Experimental Study to Analyze the Effect of Confinement and Cell Pressure on Thermal Pressurization under Fully Undrained Conditions

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ABSTRACT

The application of energy geo-structures can significantly change the soil temperature. Thermal loading induces pore water pressure due to the differences in thermal expansion coefficients of the pore fluid and the pore volume. The generation and dissipation of the thermal pore pressurizations result in thermal consolidation. In the condition that the induced pore pressure cannot dissipate, reduction of the mean effective stress may cause soil shear failure or hydraulic fracturing. The result of this research will enable us to predict the pore fluid behavior in the porous media, which will be useful to understand the thermo-hydro-mechanical process in saturated soil. Thermal pressurization is studied through a series of fully undrained tests. Therefore, a temperature-controlled triaxial cell has been used to understand the relation between thermal loadings and pore pressure changes at different temperatures and for different cell and confinement pressures. Different samples are tested under different confinement stresses (345, 480, and 520 kPa) through a modified temperature-controlled triaxial cell which provides a range of temperature changes between 3°C and 80°C. Using pore pressure transducers at the bottom and the top of the samples, pore pressure changes are recorded at different temperatures. Cell pressure during the test as well as initial pore pressure of the sample is controlled with digi-flow pumps of a triaxial setup. Results indicate that the thermal pressurization rate increases for higher confinement.

Keywords: Thermal pressurization; Excess pore pressure; Temperature controlled Triaxial Cell, Undrained tests

INTRODUCTION

Dynamic loads like an earthquake can cause rapid pore pressure changes since this happens relatively quickly and there is not enough time for excess pore water pressure dissipation. The generation of excess pore pressure reduces the effective stress and consequently decreases the soil strength. In extreme cases, the effective stress reaches zero and causes liquefaction.

Static loads like overburden pressure can generate pore pressure in a sandy layer which is entrapped between impermeable soil layers. In clayey soil, excessive pore pressure will be dissipated in a considerably longer time and will finally result in consolidation. Mechanical load is not the only way to cause pore water pressure generation. Temperature changes in the soil will increase the volume of the water and due to the difference in thermal expansion of the pore fluid and the pore volume, it induces pore water pressure (Demars and Charles 1982; Agar and Morgenstern 1986; Ghasemi-Fare and Basu 2018). The temperature increase in saturated soils under undrained conditions results in thermal pressurization. This increase in pore pressure will reduce the effective mean stress in soil and can lead to shear failure or hydraulic fracturing.

Thermal pressurization is also important in quick landslides where moving surfaces experience frictional heating and the induced pore pressure will result in the reduction of compressive stress and shearing strength of soil (Vardoulakis, 2002; Veveakis et al., 2007; Tamizdoust and Ghasemi-Fare 2020). The rapid increase in temperature can also cause damages to the cement sheath integrity of oil wells (Ghabezloo and Sulem, 2009). The effect of temperature on deep clay formations, where nuclear wastes are disposed is another important case (Gens et al., 2009; Delage et al., 2010; Vu et al., 2015; Tamizdoust and Ghasemi-Fare 2019). A high rate of heat generation in the ground like nuclear waste disposal plays a similar role to dynamic load. Any condition that makes the dissipation of this excessive pore pressure slow (e.g. impermeable layers, and poor drainage condition) will put the soil in a critical condition that can cause a failure in soil mechanical function. Thermal pressurization is one of the reasons that cause dynamic fault weakening during coseismic slip (Sulem et al., 2007; Rampel and Rice, 2006). Thermal pressurization is also very important in energy geothermal projects and harvesting energy from the ground, around the inground part of the structure (Ghasemi-Fare and Basu, 2016; 2017).

In this research, pore pressure changes in an undrained condition are studied while different thermal loading is applied. Undrained thermal pressurization coefficient which is defined as the pore pressure increase due to a unit temperature increment (Ghabezloo and Sulem, 2009) is measured for silica sand at two different confinement stresses.

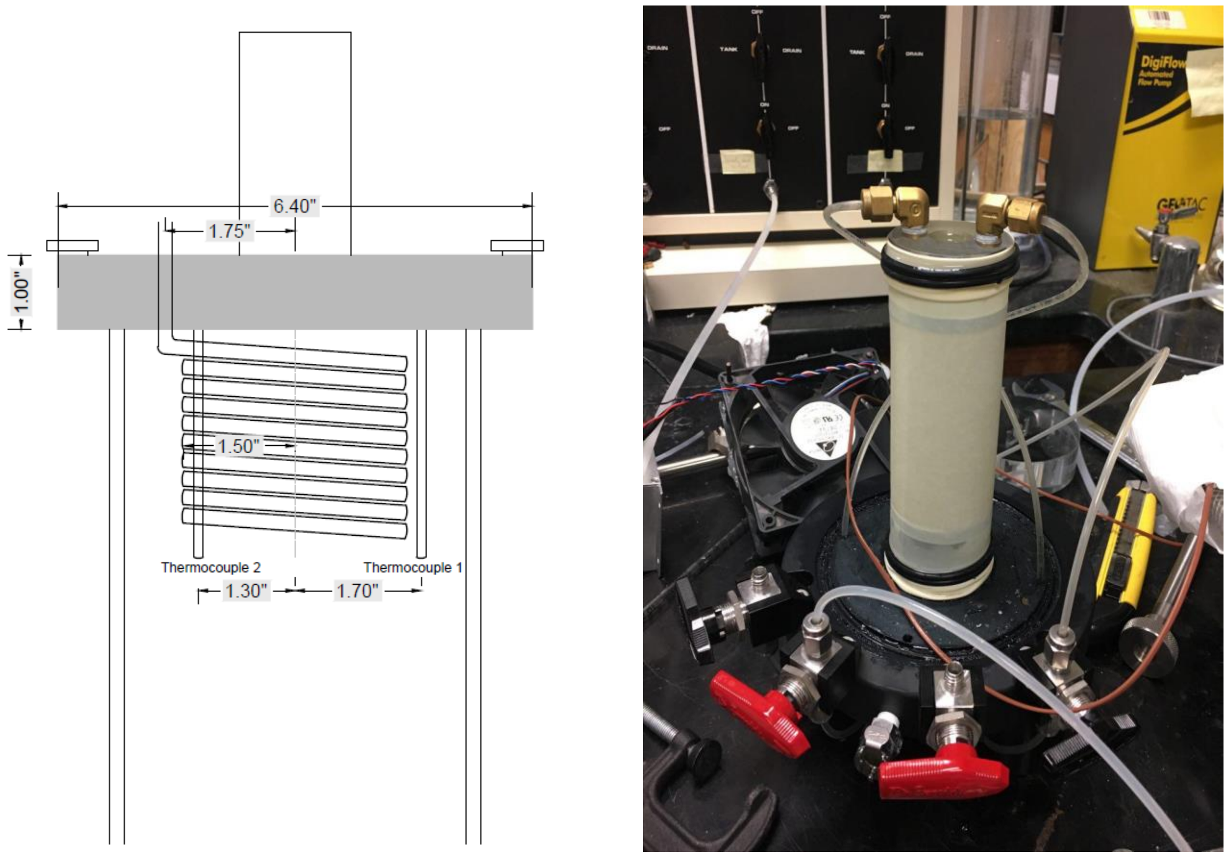
The results of this research lead us to have a better understanding of the mechanism of thermally induced pore water pressure generation and to better understand the behavior of different soil types under thermal loading. In addition, the results of this research can also be used to validate the thermo-hydro-mechanical (THM) models.

EXPERIMENTAL SETUP

To measure pore pressure generation with thermal loading, the first step is to prepare a reliable setup that can control temperature while monitoring the pore water pressure.

For this purpose, the setup which was modified by the authors was employed (Joshaghani et al., 2018; Joshaghani and Ghasemi-Fare, 2019). In this setup, the sample is placed in a triaxial cell with a temperature control system. Figure 1 shows the setup and the sample inside the triaxial cell. To change the temperature of the sample inside the cell, a copper coil is placed inside the cell which is connected to a water bath to adjust the temperature, and the heat carrier fluid is circulated inside the coil to change the temperature of the cell. The temperature changes at the core of the sample and the stabilization time were recorded in calibration tests. Also, by varying cell pressure, confining stress can be adjusted.

Soil samples are fabricated in membranes using the dry tampered method. The soil that is used in this research is SP Ottawa sand with G_s=2.655. Based on the weight of the soil used to fabricate the sample and the dimensions, the void volume is calculated. The thermocouple inside the cell helps to correlate cell and water bath temperatures. The temperature of the water bath has an accuracy of ±0.1 ^{0}C. The cell pressure is controlled by a digitally controlled flow pump from GEOTAC Co. which is facilitated by a pressure transducer. The second pressure transducer is connected to a valve that is connected to the bottom of the sample and reads the sample pore pressure. The test is started by passing de-aired water through the sample while the cell pressure is as low as 85 kPa. After making sure no more air is entrapped between soil particles, cell pressure is increased to a higher value and sample pore pressure is adjusted to have the Skempton's B value higher than 0.95. Cell pressure is adjusted by connecting the related port to a second flow pump and after each incremental step in the cell pressure, Skempton's B value is measured to ensure saturation is satisfied.



(a) **(b)**

Figure 1. Experimental setup, (a) Schematic parts in the modified cell, (b) sample fabricated inside the membrane

At this step, the setup is ready and cell temperature can be increased while the cell pressure is kept constant. Sample pore pressure is measured at each temperature after it is stabilized. The first sample used in this test consists of 318.10 grams of Illinois Ottawa silica sand. The soil properties are presented in Table 1. Soil sample diameter and height are 5.11, and 9.35 centimeters, respectively, and the void volume equals 69.74 cm^3 for the first sample. To analyze the effect of confinement stress, thermal pressurization for sample 1 is studied by considering two different cases. In the first case, cell pressure is raised to 345 kPa in one cycle while the sample pore pressure is adjusted to 70 kPa at an initial temperature of 25^0C. For the second scenario, the cell pressure is raised to 480 kPa in the second cycle while the sample pore pressure is kept constant.

Table 1. Geotechnical Properties of Illinois Ottawa Silica Sand

G_s	e_{max}	e_{min}	D_{50}	C_c	C_u
2.65	0.86	0.53	0.5 (mm)	0.92	1.02

Another sample is also prepared and tested in this study. Sample 2 is made with the same soil with 307.49 grams of Ottawa sand. The diameter and height of the second sample are 5.11, and 9.260 centimeters, respectively, and the void volume equals 74.71 cm^3. For this sample, the cell pressure is set to 520 kPa while the sample pore pressure is kept at 260 kPa at an initial temperature of 20^{o}C.

THERMAL LOADING

Figure 2 shows the temperature and sample pore pressure variation with time for sample 1. As it can be seen in Figure 2 there are two thermal loading cycles. The first thermal loading is subjected when the cell pressure is 345 kPA (in which confining pressure equals to 275 kPa) and the second one is applied when the cell pressure is set at 480 kPa (in which confining stress equals to 410 kPa). Figure 3, shows the related cell pressure for the same sample during the time.

The test starts at 25 ºC and raised to 35 ºC, 50 ºC, and 65 ºC. At 65 ºC the sample pore pressure gets very close to the cell pressure and therefore we had to stop the heating so that the effective stress does not reach zero. Heating for the first cycle is stopped at 65 ºC.

In the second cycle, the cell pressure is set to 70 kPa while cell pressure is raised to 480 kPa. The pore pressure of the sample is then measured during the heating phase. Interestingly, the result for the second cycle also determines that the sample pore pressure reaches almost the same as cell pressure at 65^{o}C. Figures 2 and 3 show that 65 ^{0}C is the temperature that cell pressure increases up to an amount that is very close to the cell pressure for both confinement stresses (310 kPa and 435 kPa, respectively for 345 kPa and 480 kPa cell pressures). This temperature seems to be a critical point for this sample for both confining pressures.

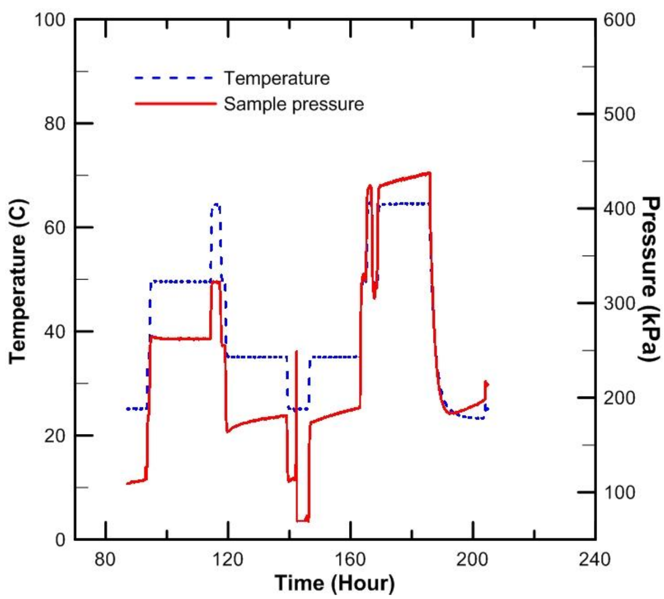


Figure 2. Sample pore pressure (kPa) and temperature (ºC) versus time (hr.) for sample 1

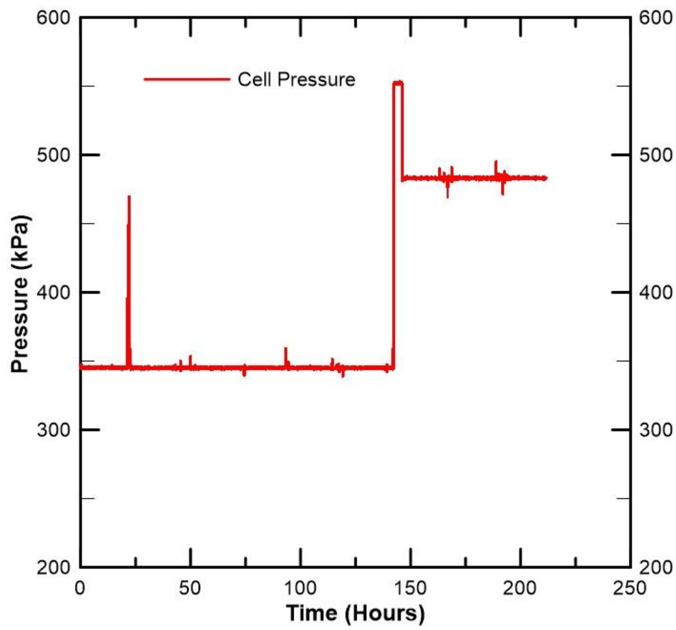


Figure 3. Cell pressure (kPa) versus time (in hr) for sample 1

Figures 4 and 5 present the variation of thermal pressurization versus temperature changes (thermal pressurization slope) which determines the rate of pore water pressure induced by thermal loading at two different confining stresses (275 kPa, and 410 kPa). Comparison of Figures 4 and 5 determines that the thermal pressurization slope is higher for higher confining stress. Also, results show that the sample pore pressure during one heating and cooling cycle does not reach the initial value and small pressure will remain after one heating-cooling cycle.

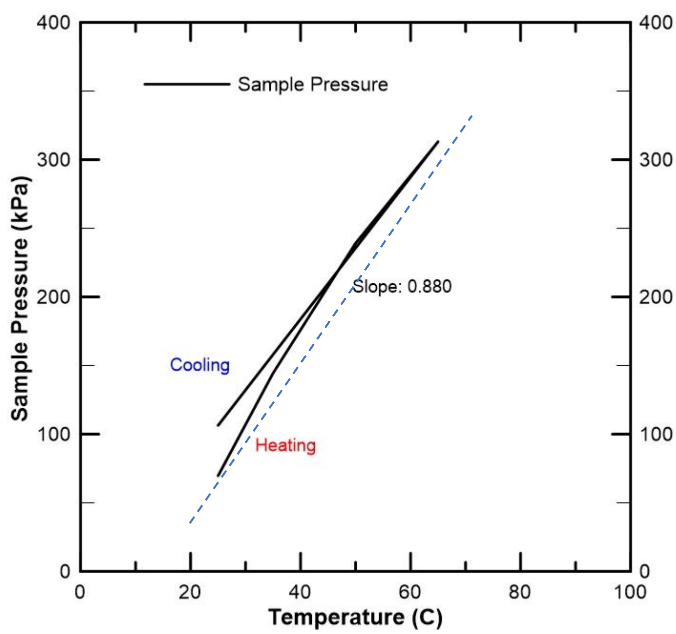


Figure 4. Thermal pressurization for confining pressure equals to 275 kPa - sample 1

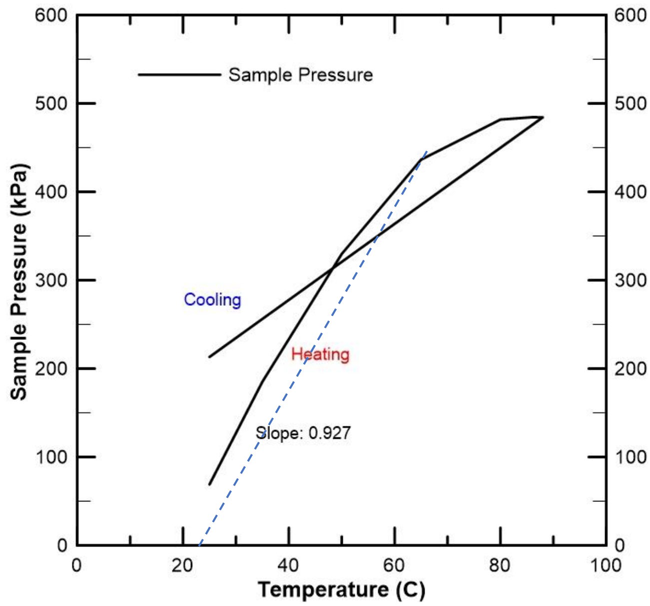


Figure 5. Thermal pressurization for confining pressure equals to 410 kPa - sample 1

For sample 2, cell pressure is raised to 520 kPa while initial sample pore pressure is set at 260 kPa (which means confining stress equals 260 kPa) at 20^{0}C. Soil temperature is increased to 65 ^{0}C with 5^{0}C temperature increments while cell pressure is recorded at each increment. Figure 6 presents the thermal loading against time for sample 2. Similarly, it is observed that at the temperature of 65^{0}C the sample pore pressure reaches 480 kPa which is very close to the cell pressure (520 kPa) (please see Figure 7). Another observation is the reduction in the rate of pore pressure generation when the effective stress is approaching zero. This can be seen in Figure 5 and Figure 7 which are, respectively, related to samples 1 and 2

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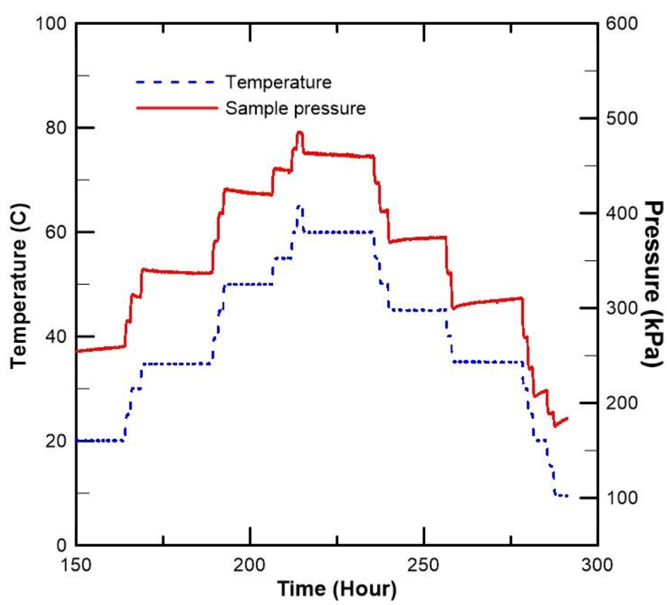

Figure 6. Sample pore pressure (kPa) and temperature (ºC) versus time (hr.) While cell pressure is 520 kPa constant – sample 2

Comparison of Figures 4, 5, and 7 with initial confining stresses equal 275 kPa, 410 kPa, and 260 kPa, concludes that the thermal pressurization slope is higher for higher confining pressure.

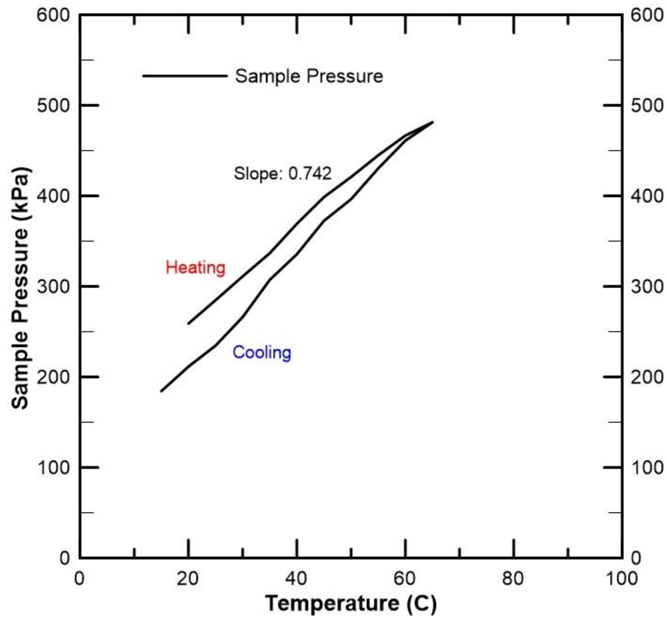

Figure 7. Thermal pressurization for confining pressure equals to 260 kPa - sample 2

CONCLUSION

In this study thermal pressurization of Ottawa sand is tested at different confining stresses. It is observed that thermally induced pore pressure is highly dependent on the confining stress. For all conditions, the pore pressure generated at 60^0C to 65^0C is almost close to the cell pressure, and it can be interpreted as a critical temperature for the tested soil. The experimental observations determine that the thermal pressurization slope is higher for larger confining stresses which represent the deeper soil layers. It is recommended to do more tests for different types of soils and compare the results, to have a better understanding of the mechanism of the generated pore pressure and obtain the critical temperature and thermal pressurization slope for each soil type.

ACKNOWLEDGEMENT

The authors would also like to gratefully acknowledge the financial support from the National Science Foundation under Grant No. CMMI-1804822.

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