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Pore Water Pressure Prediction for Undrained Heating of Soils

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Abstract

This paper focuses on the validation of a prediction model for the thermally induced excess pore water pressure generated in saturated soils during undrained heating. A thermo-elastic analysis was calibrated using experimental data presented in the literature for normally consolidated soils having different mineralogical compositions. The magnitude of thermically induced excess pore water pressure for these soils was observed to depend on the initial void ratio, the initial effective stress, the thermal coefficient of cubical expansion of the soil particles, the change in temperature, the compressibility of the soil skeleton, and the physico-chemical coefficient of structural volume change. An empirical relationship between the physico-chemical coefficient of structural volume change and the plasticity index was proposed to predict the thermally induced excess pore water pressure for saturated, normally consolidated soils. To validate the model, an undrained heating test was performed independently on a specimen of normally consolidated kaolinite clay, and the measured thermally induced excess pore water pressures were found to match well with the model predictions.

Keywords. Pore water pressure; thermal volume change; clay; geomaterial characterization; testing and evaluation.

List of notation

$\alpha_w$ is the cubical coefficient of thermal expansion of the pore water

$\alpha_s$ is the cubical coefficient of thermal expansion of the mineral solids

$V_w$ is the initial volume of pore water before heating is the volume of solids

$V_s$ is the volume of solids

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\( V_m \) is the total volume of the soil mass equal to the sum of \( V_w \) and \( V_s \)

\( \Delta T \) is the change in temperature of the soil

\( \Delta V_{st} \) is the volume change of the soil due to the reorientation and relative movement of the soil particles during heating

\( m_v \) is the compressibility of the soil skeleton

\( m_w \) is the compressibility of the water

\( n \) is the porosity of a saturated soil

\( \alpha_{st} \) is the physico-chemical coefficient of structural volume change

\( (m_v)_r \) is the compressibility of the soil skeleton determined from the recompression curves

\( e_0 \) is the initial void ratio

\( p' \) is the mean effective stress

\( p'_c \) is the mean effective preconsolidation stress

\( e_0 \) is the initial void ratio

\( \sigma' \) is the effective stress

\( w \) is the water content

\( LL \) is the liquid limit

\( PL \) is the plastic limit

\( LI \) is the liquidity index

\( PI \) is the plasticity index

\( \kappa \) is the slope of the recompression line

\( \lambda \) is the slope of the compression line

\( v \) is the specific volume
1. Introduction

It is well known that undrained heating of saturated clays leads to excess pore water pressure generation due to the differential expansion of the pore water and soil solids (Campanella and Mitchell 1968). This phenomena also occurs in other saturated geomaterials, and is also referred to as thermal pressurization (Ghabezloo and Sulem 2009). As a measure for preconsolidation of soft clay layers, combining thermal energy from embedded geothermal heat exchangers with vertical drains to cause thermal consolidation can be effective in preparing a site for subsequent foundation or embankment loading. This approach may also be suitable for mitigating the seismic amplification potential of deep clays sites because thermal consolidation of soft clay layers can be induced without surcharge from the surface. Since pore water pressures will increase in the clay depending on the change in temperature induced by conductive heat flow away from the drain, the excess pore water pressure will dissipate geometrically away from the drain, as well as toward the free drainage boundary of the drain itself. As the magnitude of permanent contraction by heating significantly affects the thermal changes of clay in strength and hydraulic conductivity, it is important for the engineers to have an approach for preliminarily prediction of the magnitude of excess pore water pressures generated by changes in temperature.

This paper is focused on predicting the magnitude of excess pore water pressure generated in clays during undrained heating. An estimate of the magnitude of excess pore water pressure information is needed for the engineering design of thermal drain systems that are used to improve the response of soft clays (Abuel-Naga et al. 2006; Salager et al. 2012). Many researchers have evaluated the undrained heating response of different types of clays under different stress states such as Campanella and Mitchell (1968), Plum and Esrig (1969), Houston et al. (1985), Moritz (1995), Burghignoli et al. (2000), Abuel-Naga et al. (2007), and Uchaipichat and Khalili (2009). These studies found that the magnitude of temperature change, initial void ratio, mean effective stress, stress history quantified using the overconsolidation ratio (OCR), soil structure, and mineralogy of the soil particles play important roles in the magnitude of thermally induced excess pore water pressure generation. Other studies have evaluated the thermal pressurization of saturated rocks (Ghabezloo and Sulem 2009; Mohajerani et al. 2012), and in addition to seeing effects from the same variables as in the studies on clays, noted that previous damage or shearing can affect the magnitude of excess pore water pressure generation.

Although Campanella and Mitchell (1968) developed a thermo-poro-mechanical approach assuming thermo-elasticity to estimate the magnitude of change in excess pore water pressure for a
given change in temperature using concepts of thermo-elasticity and linear elasticity, some of the parameters in their analysis are not straightforward to define making it difficult to apply in practice. Since this early model was developed, several studies have continued the development of thermo-poro-mechanical theories assuming thermo-elasticity to predict thermal pressurization (McTigue 1986; Aversa and Evangelista 1993; Rice 2006; Ghabezloo and Sulem 2009; Mohajerani et al. 2012) and thermo-elasto-plasticity (Veveakis et al. 2013). An issue that has been identified in these studies is the appropriate definition of material properties that govern the thermal pressurization (Ghabezloo and Sulem 2009). In addition to the topic of interest in this study, predictions of excess pore water pressure and thermal pressurization have been applied to a wide range of topics, including fault rupture in saturated rocks (Wibberley and Shimamoto 2005; Rice 2006; Sulem et al. 2007), shear band formation in landslides (Vardoulakis 2002; Cecinato et al. 2011; Veveakis et al. 2013), and radioactive waste disposal (Mohajerani et al. 2012), which implies that work in this area can have wide-ranging applications.

In order to improve the use of the thermo-elastic model of Campanella and Mitchell (1968) in practice, this study proposes an empirical relationship between the key unknown parameters governing thermal excess pore water generation and the geotechnical index properties of soils using data for normally consolidated soils reported in the literature. Further, undrained heating triaxial tests were performed in this study to measure the thermally induced excess pore water pressure in Kaolinite clay under undrained heating conditions in order to validate the proposed relationship. Further, images were taken by using high resolution camera to observe the specimen volume changes during the undrained heating process to fully capture the soil behavior.

2. Theoretical Background

Campanella and Mitchell (1968) developed a theoretical approach to estimate the excess pore water pressure generation in a specimen of saturated soil during undrained heating using the concepts of thermo-elasticity and linear elasticity. Specifically, to ensure compatibility of strains during undrained heating, the sum of the changes in volume of the soil constituents due to changes in both temperature and pressure must equal the sum of the volume changes of the total soil mass during changes in temperature $\Delta T$ and pore water pressure $\Delta u$, as follows:

$$\alpha_w V_w \Delta T + \alpha_s V_s \Delta T - (\Delta V_{st})_{\Delta T} = -m_v V_m \Delta u - m_w V_w \Delta u$$

(1)
where \( \alpha_s \) is the cubical coefficient of thermal expansion of the pore water, \( \alpha_s \) is the cubical coefficient of thermal expansion of the mineral solids, \( V_w \) is the initial volume of pore water before heating, \( V_m \) is the total volume of the soil mass equal to the sum of \( V_w \) and \( V_s \), \( \Delta T \) is the change in temperature of the soil, \( \Delta u \) is the change in pore water pressure, \( (\Delta V_s)_{\Delta T} \) is the volume change of the soil due to the reorientation and relative movement of the soil particles during heating, \( m_w \) is the coefficient of volume compressibility of water and \( m_v \) is the coefficient of volume compressibility of soil skeleton. The coefficient of volume compressibility is conventionally defined as the volumetric strain divided by the change in vertical effective stress, but in this study it is defined as the volumetric strain divided by the change in mean stress, as isotropic conditions are assumed. The compressibility of the water is assumed to be negligible compared to the value of compressibility of the soil skeleton. As the porosity of a saturated soil is equal to \( n = V_w/V_m \), Equation 1 can be rearranged to estimate the excess pore water pressure generated by a change in temperature during undrained conditions, as follows:

\[
\Delta u = \frac{n \Delta T (\alpha_s - \alpha_w)}{m_v + n \cdot m_w} + \frac{(\Delta V_s)_{\Delta T}}{V_m} = \frac{n \Delta T (\alpha_s - \alpha_w) + \alpha_s \Delta T}{m_v + n \cdot m_w}
\]

(2)

For most soils, the value of \( m_v \) is much greater than \( n \cdot m_w \) (Campanella and Mitchell 1968), so Equation 2 can be simplified as follows:

\[
\Delta u = \frac{n \Delta T (\alpha_s - \alpha_w) + \alpha_s \Delta T}{m_v}
\]

(3)

3. Estimation of Soil Properties for Pore Water Pressure Prediction

Evaluation of Equation 3 indicates that the factors affecting the change in pore water pressure change of saturated soil during undrained heating are the magnitude of the temperature change, the porosity, the difference between the coefficients of thermal expansion for soil grains and water, and the physico-chemical coefficient of the structural volume change. Of these different factors, most can be readily estimated for the soils reported in the literature except for the physico-chemical coefficient of the structural volume change. Specifically, the compressibility of the soil skeleton \( m_v \) can be estimated from the compression curve, the values of porosity can be calculated using the initial gravimetric water content and specific gravity, the value of \( \alpha_s \) depends on the clay mineral, and \( \alpha_w \) is a constant. The values of \( \alpha_s \) and \( \alpha_w \) used by most researchers such as Campanella and Mitchell (1968), Burghignoli et al. (2000) were equal to 0.000035/°C and 0.00017/°C, respectively. The value of \( \alpha_s \) does not vary significantly for the tests on different clay minerals reported in the literature, so the value used by
Campanella and Mitchell (1968) can be used to analyze the results from other clays. It is important to clarify that the value of $\alpha_w$ is an order of magnitude greater than $\alpha_s$, which is one of the primary reasons for the pore water pressure change in saturated clays. However, because the difference between these two parameters is similar for most clays, there must be another parameter that affects the thermal volume change of clays.

Regarding the estimation of the value of $m_v$ from the compression curve, Campanella and Mitchell (1968) and Uchaipichat and Khalili (2009) found that a saturated soil will expand along the recompression line during undrained heating. On this basis, the value of $m_v$ can be determined from the isotropic recompression curve $(m_v)_r$ at a given value of mean effective stress, as follows:

$$ (m_v)_r = \frac{1}{1 + e_0 p'} \kappa $$

where $e_0$ is the initial void ratio, $p'$ is the mean effective stress, and $\kappa$ is the slope of the isotropic recompression line equal to $\Delta v / \ln(p'/p'_c)$, where $v$ is the specific volume ($v = 1+e$) and $p'_c$ is the mean effective preconsolidation stress. As the slope of the isotropic compression line is more commonly reported than the isotropic recompression line in studies on the thermal volume change of normally consolidated soils, the value of $\kappa$ can be assumed to be related to the slope of the isotropic compression line $\lambda$ using the ratio $\Lambda = (1-\kappa / \lambda)$. The ratio $\Lambda$ is typically ranges from 0.7 to 0.9 for low plasticity clays (Schofield and Wroth 1984), and a value of 0.9 was used when the actual value of $\kappa$ was not reported.

Equation 3 can be rewritten in the following form after incorporating the definition of $m_v$ and the ratio $\Lambda$:

$$ \Delta u \left( \frac{1}{1 + e_0} \right) \frac{(1 - \Lambda) \lambda}{p'} = n \Delta T (\alpha_s - \alpha_w) + \alpha_{st} \Delta T $$

This equation can be solved for the ratio of the pore water pressure to the initial mean effective stress $p'_0$ before the start of undrained heating, as follows:

$$ \frac{\Delta u}{p'_0} = \frac{[n (\alpha_s - \alpha_w) + \alpha_{st}]}{(1 - \Lambda) \lambda} (1 + e_0) \Delta T $$

Although this equation contains both the porosity and void ratio, which are directly related $[n = e/(1+e)]$, the value of porosity $n$ is not combined with the initial void ratio because the volume of voids (equal to the volume of water for saturated soil) and the total volume will change by a small amount during undrained heating due to thermal expansion. However, as experimental studies on the thermal excess pore water pressure generation typically do not present the change in total volume of the specimen during undrained heating, it can be assumed that $n = n_0$. This assumption was checked using the
experimental total volume change data from this study that will be presented later and similar data from Uchaipichat and Khalili (2009), and the changes in \( n \) during undrained heating were found to be small enough that they have a negligible effect on the prediction of pore water pressure generation. The form of Equation (6) confirms that the magnitude of thermally induced excess pore water pressure depends on the initial mean effective stress, a trend that is clear in the data presented by several authors, in particular Uchaipichat and Khalili (2009). The remaining parameter that is not straightforward to estimate for a clay soil is the value of the physico-chemical coefficient \( \alpha_{st} \), which may depend on several parameters. For a normal consolidated clay, it is expected that this parameter depends primarily on the soil mineralogy. Accordingly, the values of \( \alpha_{st} \) can be estimated from the \( \Delta u \) data reported for a given \( \Delta T \) by the different studies in the literature, as follows:

\[
\alpha_{st} = \frac{\Delta u}{\rho'_0 \cdot \left(1 - \Lambda \right) \cdot \lambda} \cdot \frac{1}{1 + e_o} \cdot \frac{1}{\Delta T} - n(\alpha_s - \alpha_w) \tag{7}
\]

4. Thermal Soil Response

Data from undrained heating tests on saturated soils collected from the literature are investigated in this study. Properties of the soil specimens are shown in Table 1. The Atterberg limits for these clays vary widely (liquid limit \( LL \) ranging from 21 to 186 and plasticity index \( PI \) ranging from 6 to 109), and the coefficient of compressibility indicates that the soils range from soft (high \( \lambda \)) to stiff (low \( \lambda \)). The liquidity index is greater than 1.0 for many of the soils listed below, indicating that they are wetter than the liquid limit and could have a sensitive response. A summary of the 13 normally-consolidated soil specimens under investigation from these different studies is shown in Table 2, along with the initial mean effective stress at the start of heating of each soil specimen. The soils were all heated by different magnitudes, with the greatest change in temperature being approximately 80 °C.

The results of the change in pore water pressure with change in temperature are shown in Figure 1 for the different soil specimens listed in Table 2. Due to the difference in the thermal expansion coefficient of water and soil particles, the change in pore water pressure increases with increasing change in temperature. The excess pore water pressure induced by the change in the temperature normalized by the initial effective stress is shown in Figure 2. The spread in the normalized pore water pressure changes is lower than the raw changes in pore water pressure shown in Figure 1. The initial mean effective stress plays an important role, as the stiffness of the soil skeleton is expected to increase with increasing mean effective stress which may affect the pore water pressure generation during heating. The results in Figure 2 imply that greater pore water pressures will be expected deeper in a
soil deposit. Further, evaluation of the results in Figure 2 indicates that, for most soils, the thermally
induced pore water pressure is greater than half the mean effective stress during a change in
temperature of 35 °C. The normalized pore water pressures was consistently less than 1.0, which
confirms that thermal failure did not occur in the specimens evaluated in this study.

5. Data Synthesis

The values of $\alpha_{st}$ were calculated using Equation 7 for each of the data points in Figure 2. In most
cases, the slope for each data set was approximately linear. As there is some scatter in the increase in
pore water pressure with temperature for soil specimen SPC2, a best fit slope was obtained for this soil
specimen. The trend between the average values of $\alpha_{st}$ and the plasticity index (PI) for the different soil
specimens listed in Table 2 is shown in Figure 3. The only study that reported a value of $\alpha_{st}$ was
Campanella and Mitchell (1968), who reported a value of 0.00005/°C for SPC1. This value is slightly
different from the value of 0.0006/°C calculated for SPC1 using Equation 7 and the normalized changes
in pore water pressure for this soil shown in Figure 2. However, they used the results from drained
thermal consolidation tests to estimate the value of $\alpha_{st}$, and also observed a discrepancy when using
their value of $\alpha_{st}$ to predict the change in pore water pressure observed during a separate undrained
heating test. This may have been due to experimental differences between their drained and undrained
heating tests. Further, as noted in Table 1, Campanella and Mitchell (1968) did not report Atterberg
limits, so the average PI for a pure Illite reported by Mitchell (1993) was used in plotting Figure 3. The
trend in Figure 3 shows the PI has significant effect on the $\alpha_{st}$. Although there is some scatter, the value
of $\alpha_{st}$ decreases nonlinearly with PI. This is especially clear for specimens SPC2 and SPC3 which have
very different PI values but were tested under the same initial effective stress and the same testing
conditions. Comparison of the values of the $\alpha_{st}$ for the soils that were tested at different initial effective
stresses (Houston et al. 1985; Uchaipichat and Khalili 2009; Abuel-Naga et al. 2007) indicates that the
initial effective stress does not have a major effect on the value of $\alpha_{st}$. The small differences for the
same soils tested under different effective stresses are due to scatter in the reported experimental
changes in pore water pressure with temperature.

The effect of the liquidity index LI on the physico-chemical coefficient was studied as well, as this
parameter may permit assessment of the role of sensitivity on the thermal volume change. This was
performed as several of the clays in the literature had relatively high water contents compared to the
liquid limit. The relationship between the physico-chemical coefficient $\alpha_{st}$ and LI is shown in Figure 4.
Although no clear trend was observed for the specimens evaluated, it is interesting to note that the specimens with liquidity index values greater than 1.0 had relatively high values of $\alpha_{st}$.

As the trends with the plasticity index was found to be the most significant, a best-fit empirical relation between the plasticity index and the physico-chemical coefficient $\alpha_{st}$ was fit to the data as shown in Figure 5. The empirical relationship can be expressed as follows:

$$\alpha_{st} = 1.0 \times 10^{-4} e^{0.014 \text{PI}}$$ (8)

Despite the scatter in the data and the low $R^2$ value, the empirical expression provides a reasonable representation of the trend in the data. Equation 8 may be useful in providing preliminary estimates of the change in pore water pressure during undrained heating of soils.

6. Validation of the Model

6.1 Materials and Specimen Preparation

In order to validate the prediction of the value of $\alpha_{st}$ for a soil in the prediction of the thermally induced pore water pressure, an independent experiment was performed on a saturated, normally consolidated clay specimen. Commercial kaolinite clay from M&M Clays Inc., McIntyre, Georgia was used for the experiment. The geotechnical properties of the clay are summarized in Table 3. As the clay has a liquid limit and plastic index of 47 and 19, respectively, it is classified as CL according to the Unified Soil Classification Scheme (USCS) medium plasticity. The clay has a specific gravity of 2.6.

The kaolinite clay layer was prepared by mixing the kaolinite clay powder and deionized water in a vacuum mixer to form a slurry with a water content of 135%. The slurry was then slowly poured into a 242 mm-diameter acrylic cylinder with a porous stone and filter on the top and bottom of the specimen. The clay layer was consolidated using a compression frame at a constant rate of 0.04 mm/min for 48 hours. After this point, constant vertical stresses of 124, 248, and 352 kPa were applied to the clay layer in 24 hour increments. The preconsolidated clay layer was extruded from the cylinder, and divided into four equal pieces. One of these pieces was then trimmed into a cylindrical specimen having a diameter of 72.4 mm and a height of 147.3 mm. The specimen was then placed into the thermal triaxial cell for testing. The water content and initial void ratio values after consolidation but before application of a change in the temperature are also summarized in Table 3.

6.2 Equipment and procedures

The test was performed by using a modified triaxial system originally developed by Alsherif and McCartney (2013, 2015). A schematic of the system is shown in Figures 6. The cell is comprised of a
Pyrex pressure vessel that has the advantage of having low thermal creep behavior while still remaining transparent after repeated heating and cooling cycles. The temperature within the cell is controlled by circulating heated water from a heated water bath through a stainless steel pipe bent into a “U” shape over the specimen. A solar pump is used to circulate the cell water to ensure that it is uniformly mixed, and a thermocouple is used to monitor the cell temperature changes. A pore water pressure transducer is used to monitor the pore water pressure during undrained heating. The cell fluid temperature was monitored using a thermocouple and temperature recorder having a precision of 0.5 °C. The cell pressure and backpressure were controlled using a pressure panel.

The testing procedure first involved back-pressure saturation of the specimen, which was performed by applying the cell pressure and backpressure in stages until reaching a value of Skempton's pore water pressure parameter B of 0.98 while maintaining a constant seating mean effective stress of 69 kPa. The specimen was then consolidated isotropically to a mean effective stress of 414 kPa, which corresponds to normally consolidated conditions. After this point, the specimen was heated in undrained conditions from 23 to 54 °C in increments of 5 to 10 °C. Each increment was maintained until the pore water pressure stabilized. The rate of heating rate between each increment is approximately 1.3 °C/hr. During the heating process, images of the specimen were taken using a high resolution camera (model D610 from Nikon) to measure changes in volume of the specimen throughout the test.

6.3 Experimental results and analysis

The experimental results from the undrained heating test were illustrated in Figure 7. The thermally induced excess pore water pressure was observed to increase linearly with the change in temperature for the normally consolidated kaolinite clay. The physico-chemical coefficient was estimated using Equation 8 to be $\alpha = 7.7 \times 10^{-5} \text{ Pa/°C}$, which was then used to predict the pore water pressure as a function of temperature using Equation 3. The predicted thermally induced pore water pressures are also shown in Figure 7, and good correspondence between the experimental and predicted pore water pressures for the normally consolidated kaolinite clay are observed. As a check, the physico-chemical coefficient was also calculated using Equation 7 with the experimentally measured pore water pressure values to be $\alpha = 9.1 \times 10^{-5} \text{ Pa/°C}$, which is a reasonable match with the empirically-estimated value. This confirms that the proposed empirical equation can be used as part of preliminary predictions of the generation of pore water pressure during undrained heating, and that the magnitude of $\alpha$ can be...
determined by basic properties of soils and knowledge of the current stress condition without having to perform complex experiments.

Images were taken during the undrained heating test to measure the effect of the temperature change on the specimen volume. The specific volume $v$ plotted against the mean effective stress (calculated as the initial effective stress minus the thermally induced pore water pressure) at temperatures of 24, 40.5, and 53 °C is shown in Figure 8. The specific volume increased with temperature along the elastic recompression curve ($\kappa = -0.0136$). The isotropic compression curve with an unloading cycle for the kaolinite clay (measured from an isotropic consolidation test performed on a separate specimen of the clay under the same initial conditions) is also shown in Figure 8. Similar to observations of Uchaipichat and Khalili (2009), the value of $\kappa$ from the recompression curve is similar to that measured from the thermal volume changes during the undrained heating test. This confirms the choice of $\kappa$ in the definition of the physico-chemical coefficient of structural volume change in Equation 4.

### 7. Role of Stress History in Pore Water Pressure Prediction

Although the model for the physico-chemical coefficient in Equation 8 was developed using tests on soils under normally consolidated conditions, it may also be possible to apply use this parameter to predict the thermally induced pore water pressures in overconsolidated soils. When unloading a normally consolidated soil along the recompression curve, the void ratio will increase and the value of $p'$ will decrease. These two variables play a key role in the predicting the thermally induced pore water pressure using Equation 6. Relatively few studies have investigated the thermally induced pore water pressure in overconsolidated clays. One such study is Abuel-Naga et al. (2007), who evaluated the behavior of overconsolidated specimens in addition to investigating the effects of temperature on the pore water pressure in normally consolidated Bangkok clay specimens. Their experimental results were compared with the prediction from Equation 6 using the same value of $\alpha$ as that defined for the normally consolidated specimens, but with different values of initial void ratio, porosity, and initial effective stress. The comparison is shown in Figure 9. A good match was obtained for the specimens with increasing OCR values, which confirms the flexibility of the model in considering different stress states in the prediction of the thermally induced excess pore water pressure. Additional research is needed to evaluate whether Equation 6 could be used to evaluate thermal pressurization in saturated rocks, a
topic that has been studied by Ghabezloo and Sulem (2009) and Mohajerani et al. (2012). An issue with that may be encountered is that the plasticity index is typically not measured for rock specimens.

8. Conclusion

A prediction model for the thermally induced pore water pressure was proposed and experimentally validated in this study. Normalized pore water pressures measured during changes in temperature during undrained heating tests on soil specimens reported in the literature were used to calculate the physico-chemical coefficient. Normalization of the pore water pressures helped remove the effects of the initial effective stress from the analysis, and specimens of the same soil tested under different initial mean effective stresses had similar physico-chemical coefficients of structural volume change. Relationships between the calculated values of the physico-chemical coefficient and the plasticity index and liquidity index were investigated. Although a nonlinear decreasing trend was observed with the plasticity index, no trend was observed with the liquidity index. A prediction model was proposed based on an empirical relationship between the physico-chemical coefficient of structural volume change and plasticity index. The pore water pressure values predicted by this model for kaolinite clay were matched well with those measured in an independent undrained heating test. This confirms that this simple, empirical approach to define the physico-chemical coefficient in the thermo-elastic model is effective in making preliminary estimates of the thermally induced pore water pressures expected in saturated soils used in thermal soil improvement or in thermally active geotechnical engineering systems. The thermal expansion of the specimen calculated using image analysis was found to match well with the slope of the recompression curve, confirming the assumption of the magnitude of the coefficient of volume compressibility used in the analysis. Although only limited data is available in the literature for overconsolidated clays, the validated model was found to also provide a good fit to the thermally induced pore water pressure in saturated, overconsolidated clays.

Acknowledgements

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References


Table 1. Properties of the soil specimens reported in the literature.

Table 2. The numbers designations for the soil specimens evaluated in the study.

Table 3. Properties of the Kaolinite clay.

Figure 1. Effect of temperature change on the change in pore water pressure for all soil specimens.

Figure 2. Effect of temperature change on the change in pore water pressure normalized by the initial effective stress for all soils specimens.

Figure 3. Effect of temperature change on the change in pore water pressure normalized by the initial effective stress for all soils specimens.

Figure 4. Physico-chemical coefficient as a function of liquidity index for different clays from the literature.

Figure 5. Physico-chemical coefficient as a function of plasticity index for different clays from the literature.

Figure 6. Thermal triaxial cell schematic.

Figure 7. Effect of temperature change on the change in pore water pressure for kaolinite clay along with the predicted trend using the estimated value of the physico-chemical coefficient of structural volume change.

Figure 8. Specific volume against isotropic effective stress during heating.

Figure 9. Impact of temperature change on the change in pore water pressure in Bangkok clay specimens having different OCRS along with predicted pore water pressure trends.
### Table 1. Properties of the soil specimens reported in the literature.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Soil Type</th>
<th>$e_0$</th>
<th>$w_0$ (%)</th>
<th>LL</th>
<th>PI</th>
<th>$\lambda$</th>
<th>Main Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campanella and Mitchell (1968)</td>
<td>Remolded Illite Clay</td>
<td>0.90</td>
<td>34</td>
<td>94'</td>
<td>62'</td>
<td>0.39</td>
<td>Illite</td>
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<td>Plum and Esrig (1969)</td>
<td>Newfield Clay</td>
<td>0.50</td>
<td>18</td>
<td>25</td>
<td>11</td>
<td>0.09</td>
<td>Chlorite, Mica</td>
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<tr>
<td>Houston et al. (1985)</td>
<td>Illite Clay</td>
<td>2.90</td>
<td>111</td>
<td>88</td>
<td>47</td>
<td>0.43</td>
<td>Quartz, Illite</td>
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<td>Houston et al. (1985)</td>
<td>Pacific Smectite Clay</td>
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<td>138</td>
<td>186</td>
<td>109</td>
<td>0.52</td>
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<tr>
<td>Abuel-Naga et al. (2007)</td>
<td>Bangkok Clay</td>
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<td>93</td>
<td>103</td>
<td>60</td>
<td>0.46</td>
<td>Smectite, Kaolinite, and Mica</td>
</tr>
<tr>
<td>Uchaipichat and Khalili (2009)</td>
<td>Bourke Silt</td>
<td>0.70</td>
<td>26</td>
<td>21</td>
<td>6</td>
<td>0.09</td>
<td>Montmorillonite, Illite, Kaolinite, Calcite, Quartz</td>
</tr>
<tr>
<td>Burghignoli et al. (2000)</td>
<td>Todi Clay</td>
<td>0.89</td>
<td>40</td>
<td>52</td>
<td>30</td>
<td>0.1</td>
<td>Not reported</td>
</tr>
<tr>
<td>Burghignoli et al. (2000)</td>
<td>Fiumicino Clay</td>
<td>0.81</td>
<td>30</td>
<td>55</td>
<td>32</td>
<td>0.09</td>
<td>Not reported</td>
</tr>
</tbody>
</table>

*Note: Values not reported in the original study, the values shown here are for a typical pure Illite clay.*

### Table 2. The numbers designations for the soil specimens evaluated in the study.

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Soil Type</th>
<th>Reference</th>
<th>$p'$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPC1</td>
<td>Remolded Illite Clay</td>
<td>Campanella and Mitchell (1968)</td>
<td>196</td>
</tr>
<tr>
<td>SPC2</td>
<td>Pacific Specitite Clay</td>
<td>Houston et al. (1985)</td>
<td>98</td>
</tr>
<tr>
<td>SPC3</td>
<td>Illite Clay</td>
<td>Houston et al. (1985)</td>
<td>98</td>
</tr>
<tr>
<td>SPC4</td>
<td>Illite Clay</td>
<td>Houston et al. (1985)</td>
<td>29</td>
</tr>
<tr>
<td>SPC5</td>
<td>Bourke Silt</td>
<td>Uchaipichat and Khalili (2009)</td>
<td>50</td>
</tr>
<tr>
<td>SPC6</td>
<td>Bourke Silt</td>
<td>Uchaipichat and Khalili (2009)</td>
<td>100</td>
</tr>
<tr>
<td>SPC7</td>
<td>Bourke Silt</td>
<td>Uchaipichat and Khalili (2009)</td>
<td>150</td>
</tr>
<tr>
<td>SPC8</td>
<td>Bangkok Clay</td>
<td>Abuel-Naga et al. (2007)</td>
<td>200</td>
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<tr>
<td>SPC9</td>
<td>Bangkok Clay</td>
<td>Abuel-Naga et al. (2007)</td>
<td>300</td>
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<tr>
<td>SPC10</td>
<td>Bangkok Clay</td>
<td>Abuel-Naga et al. (2007)</td>
<td>400</td>
</tr>
<tr>
<td>SPC11</td>
<td>Todi Clay</td>
<td>Burghignoli et al. (2000)</td>
<td>196</td>
</tr>
<tr>
<td>SPC12</td>
<td>Fiumicino Clay</td>
<td>Burghignoli et al. (2000)</td>
<td>147</td>
</tr>
<tr>
<td>SPC13</td>
<td>Newfield Clay</td>
<td>Burghignoli et al. (2000)</td>
<td>275</td>
</tr>
</tbody>
</table>

### Table 3. Properties and initial conditions of the Kaolinite clay specimen evaluated in this study.

| LL  | 47 |
| PL  | 28 |
| PI  | 19 |
| $w_0$ (%) | 31 |
| $G_s$ | 2.6 |
| $e_0$ | 0.81 |
| $n$ | 0.45 |
Figure 1. Effect of temperature change on the change in pore water pressure for all soil specimens.

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Figure 2. Effect of temperature change on the change in pore water pressure normalized by the initial effective stress for all soils specimens.
Click here to download Figure: Fig 2.tif
Figure 3. Effect of temperature change on the change in pore water pressure normalized by the initial effective stress for all soils specimens.
Click here to download Figure: Fig 3.tif
Figure 4. Physico-chemical coefficient as a function of liquidity index for different clays from the literature.

Click here to download Figure: Fig 4.tif
Figure 5. Physico-chemical coefficient as a function of plasticity index for different clays from the literature.

\[ \alpha_{st} = 0.0001e^{-0.014 \text{ PI}} \]

\[ R^2 = 0.5433 \]
Figure 6. Thermal triaxial cell schematic.

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Figure 7. Effect of temperature change on the change in pore water pressure for kaolinite clay along with the predicted trend using the estimated value of the physico-chemical coefficient of structural volume change.

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Figure 8. Specific volume against isotropic effective stress during heating.
Click here to download Figure: Fig 8.tif
Figure 9. Impact of temperature change on the change in pore water pressure in Bangkok clay specimens having different OCRs along with predicted pore water pressure trends.

Click here to download Figure: Fig 9.tif