Performance of Prefabricated Thermal Drains in Soft Clays

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ABSTRACT

This paper focuses on the behavior of prefabricated thermal drains used to improve saturated clay layers using heating. A prefabricated thermal drain can be formed by integrating a closed-loop geothermal heat exchanger within a conventional prefabricated vertical drain (PVD). Prefabricated thermal drains can be installed in a similar way to a PVD but operate by circulating a heated fluid through the heat exchanger tubing to induce an increase in temperature of the soft clay. This increase in temperature will lead to thermal consolidation, which can be accelerated by drainage through the PVD. Although thermal drains have been tested in proof of concept field experiments, there are still several variables that need to be better understood. This paper presents numerical simulations of the coupled heat transfer, water flow, and volume change in layers of kaolinite, illite and smectite clays within a large-scale oedometer with a prefabricated thermal drain embedded at the center. Thermally induced excess pore water pressures and a slight initial expansion was observed for clay layers with lower hydraulic conductivity. However, the overall volume change resulted in contraction where the rate as well as the magnitude of settlement was greater for a thermal PVD compared to a conventional PVD. A further analysis of kaolinite layers with different initial porosities indicated that the increase in the magnitude of settlement observed when using a thermal PVD was independent of the hydraulic conductivity of the clay whereas the increase in the rate of settlement was more pronounced for clays with lower hydraulic conductivity.

INTRODUCTION

Soft soil deposits often cause issues for structural stability due to their undesirable properties such as high compressibility and low shear strength. Prefabricated vertical drains (PVD) are widely used for ground improvement prior to construction. A PVD is a type of geosynthetic consisting of a perforated plastic core with high transmissivity wrapped with a nonwoven geotextile that provides filtration. PVDs help accelerate drainage processes in soft soils by shortening the drainage path for excess pore water pressures and shortening the time required for consolidation. PVDs are typically used in combination with a surcharge to induce an excess pore water pressure.

Although the use of PVDs helps expedite consolidation of soft clay layers, there still exist challenges when they are being used in ground improvement applications. Installing and maintaining a stable embankment above the clay layer may be expensive and time consuming, especially for very soft soils. Furthermore, in some instances the time required for primary consolidation can still be significant. PVDs are installed in the field using a mandrel and the installation process causes disturbance of the soil adjacent to the drain. This region of disturbance is referred to as the smear zone and several researchers have investigated its effects on the performance of PVDs (e.g., Hansbo 1981, Indraratna and Redana 1998). The hydraulic conductivity of the soil in the smear zone has been found to be significantly lower than the hydraulic conductivity of the intact soil, which would decrease the rate of the consolidation process. To address some of these challenges, the use of thermal prefabricated vertical drains (thermal PVDs) has been investigated in recent studies (Abuel-Naga et al. 2006, Pothiraksanon et al. 2010). This technique combines a geothermal heat exchanger with a vertical drain where it can also conduct heat to the surrounding soil. The studies in literature have observed an increase in the rate as well as the magnitude of settlement when using a thermal PVD, in comparison to a conventional PVD. Furthermore, thermal PVDs can be used for geothermal heat exchange or underground heat storage for overlying structures after the ground improvement process is complete.

This paper focuses on the behavior of thermal PVDs embedded in different clay types using a numerical model developed by the authors in a previous study (Samarakoon and McCartney 2020). Operation of thermal PVDs in saturated normally consolidated layers of kaolinite, illite and smectite were considered in this analysis. Specifically, the coupled processes of heat transfer, fluid flow and volume change in the soil surrounding a thermal PVD were modeled using a finite difference formulation. A further analysis on the effect of hydraulic conductivity on the performance of a thermal PVD is presented using a kaolinite clay layer. The boundary conditions evaluated in this study are representative of a large-scale oeodometer which was used for validation of the numerical model of Samarakoon and McCartney (2020). Future studies will investigate the boundary conditions representative of thermal prefabricated drains in field conditions.

BACKGROUND

A thermal PVD is a prefabricated vertical drain which can also behave as a geothermal heat exchanger. This can be achieved by placing closed-loop plastic tubing within or around the core of a conventional PVD through which heated fluid will be circulated. A limited number of studies found in literature observed an increase in the magnitude as well as the rate of settlement when using thermal PVDs in lieu of conventional PVDs (Abuel-Naga et al. 2006, Pothiraksanon et al. 2010, Artidteang et al. 2011, Salager et al. 2012).

In these studies, thermally induced excess pore water pressures, increases in hydraulic conductivity and thermo-plastic volumetric strains in normally consolidated clays due to elevated temperatures were found to be factors influencing the settlements observed in soil surrounding a thermal PVD. Excess pore water pressure generation at elevated temperatures in undrained or partially drained soils has been observed by several researchers (Campanella and Mitchell 1968, Hueckel and Pellegrini 1992, Abuel-Naga et al. 2006). The generation of thermally induced excess pore water pressure is attributed to the differences in the coefficients of thermal expansion of soil particles and the pore fluid. The soil will undergo volumetric contraction as the excess pore water pressures are dissipated.

An increase in temperature will also decrease the density and viscosity of the pore fluid which will result in an increase in hydraulic conductivity. The relationship between hydraulic conductivity (k) with fluid and soil properties can be understood using the definition of the intrinsic permeability K in Equation 1.

$$K = \frac{k\eta_w}{\rho_w g} \qquad [1]$$

where K is the intrinsic permeability, η_w is the dynamic viscosity of the fluid, ρ_w is the fluid density and g is the coefficient of gravity. An increase in hydraulic conductivity was observed with an increase in temperature by Abuel-Naga et al. (2006) for Bangkok clay. However, the intrinsic permeability was found to be independent of temperature. The density of water will vary with temperature (T) according to the relationship in Equation 2 where α_w is the volumetric coefficient of thermal expansion of water.

$$\frac{\partial \rho_w}{\partial t} = -\rho_w \alpha_w \frac{\partial T}{\partial t} \qquad [2]$$

The fluid viscosity will vary with temperature following the empirical relationship given by Hillel (1980) in Equation 3.

$$\eta_w(T) = -0.00046575 \ln(T) + 0.00239138 \qquad [3]$$

Many studies have investigated the changes in volume of soils with changes in temperature under different stress states and drainage conditions (e.g., Campanella and Mitchell 1968, Baldi et al. 1980, Abuel-Naga et al. 2006). Most relevant to the application of thermal PVDs in ground improvement is that normally consolidated clays experience permanent, plastic volumetric contraction during drained heating (Abuel-Naga et al. 2006). On the other hand, overconsolidated soils typically show recoverable, elastic volumetric expansion during drained heating. These thermally induced volume changes are attributed to a thermal yielding mechanism that has been integrated into thermo-elasto-plastic models (Hueckel and Borsetto 1990, Cui et al. 2000, Laloui and Cekerevac 2003, Abuel-Naga et al. 2006). A thermal yield limit is defined for the soil where thermo-elastic strains occur at stress levels or temperatures below the thermal yield limit whereas thermo-plastic strains occur at stress levels on or above the thermal yield limit. Using a thermo-elasto-plastic model, Laloui and Cekerevac (2003) proposed the following relationship to obtain the thermo-plastic volume changes for normally consolidated soils during drained heating.

$$\partial e_T = \frac{(1+e_0)\gamma \partial T}{2.303\beta T(1-\gamma log\left[\frac{T}{T_0}\right])} \qquad [4]$$

where γ is a material parameter, e_0 is the initial void ratio, β is the inverse of the plastic compressibility and T_0 is the room temperature.

When a thermal PVD is being used, the temperature of the surrounding soil will increase. Heat transfer through the soil medium can be considered using Fourier's law and energy conservation principles. This increase in temperature will impact the fluid flow through the porous media by thermally induced excess pore water pressures and increased hydraulic conductivity. Fluid flow through the porous media can be expressed using principles of mass conservation and Darcy's law where Equations 2 and 3 can be incorporated to account for the effects of temperature. The volume change in a thermal PVD application will consist of mechanical and thermal components. The mechanical volume change due to a surcharge can be obtained using compressibility relationships for a normally consolidated clay. The thermo-plastic volume changes are obtained using a constitutive relationship like that in Equation 4. For a simultaneous application of a surcharge and heat, the total stress will remain constant. The change in effective stress resulting from a change in the pore water pressure can be obtained by subtracting the pore water pressure from the total stress. Furthermore, the volume change will also lead to a change in the thermal conductivity of the bulk soil. As the void space reduces, more heat conduction can occur through the soil particles. The theoretical framework and the numerical formulation simulating the coupled phenomena of heat transfer, fluid flow and volume change in soft clay surrounding a thermal PVD are described in detail in previous work by the authors (Samarakoon and McCartney 2020). The numerical model was validated using experimental data available in literature. A parametric analysis conducted on the performance of a thermal PVD showed that the amount of surcharge required when using a thermal PVD was significantly less compared to that used in combination with a conventional PVD. In addition, higher magnitudes of settlement and faster rates of consolidation were observed as the magnitude of the temperature at the drain increased.

NUMERICAL STUDY

Soil domain geometry. To simulate the behavior of a clay layer around a thermal PVD, a finite soil domain representing a large-scale oedometer experiment by Artidteang et al. (2011) was considered in this study. Specifically, a clay layer with a diameter of 0.45 m and a height of 0.70 m with a single thermal PVD located at the center was considered as shown in Figure 1. This geometry was selected as it was used by Samarakoon and McCartney (2020) to validate the numerical model used in this study. Although this geometry does not represent the boundary conditions expected in a field deployment of thermal PVDs, it permits the effects of clay type and corresponding hydraulic conductivity values on the transient thermal consolidation process.

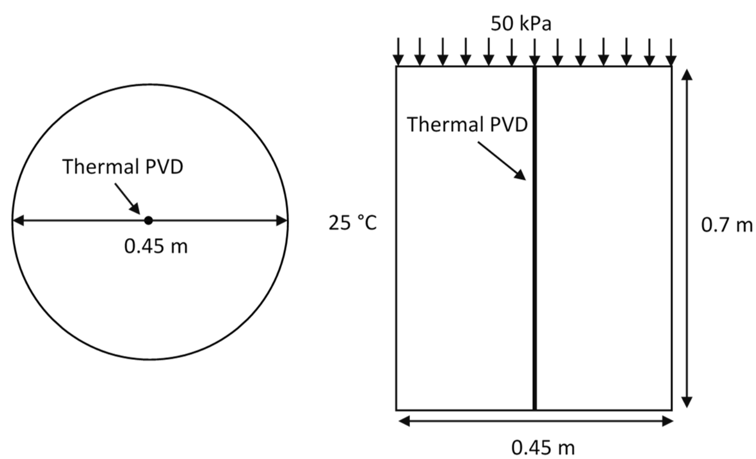

Figure 1. Schematic diagram of the thermal PVD arrangement in a finite soil domain.

Boundary and initial conditions. A 50 kPa surcharge stress was applied to a top of the saturated clay layer simultaneously with an increase in temperature from 25 °C to 90 °C applied along the length of the thermal PVD. The clay layer was assumed to be normally consolidated under the surcharge stress. Heat transfer and fluid flow were considered to be axisymmetric about the axis of the drain for the numerical simulation presented in this study. The variation of temperature in the vertical direction was assumed to be uniform thereby simplifying the geometry to a radial drainage problem. The outer edge of the oedometer permits zero radial strain. However, a variation in void ratio within the clay layer with radius is expected due to heating from the central thermal PVD. The surcharge is applied in stress-control conditions so settlements in the clay layer can be nonuniform as a function of the radius from the thermal PVD. The settlement values presented in this presentation are for the surface at a radius of 112.5 mm from the center, except in the case that radial settlement profiles are shown. A constant temperature boundary condition was imposed at the thermal drain whereas a convective temperature boundary condition was maintained at the outer edges of the clay layer to represent the edges of a container in the laboratory. Drainage was only permitted at the location of the thermal PVD (i.e., no vertical drainage from the top and bottom of the cylinder or radial drainage from the outer boundary). Accordingly, a constant hydrostatic pressure boundary was also applied at the drain location and the fluid velocity at the outer edge of the clay layer was taken as zero (i.e., no flow) representative of a large-scale oedometer. In a field application where multiple drains are used, the influence of other drains in the vicinity will have to be considered. For instance, multiple drain locations will be at constant temperature and hydrostatic pressure boundary conditions. Although not within the scope of this study, a more complex analysis with multiple drains will aid in determining the optimum spacing arrangements for thermal drains.

The initial temperature in the soil domain was 25 °C and the initial pore water pressure was determined based on the hydrostatic conditions and the applied surcharge. The initial porosity of the three clay layers considered (kaolinite, illite, and smectite) was 0.5. The assumed soil geometry and boundary conditions were validated using experimental data of Artidteang et al. (2011) asdemonstrated in detail in a previous study by the authors (Samarakoon and McCartney 2020). Building upon the above work of the authors, this paper focuses on the effect of material properties such as hydraulic conductivity on the performance of a thermal PVD.

Numerical formulation. For this study, a saturated normally consolidated clay was simulated considering the coupled processes of heat transfer, fluid flow and volume change. The coupled phenomena were simulated using the finite difference method. Both steady state as well as transient variations in temperature, pore water pressure and settlement were solved for using the numerical model. A central difference scheme was used in the spatial domain and a forward difference scheme was used in the time domain. The numerical formulation was implemented and solved using Matlab.

Material properties. This study focuses on the behavior of three clay types surrounding a thermal PVD: kaolinite, illite and smectite. A detailed study on the hydraulic conductivity of these clays as a function of void ratio was conducted by Mesri and Olson (1971). They found that the hydraulic conductivity is sensitive to the clay mineralogy and associated particle size and shape as well as the interaction of the clay particles with the pore fluid. For the void ratio of 0.5 considered in this study, kaolinite will have the highest hydraulic conductivity while smectite will have the lowest as shown in Table 1. The other material parameters used in the numerical simulation including the compressibility indices and the material specific thermal parameter, γ were obtained from literature (Laloui et al. 2008, Ye et al. 2015). The material parameters for each soil type are summarized in Table 1. The thermal conductivity and the specific heat capacity of soil particles were assumed to be 1.9 W/m/°C and 1500 J/kg/°C, respectively, for all three soil types for simplicity. It is acknowledged that the clay mineralogy likely affects the particle thermal conductivity values, but this topic has not been well studied in the literature. The thermal conductivity of pore water was 0.6 W/m/°C. The poromechanics approach used in the analysis permits consideration of changes in thermal conductivity of the bulk soil with changes in volume.

Table 1. Material parameters of the three clays considered in this study (Mesri and Olson 1971, Laloui et al. 2008, Ye et al. 2015).

Parameter	Kaolinite	Illite	Smectite
Specific gravity	2.66	2.72	2.69
Hydraulic conductivity at room temperature (m/s)	7.75×10^{-9}	5.50×10^{-11}	1.35×10^{-12}
Initial porosity	0.5	0.5	0.5
Initial total unit weight (kN/m^3)	1830	1860	1845
κ (slope of RCL)	0.01	0.02	0.04
λ (slope of VCL)	0.07	0.11	0.40
γ (soil thermal volume change parameter)	0.53	0.56	1.16

THERMAL PVD RESPONSE IN CLAY

Heat Transfer. A thermal PVD leads to an increase in temperature of the surrounding clay due to radial heat transfer through the soil medium. Spatial as well as temporal variations of temperature within the clays were obtained for each type of clay. The time series of temperature at different radial distances for each clay type is shown in Figure 2. The results in Figure 2 indicate that the soil domain reached thermal equilibrium after about 100 hrs. The locations closer to the drain reached higher temperatures at equilibrium whereas locations farther away reached lower temperatures at equilibrium.

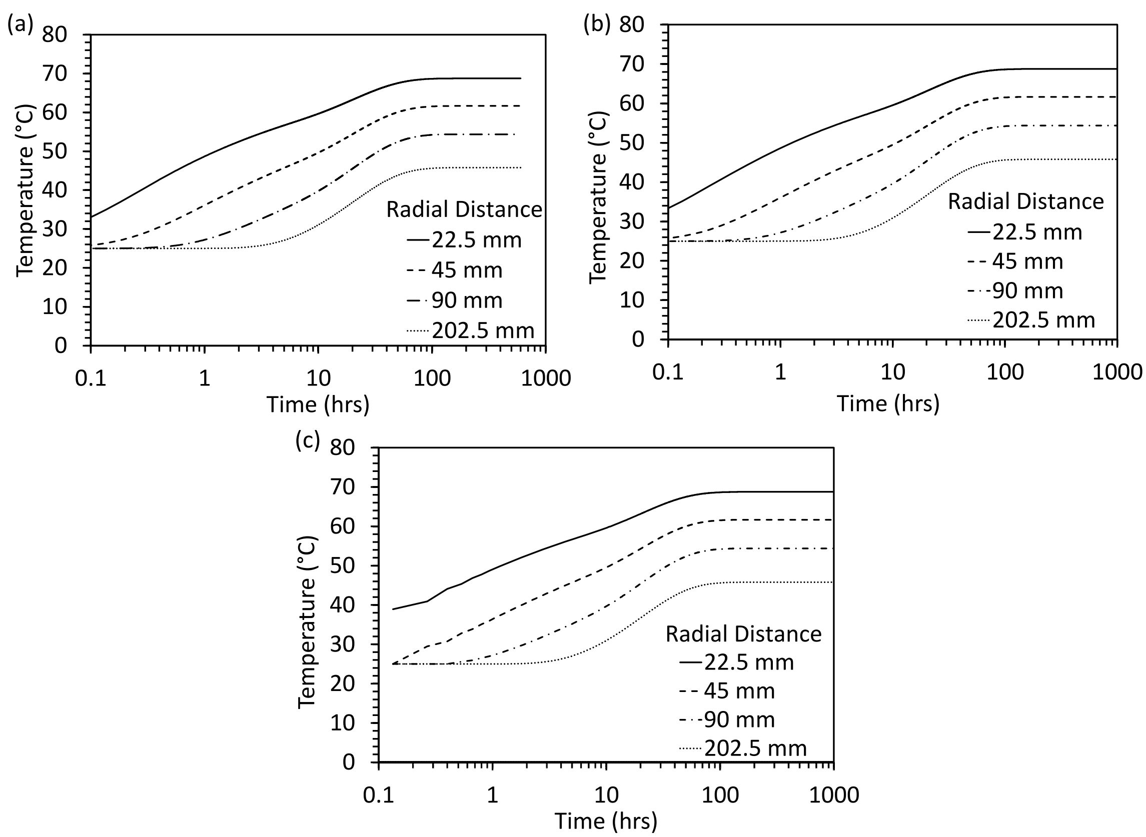

Figure 2. Time series of temperature for (a) kaolinite; (b) illite; (c) smectite.

Excess pore water pressure. The excess pore water pressures generated in each clay layer at a radial location halfway between the thermal PVD and the edge of the container are shown in Figures 3-5. Two cases were compared in which the drain temperature was maintained at 25 °C and 90 °C. The drain temperature of 25 °C is considered to be representative of a conventional PVD where excess pore water pressures are generated only due to the application of the surcharge, whereas the temperature of 90 °C represents a thermal PVD with excess pore water pressures induced by both the surcharge and heating. For kaolinite, the excess pore water pressures generated at both temperatures seem to be almost the same. However, the excess pore water pressures at 90 °C dissipates at a faster rate compared to that at 25 °C. For illite, a higher magnitude of excess pore water pressure is observed at 90 °C. Although the initial excess pore water pressure is higher at 90 °C, it is still observed to dissipate faster compared to a conventional PVD. Thermally induced excess pore water pressures are also observed in the smectite layer and their magnitudes are greater than those observed for illite. The dissipation of excess pore water pressures in smectite with both a conventional as well as a thermal PVD occur over a similar duration of time.

The differences observed in the generation of excess pore water pressures can be attributed to the different hydraulic conductivity values of each clay type. In the relatively fast-draining kaolinite layer, almost no thermally induced excess pore water pressure is generated at this location for the setting considered in this study. The main contribution to excess pore water pressure is from the applied surcharge load. On the other hand, in the slower draining clay layers of illite and smectite, some thermally induced excess pore water pressure is observed as the temperature is increased from 25 to 90 °C. The sudden increase in temperature and the low hydraulic conductivity value in a partially drained condition may have resulted in the observed increase in excess pore water pressure. On the other hand, the increase in temperature results in a decrease in viscosity of the pore fluid increases the hydraulic conductivity which in turn results in faster rates of dissipation. However, for very slow draining clays, this increase in hydraulic conductivity may still not be sufficient to offset the thermally induced excess pore water pressures during the initial stages of consolidation. However, the additional thermally induced excess pore water pressures generated when using a thermal PVD will contribute towards the thermally induced settlement of the clay layer.

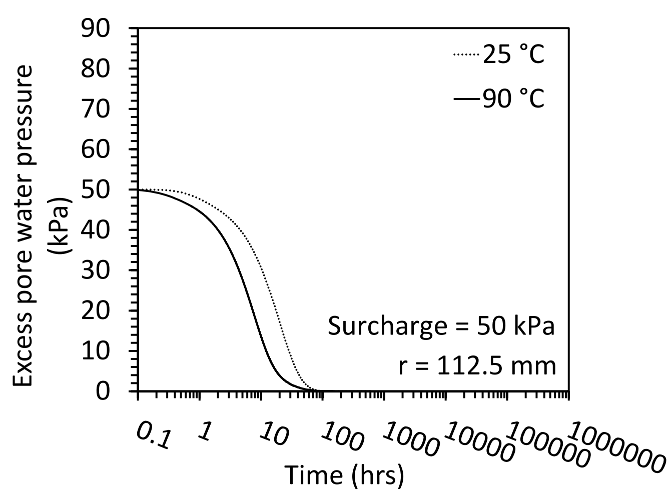

Figure 3. Excess pore water pressure during consolidation under different temperatures for kaolinite.

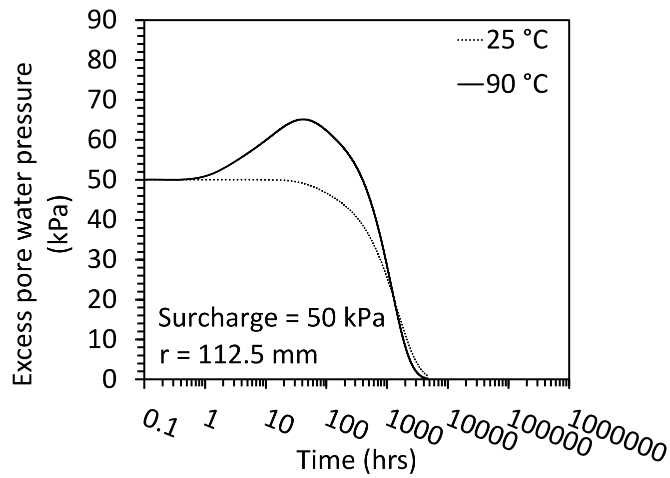

Figure 4. Excess pore water pressure during consolidation under different temperatures for illite.

Volume change. With simultaneous application of a surcharge load and heat, the clay layer will be subjected to mechanically induced as well as thermally induced strains. Mechanically induced contractile strains can be obtained using the one dimensional compressibility relationships for a normally consolidated clay. Thermo-plastic contractile strains were obtained from the relationship proposed by Laloui and Cekerevac (2003) shown in Equation 4, which is only valid for normally consolidated soils. A comparison of settlements obtained when using a conventional PVD and a thermal PVD for each clay type are shown in Figures 6-8. For all three clay types an increase in the magnitude as well as the rate of settlement is observed when using a thermal PVD, conforming with the observations made in literature. The differences in the magnitude of thermally induced settlement can be attributed to the differences in the material properties such as hydraulic conductivity, compressibility indices and the thermal parameter, which influences the volume change of each clay type.

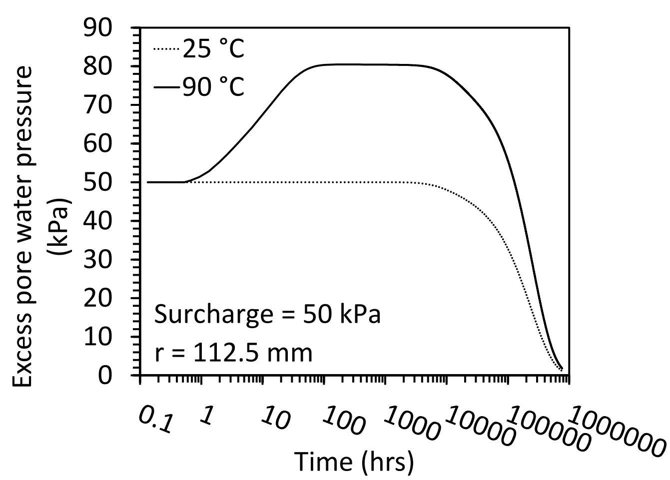

Figure 5. Excess pore water pressure during consolidation under different temperatures for smectite.

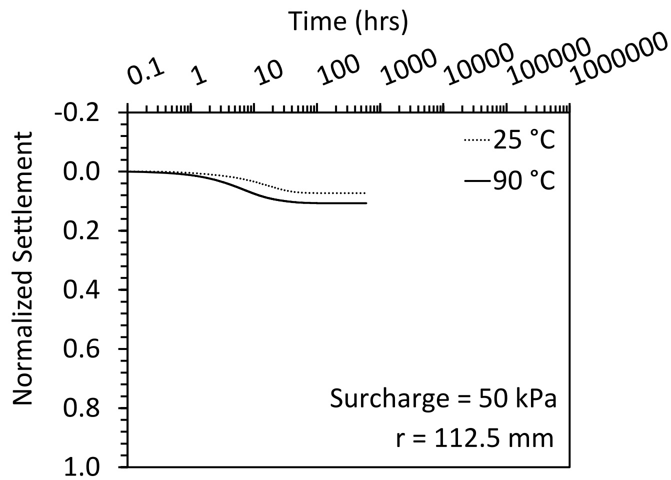

Figure 6. Comparison of settlement time series at different temperatures for kaolinite.

An interesting observation made from the simulation results was the slight initial expansion observed in illite and smectite clay layers at 90 °C. Thermally induced excess pore water pressures were observed in the same two clays. As discussed in the previous section, under partial drainage conditions, some initial expansion can be expected corresponding with the increase in thermally induced excess pore water pressure. Laboratory tests conducted by Campanella and Mitchell (1968) and Ghaaowd et al. (2016) where soil specimens were subjected to an increase in temperature under fully undrained conditions have reported expansion during heating. However, as the clay layer continues to drain, volumetric contraction occurs and the net volume change at the end of consolidation results in contraction. A closer observation of the impact of temperature on the initial expansion and excess pore water pressure in smectite is shown in Figure 9. It can be observed that the magnitude of initial expansion increases as the temperature is increased. As expected, the amount of excess pore water pressure generated also increases with temperature.

The temperatures at equilibrium varied as a function of radius as shown in Figure 2 and therefore nonuniform settlements can be expected in the clay layer. The equilibrium settlement along a radius for each clay type is shown in Figure 10. The change in settlement along the radius for smectite was more significant where higher settlements were observed closer to the drain. Changes in settlement along a radius for kaolinite and illite were less pronounced.

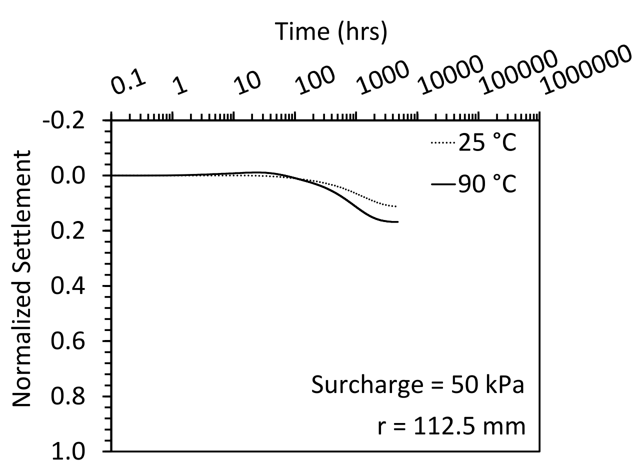

Figure 7. Comparison of settlement time series at different temperatures for illite.

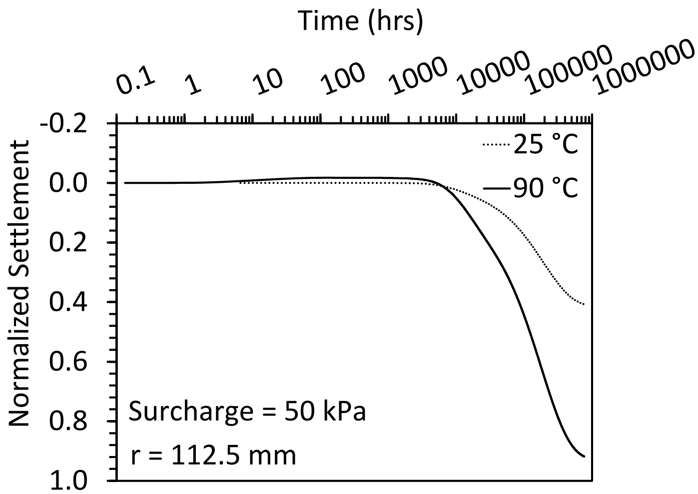

Figure 8. Comparison of settlement time series at different temperatures for smectite.

Hydraulic Conductivity. The hydraulic conductivity of the soil surrounding a thermal PVD will increase as the temperature of the soil domain increases. This increase can be obtained using Equations 1 and 3. For the clay types evaluated in this study, the hydraulic conductivity of the clay when using a thermal PVD was 1.62 times faster than the hydraulic conductivity of the clay when a conventional PVD was being used. Pothiraksanon et al. (2010) estimated the hydraulic conductivity with a thermal PVD to be 1.8 time faster when compared to the hydraulic conductivity with a conventional PVD for a field scale test on Bangkok clay. For, the clay types considered in this study, the decrease in viscosity of the pore fluid for a given temperature increment will be the same and as a result, the hydraulic conductivity of each clay type increased by a similar amount. However, the compressibility characteristics and the material specific thermal parameter influenced the differences observed in the mechanical and the thermo-plastic volume change of each clay.

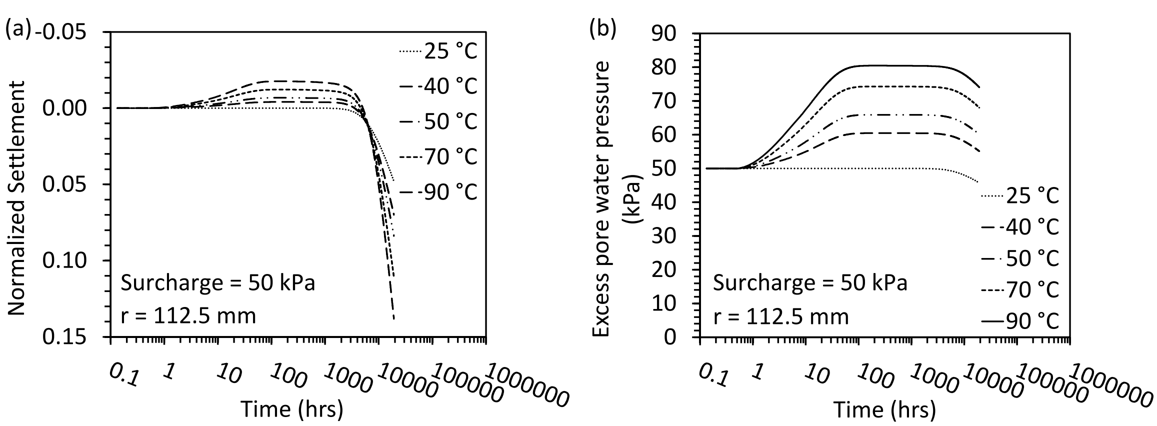

Figure 9. Effect of temperature on the (a) initial expansion and (b) excess pore water pressure in smectite.

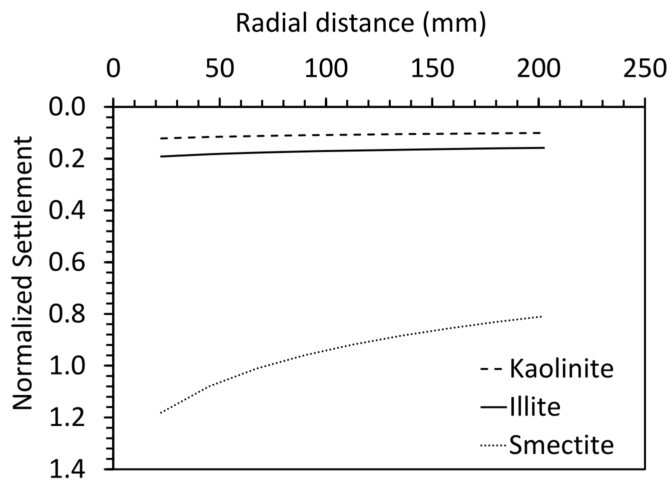

Figure 10. Radial profiles of equilibrium settlement obtained from a thermal PVD.

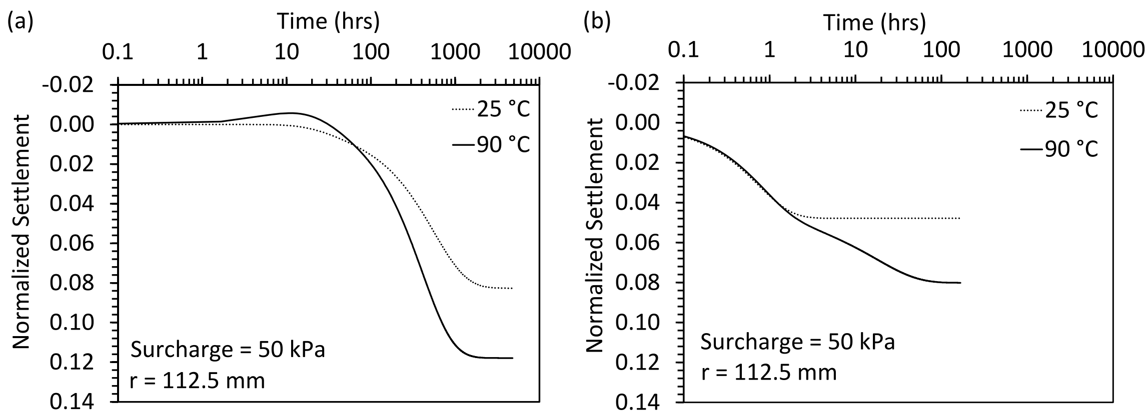

Figure 11. Comparison of settlement time series in kaolinite; (a) n = 0.43 (b) n = 0.67.

To investigate the effect of hydraulic conductivity on the performance of a thermal PVD, kaolinite layers at different initial porosities were considered. The change in hydraulic conductivity with porosity was obtained from Mesri and Olson (1971). Settlement curves obtained for clay layers with initial porosities 0.43 and 0.67 under similar loading conditions as described above are shown in Figure 11. A slight initial expansion was observed in the kaolinite clay layer with the lower initial porosity (i.e., low hydraulic conductivity), similar to the slower draining illite and smectite clay layers. The maximum settlements obtained at different hydraulic conductivity values are summarized in Figure 12.

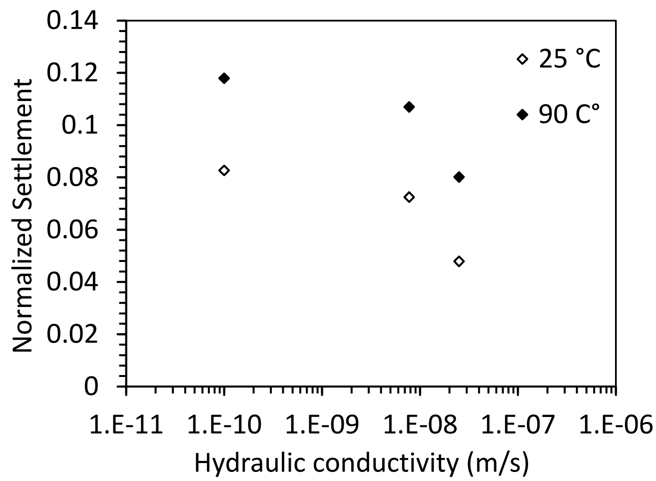

Figure 12. Effect of hydraulic conductivity on equilibrium settlement in kaolinite.

CONCLUSION

A study was conducted on the performance of a thermal PVD on saturated normally consolidated layers of kaolinite, illite and smectite clay. Specifically, a simultaneous application of mechanical and thermal loads was considered and the coupled processes of heat transfer, fluid flow and volume change were simulated using a numerical model. In general, the main conclusion is that the properties of the clay will determine the effectiveness of thermal consolidation as a means of soil improvement. Thermally induced excess pore water pressures were initially observed for the low permeability illite and smectite clay layers, but not in the higher permeability kaolinite clay layer. At the same time, a slight initial expansion was also observed in the illite and smectite clay layers. The observed initial expansion and the thermally induced excess pore water pressure were found to increase with an increase in applied temperature to the thermal PVD. Despite the difference in initial behavior for the illite, smectite, and kaolinite clays, a net contraction was observed for all three clay layers with an increase in the rate as well as magnitude of settlement when a thermal PVD was used. An analysis conducted on the effect of hydraulic conductivity on the performance of a thermal PVD in kaolinite also observed a slight initial expansion for the clay layer with low hydraulic conductivity. Clay layers with different hydraulic conductivity values was observed to have a similar increase in the magnitude of settlement obtained when using a thermal PVD. However, the effect of temperature on the rate of settlement is more significant for clay layers with low hydraulic conductivity. A study on the use of a thermal PVD in different clay types demonstrated that some initial expansion would occur in clays with low hydraulic conductivity values. As this was dependent on the magnitude of temperature at the drain, slower heating using incremental steps may help reduce the initial expansion observed in these clay layers. Future studies will use this model to study the interaction between thermal PVDs in the field to understand the ideal temperature and drain spacing to reach a desired settlement.

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