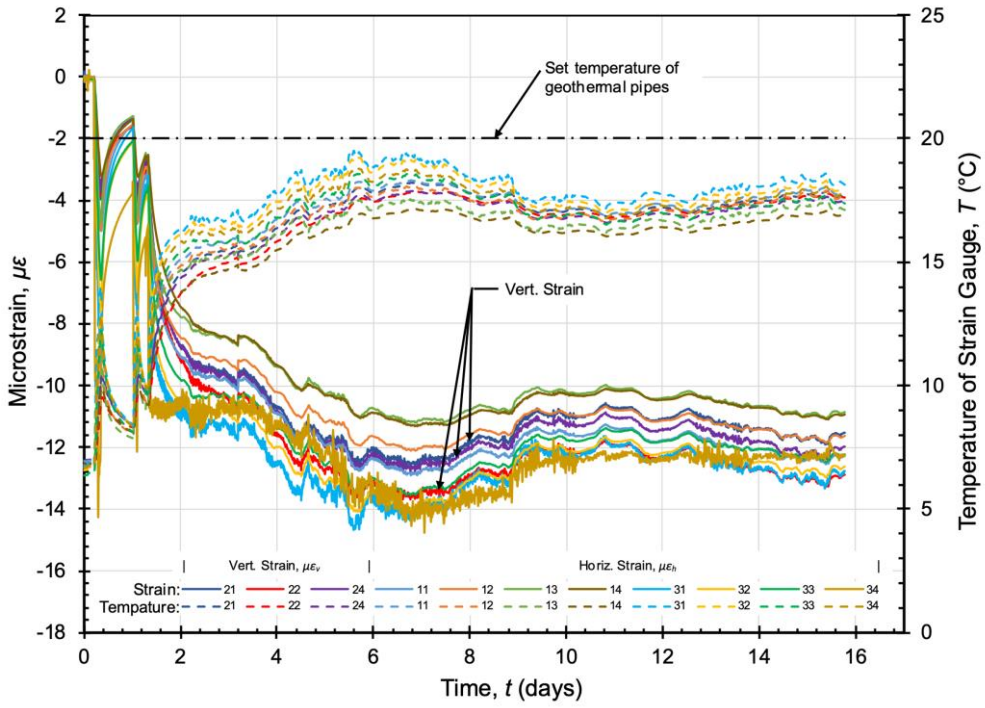
5 DISCUSSIONS

As shown in Figures 7a and 7b, SGs that experienced greater temperature change recorded greater tension. An increase in tension may be due to the expansion of the soil due to temperature changes. However, when comparing SG 12 (horizontal strain) to SG 21, 22, and 24 (vertical strain), vertical SGs experienced greater tension than SG 12 at a similar temperature (see Figure 3 for instrumentation location). This may be due to the effect of boundary conditions, similar to K_o conditions, where the soil is constrained more laterally by the concrete walls, panels, and soil ramp, causing most of the expansion to occur upward. Of the vertical SGs, SG 22 has greater tension than SG 21 and 24 due to boundary conditions. SG 22 was positioned towards the center of the backfill area, and SG 21 and 24 were positioned towards the edges.

As shown in Figures 8a and 8b, higher temperatures induced more compression for horizontal or lateral earth pressure (PC31 and PC22). Like the SGs, heat resulted in soil expansion increasing the pressure within the soil. However, this observation does not agree with vertical pressure, where PC11 experienced much greater compression with less temperature change than PC21. The boundary conditions of both PCs are similar, being confined by the rigid concrete walls. The orientation of PC21 may have been disrupted during compaction, placing the cell at an angle and resulting in lower pressure readings than PC11.

PCs experienced greater pressure than expected due to temperature changes, where from 20˚C to 70˚C, pressure increased 2 to 4.5 times (Figure 8b). This phenomenon may be explained by how the PCs are thermally calibrated. Daigle and Zhao (2004) explained how the manufacturer's temperature calibration for vibrating wire pressure cells is done only for the transducer before the pressure pad is installed. This was confirmed by the manufacturer, Roctest. Changes in pressure are measured by the change of fluid oil pressure within the pressure pad due to applied pressure. The thermal calibration does not account for the thermal expansion of the oil within the pad, which may affect the pressure reading. Daigle and Zhao found the temperature calibration coefficient, C_f, to change with increasing applied pressure at constant temperature and become nonlinear, unlike the manufacturer's C_f. An ongoing thermo-mechanical calibration of the used PCs is undergoing, and the experimental results will be corrected in future studies.

(a)



(b)

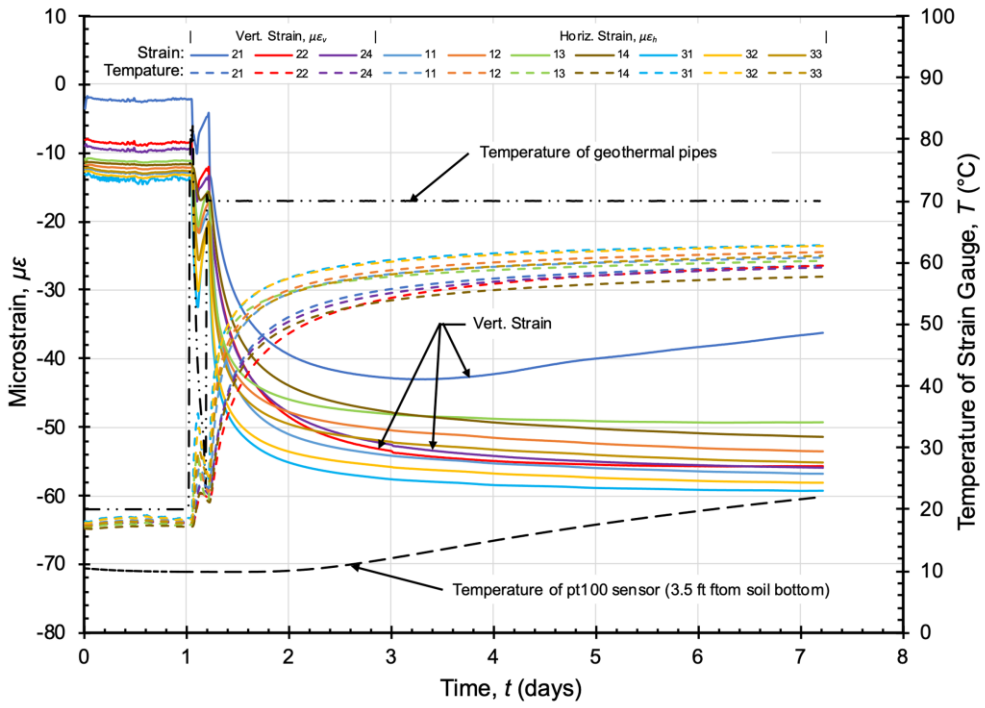
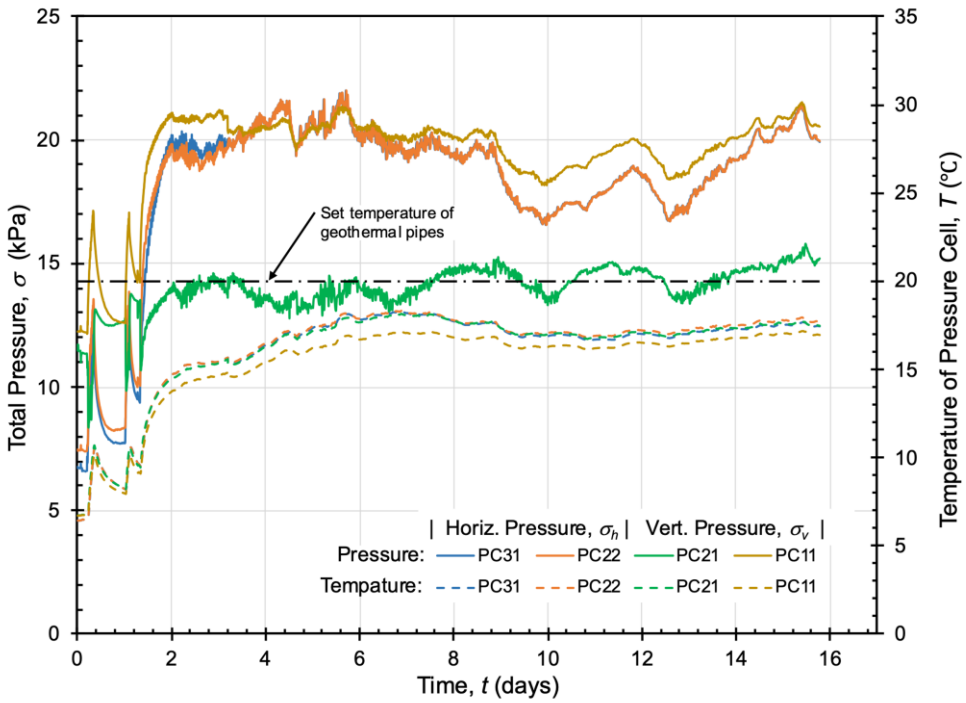


Figure 7. *Micro strain of the lower level of strain gauges due to heating from the lower level geothermal pipe at a) 20˚C for 2 weeks and b) 70˚C* for 6 days

(a)



(b)

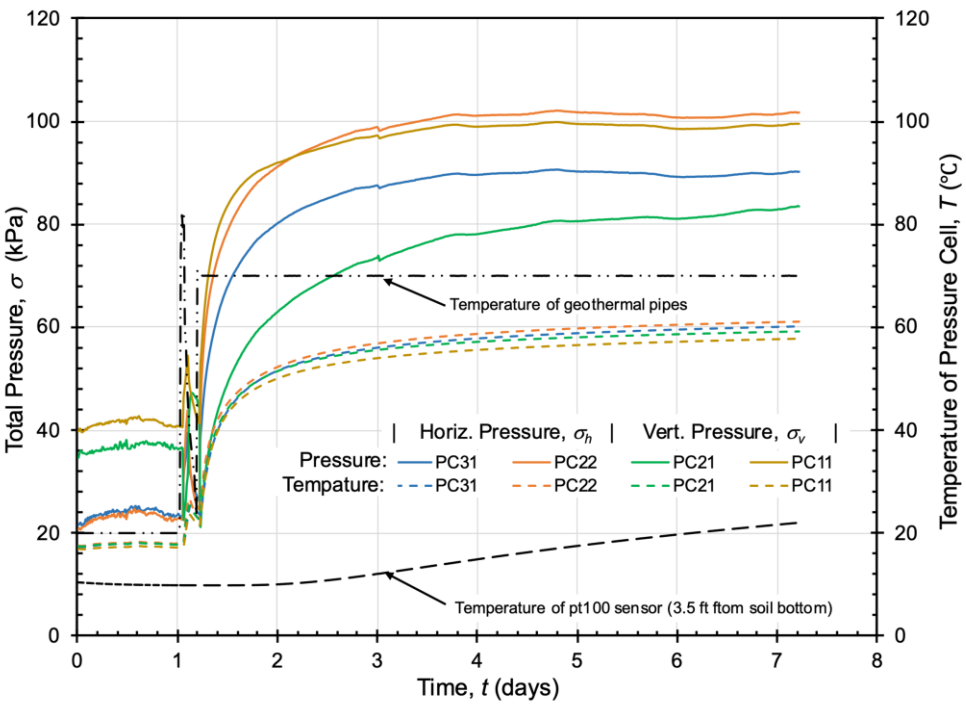


Figure 8. *Pressure of the lower-level pressure cells due to heating from the lower level geothermal pipes at a) 20˚C for 2 weeks and b) 70˚C* for 6 days

6 CONCLUSIONS

The effect of temperature on lateral earth pressure on geostructures at the field scale was investigated. The current retaining wall facility at Virginia Tech was upgraded to measure the thermo-mechanical behavior of dry well-graded sand. The upgraded facility has the capability to change the temperature within the backfill soil through geothermal pipes. The backfill soil is embedded with instrumentation to measure stresses and strains when the temperature is induced. To improve efficiency when conducting

future experiments, a method of placing and compacting sand in the backfill was practiced. Curves were developed to obtain a desired relative compaction based on the number of passes of a plate compactor.

Strains and pressures within the backfill soil and lateral earth pressure along the retaining wall were recorded under no heating (20˚C) and elevated temperature (70˚C) . Overall, vertical and horizontal strains (tension) and pressures (compression) within the soil increased with temperature, which can be explained by the expansion of the soil. Obscurities in data may be due to the influence of boundary conditions or the orientation of instrumentation being disturbed during soil compaction. The unexpected large changes in pressure due to increasing temperature may be explained by how the manufacturer's thermal calibration is found.

The study of soil thermo-mechanical behavior will be continued by inducing additional heating and cooling in the backfill soil, ranging from 10 to 80˚C with additional heating from the upper level of the geothermal pipes. The instrumentation placements will be rearranged better to understand the effect of boundary conditions on the instrumentations. A study will be conducted to relate the change in soil temperature to the lateral earth pressure coefficient, K_o. Further study will be done to relate changes in lateral earth pressure due to temperature to the toe and shaft resistance of energy piles.

7 ACKNOWLEDGEMENTS

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