A Study on Thermal Consolidation of Fine Grained Soils Using Modified Consolidometer

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ABSTRACT

In order to fully understand the thermo-hydro-mechanical behavior of the geotechnical infrastructures, the effects of temperature variations on soil properties and soil behavior have to be studied. Hydraulic conductivity, strength, volume change, moisture content, and pore pressure generation and dissipation rates depend on temperature variations. Thermal loading might induce excess pore water pressure and volumetric changes. Temperature changes in the fine-grained soils will cause expansion in water and soil particles. Since the coefficient of expansion for soil particles is much smaller than that for water, a generation of pore water pressure is expected. This thermally induced pore water pressure and then its dissipation during the relaxation period results in a time dependent consolidation. Thermal consolidation in fine grained soil is more dominant and can be irreversible in normally consolidated clay. However, the volumetric changes of highly over consolidated soil caused by temperature increment is reversible by temperature reduction. In this research, a modified consolidation testing device is used to study the effect of temperature increments (e.g., increasing step by step temperature increments to 80ºC) on the consolidation of fine grained soils. In another words the effect of temperature increments during the test on the consolidation process is studied. Time of applying the heating, target temperature, and initial void ratio are parameters affecting the rate and the amount of consolidation in the samples.

KEYWORDS: Thermal consolidation, Hydraulic conductivity, Moisture content, Stress history, Fine grained soil, Consolidation test

INTRODUCTION

Compaction of soil at different layers is important but is also challenging for deeper soil layers. The reason is not limited to the restrictions due to the interaction with structures (Jafarzadeh et al. 2012), but because of the very low rate of consolidation in deep layers containing clay. Several researchers studied the new innovative methods to measure the consolidation at different depth (Rashidi et al. 2017, Lemus et al. 2018, Fathi et al. 2018, Bakhshi et al. 2018, Ramezanianpour et al. 2018). One of the newly innovated methods to compact the deeper clays, is embedding heat sources within the soil to increase the temperature of the soil around them to ease the consolidation process. Thermal consolidation is a result of the plastic behavior of wet clay formations and the expansion of water which increase pore pressure and a subsequent consolidation will occur. Ghasemi-Fare and Basu (2016a, and 2017) showed the changes in excessive pore fluid pressure during a fully controlled thermal test. This thermally induced pore pressure will be dissipated and will result in thermal compaction. Temperature effects on soil was paid attention in an early study by Lewis (1950) for the first time. He studied the coefficient of compressibility and consolidation of London clay in the temperature range of 5 °C to 15 °C. He observed that the coefficient of compressibility in that range of temperature is independent of temperature while the coefficient of consolidation significantly changes with temperature. Soil temperature varies surrounding the heat exchanger piles (Ghasemi-Fare and Basu 2013, 2015b, 2016b). Temperature changes can change the thermo-mechanical behavior of the soil (Ahmadipur and Basu 2016, Razmkhah et al. 2018), or it may affect the soil hydraulic conductivity and absolute permeability (Joshaghani et al. 2018). Further research showed that temperature change will alter the physio-chemical forces between clay layers (Burmister 1951, Lambe 1958, Sridharan, and Venkatappa 1973, Morgenstern and Balasubramonian 1980, Mitchell 1993). Plum and Esrig (1967) found the conclusion of Lambe's model (1960) and Yong et al. (1962) conclusion contradictory. Lamb (1960) predicted a depression of the double layer with increasing the temperature, while Yong et al. (1962) concluded increasing temperature will result in an increase of the double layer thickness and resulting in an increase in the compulsive forces. Paaswell (1967) conducted thermal consolidation tests under a constant load. He observed that the thermal consolidation curves were similar to a conventional consolidation. Campanella and Mitchell (1968) used a cyclic thermal loading on clay and observed a minor volume expansion during cooling load. Demars and Charles (1982) among other, showed that the amount of the contraction during heating for overconsolidated clays was smaller than that of normally consolidated clays. Baldi et al. (1988) resulted that a highly overconsolidated clay shows volume expansion by heating. Towhata et al. (1993) heated clay samples at several increments at the end of primary and secondary stages of consolidation in MC clay and Bentonite. He showed the effect of temperature increments on void ratio is independent of the temperature that the sample has. He also showed that the cyclic thermal loading will result in a quasi-overconsolidation of MC clay and make the sample more resistant against compression and will result in a higher pre-consolidation pressure in the sample. Delage et al. (2000) studied thermal consolidation of Boom clay and showed that temperature does not significantly affect the consolidation coefficient. Recent studies have been done on the effect of thermal loading on volumetric changes of the soil and the effect of heating rate on consolidation of the clay (Vega et al. 2012, Liu et al. 2018, Boushehri et al. 2019). However, more research is needed to find the rate of pore pressure dissipation and vertical settlement rates during the thermal loading and relaxation time. In this paper thermal consolidation of normally consolidated clay is studied. And the rate of consolidation is studied through comparison of two identical thermal loading (e.g. identical temperature gradient) with different relaxation time.

EXPERIMENTAL SETUP

In order to do consolidation test under different temperature, an improved consolidometer was designed and built in this study. A triaxial-insert consolidometer was placed in a modified triaxial cell. The cell temperature is adjustable in the range of 4 °C to +90 °C. This alteration in the cell temperature is controlled by a water bath which circulates the fluid inside a copper coil inside the triaxial cell. The two ends of the cooper coil are extruded from the cell top cap (Figure 1b). The acrylic chamber was replaced with an aluminum one to make sure a resistible cell is provided, since cyclic temperature resulted deformation in acrylic cell. Preliminary results showed that the natural convection of the water inside the cell makes a huge temperature differences between the top and bottom of the cell. Therefore, in order to make the water and soil temperature uniform, a circulation system is used inside the cell. The circulation system can work independently from the other parts of the system. Results from measuring temperature at different points inside the cell, confirm that this circulation system will provide a uniform temperature inside the cell. In a previous study by the authors, same technique was employed to modify the permeameter cell to predict the soil permeability variation with temperature (Joshaghani et al. 2018). Two thermocouples are used in this setup, one is measuring the temperature inside the cell and the other one is measuring the room temperature. Calibration tests have been performed to predict the temperature inside the soil from the correlation between cell temperature and the water bath temperature. From preliminary results, it was found that when water bath temperature is set to 52.7 °C, cell temperature will reach to 50 °C. The temperature difference is because of the heat loss from the system. Calibration results confirmed that soil temperature will reach to the cell temperature in a very short period of time (e.g., in 40 minutes). Figure 1 shows the triaxial-insert consolidometer which is attached to the bottom cap of the triaxial cell. The bottom cap has four valves; two of which connect to the bottom of the sample and the other two are connected to tubes which go inside the cell. Two pressure meters are used to measure the pore pressure and cell pressure by connecting to bottom and cell valves, respectively. The other two valves are connected to a pump by a T-fitting to control the back pressure. This controlling includes keeping both valves open during saturation and closing the sample valve to measure Skempton B value and also during consolidation. Figure 2 shows complete setup of the cell and water bath which is placed in the automatic loading frame.

(a) (b)

Figure 1. The modified cell a) Triaxial-insert consolidometer fitted on the bottom cap of a triaxial cell b) Modified top cap of a triaxial cell, accommodating copper coil heating system

The modified deice is used to do thermal consolidation tests. Kaolin clay was used in this research to study the thermal consolidation. Samples were prepared using slurry method which thereafter were normally consolidated using conventional oedometer. The Specimens were 2.5 inches in Diameter and 1 inch in height within a rigid stainless-steel consolidation ring. Both bottom and top porous stones and filter paper were saturated in deaired water. In the next step, the specimen ring was placed between the porous stone and the filter papers. After placing the chamber, the cell was filled with deaired water and circulation system inside the cell was started. Saturation of the sample started with 689.5 kPa (100 psi) pressure which was applied on both cell and sample and continued for 24 hours at 25 °C.

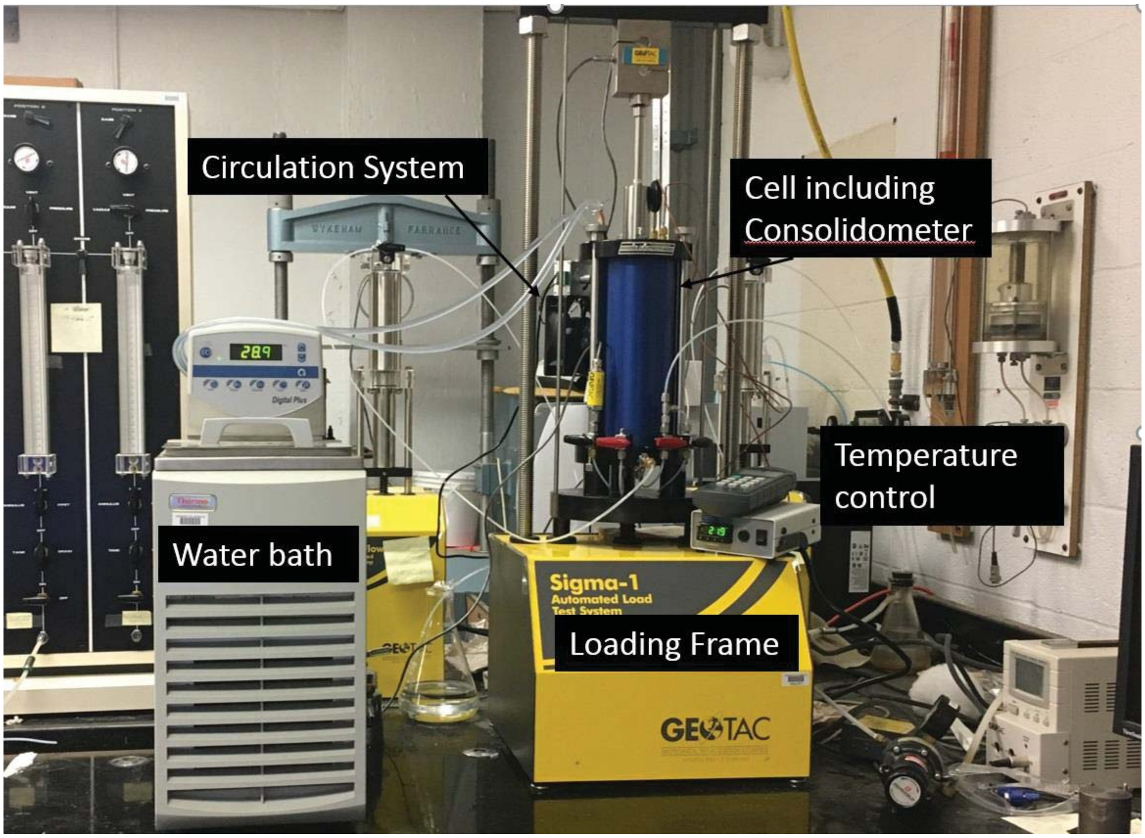

Figure 2- Complete setup of triaxial-insert consolidometer, water bath, Loading frame, temperature control

Skempton B value was measured 0.981 at the end of saturation time. At 689.5 kPa pressure of the cell, the uplift force to the loading piston was measured as 8.84 kg. Therefore, from the beginning of the saturation period to the end of the test a vertical load equal to 13.6 kg was applied to the specimen to overcome the uplift pressure and to provide the specimen with a vertical stress before and during thermal consolidation. Thermal loading was applied through several steps. In the first step the cell temperature was heated to 50 °C. During the thermal loading, the vertical load and cell pressure were kept constant at the mentioned values. It almost takes 45 minutes for the cell to reach to 50 °C. In a similar test while sample was placed inside a latex membrane, it was observed that it takes 40 minutes for the sample temperature to reach to the cell temperature (Joshaghani et al. 2018). It is expected that this time for the current test, with a smaller size of sample and steel ring will definitely be shorter. Cell temperature kept at 50 °C for two different time periods at different tests. In order to compare the effect of thermal gradient, the cell temperature was increased to 80 °C for the next step. It takes almost 110 minutes for the cell to reach to 80 °C. For the first test, thermal loading was kept for 36 hours to make sure there in no further volume contraction happening. However, for the second and third test we let the system to consolidate only for 12 hours and then we increased the soil temperature. This shows the maximum time we might need to keep the soil temperature in the field. Predicting the optimum thermal loading duration is an important parameter which can reduce the cost while creates the maximum thermal consolidation (e, maximum vertical displacement). The last step is getting back to the initial condition (reducing the temperature from 80 °C to 25 °C) and waiting another 36 hours so the system reaches to a balance. Recorded results of vertical displacement were carefully calibrated considering the room temperature changes, machine deflection for vertical load, and most importantly, the effect of temperature changes which cause every part in the system experience an expansion or contraction. To perform calibration, a test was run including all different parts in the cell with no soil sample. Cell pressure and vertical load, and cell temperature variations (thermal loading) were identical with the main tests.

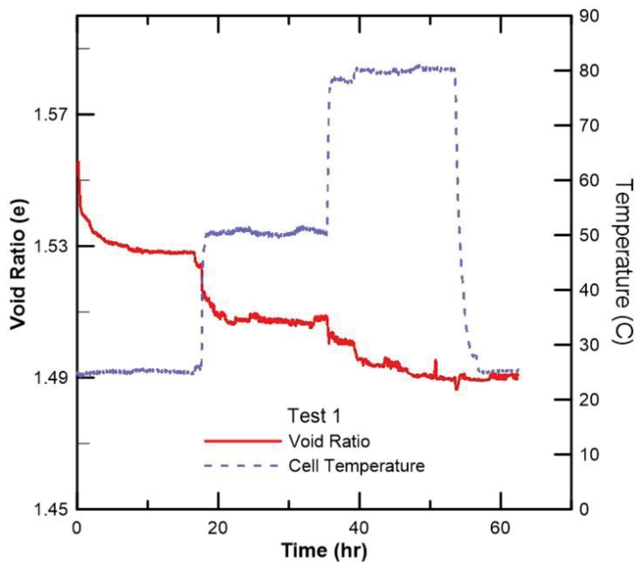

Figure 3- Test 1, consolidation time: 36 hours

RESULTS

In this section the changes in soil vertical displacement, and void ratio are studied for three different tests. As mentioned earlier Kaolin clay were selected in this research. Dimensions of the samples are 2.5 inches in diameter and 1 inch in height. Three different thermal consolidation tests were conducted. Soil temperature increased from 25 °C to 50 °C and then from 50 °C to 80 °C and the last step is decreasing temperature from 80 °C to 25 °C. For tests two, and three, consolidation time at each load step was reduced to 12 hours to analyze if thermal consolidation could happen in a shorter period. Excess pore pressure inside the sample during the thermal loading was insignificant (up to 1.5%) during all tests. This confirm that the excessive pore pressure dissipates during the thermal loading because of a saturated condition. Same results were observed during the thermopile analysis in literature (Ghasemi-Fare and Basu 2015a, 2018). The initial void ratio of sample 1 was 1.560. However, by applying vertical load (=13.6 kg) the void ratio is reduced from 1.560 to 1.523 (2.4% reduction). In the next step, by increasing temperature from 25 °C to 50 °C, thermal consolidation was started and resulted in decreasing void ratio from 1.523 to 1.505 (=1.2% reduction). As it can be seen in Figure 3, increasing temperature results in a progressive consolidation in test 1. Increasing temperature from 50 °C to 80 °C as the second thermal loading step, void ratio decreased from 1.505 to 1.489 (=1.1%

reduction). When temperature was reduced from 80 °C to room temperature, void ratio was measured 1.486 at minimal amount which showed no change. As a result, thermal consolidation resulted a decrease in void ratio from 1.523 to 1.468, representing 3.61% reduction. In test 2, vertical load (=13.6 kg) reduced the void ratio from 1.700 to 1.562 (=7.94% reduction). In the next step, by increasing temperature from 25 °C to 50 °C, thermal consolidation was started and resulted in void ratio reduction from 1.562 to 1.427 (=8.64% reduction). However, increasing temperature from 50 °C to 80 °C, changes void ratio from 1.427 to 1.413 (=1.0% reduction). This is an insignificant change in void ratio. For the last phase, when temperature gets back to 25 °C (room temperature) from 80 °C, void ratio increases from 1.413 to 1.425. Therefore, thermal consolidation results in void ratio changes from 1.562 to 1.425 (=8.8% reduction). For test 3 (with the same initial void ration as in test 2), results are close to those in test 2. Thermal consolidation resulted a change in void ratio from 1.562 to 1.480 (=5.2% reduction)

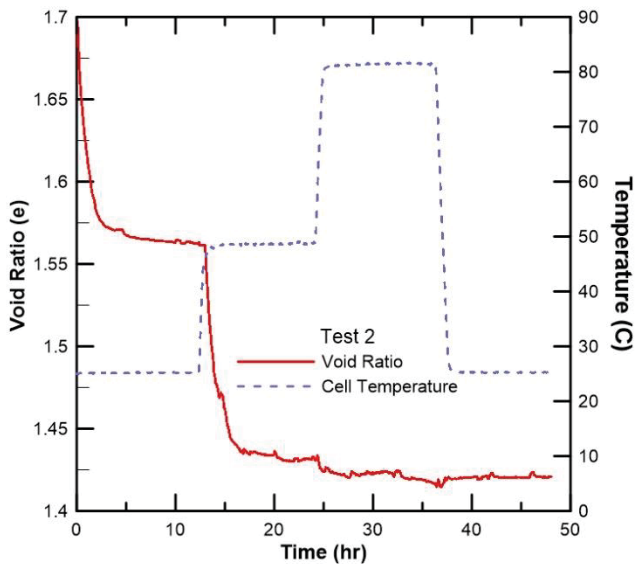

Figure 4- Test 2, consolidation time: 12 hours

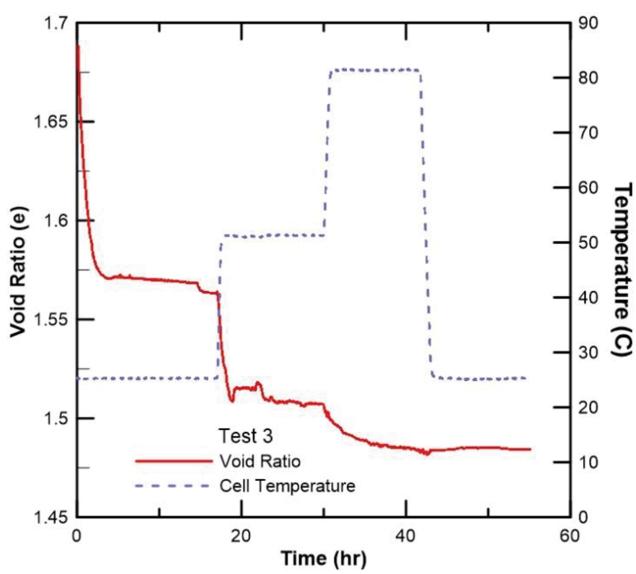

Figure 5- Test 3, consolidation time: 12 hours

As it can be seen, Test 2 shows more changes in void ratio due to thermal loading. This clearly confirm that thermal loading is more efficient for the soft samples with higher void ratio. Thermal consolidation might not be an effective method for the over consolidated soil and stiff clay.

CONCLUSION

Results in this study confirmed thermal loading has more effects on soft sample clays with large void ratios (like in test 2 and 3, with e_0=1.700). While thermal loading has minimal effect on stiff clays (Test 1, e_0=1.560). It is also observed that thermal consolidation from room temperature to 50 °C is less time dependent than in higher temperature (=80 °C). For sample 1, even after 36 hours, the consolidation showed a progressive behavior. However, for the initial thermal loading 12 hours was enough to make almost 100% of the thermal consolidation. Therefore, it can be concluded that, 12 hours is not an enough time span for the sample 2 to start the consolidation in 80 °C. However, since samples get stiffer after initial consolidation (=50 °C), therefore, small changes in void ratio may occur in higher temperature. Another conclusion that can be made from these three tests is that temperature increment from 25 °C to 50 °C results in a higher amount of consolidation compared to increment from 50°C to 80°C. To apply the thermal consolidation in practice, we need to know exactly the maximum thermal loading and the optimum time interval between the thermal loadings which can make an effective consolidation. Since this method can be pretty expensive in the field, the efficiency design and optimum thermal loading and their intervals must be studied and predicted.

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