# Simulations of PVD Improved Reconstituted Specimens with Surcharge, Vacuum and Heat Preloading using Axi-symmetric and Equivalent Vertical Flow Conditions

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**ABSTRACT:** This paper presents the simulations of prefabricated vertical drain (PVD) improved reconstituted specimens with surcharge preloading (PVD), vacuum and surcharge with PVD (Vacuum-PVD), heat and surcharge with PVD (Thermo-PVD), heat plus vacuum and surcharge with PVD (Thermo-Vacuum-PVD) from large scale consolidometer tests in the laboratory. The flow conditions included axi-symmetric conditions with horizontal ($K_h$) and vertical ($K_v$) permeabilities as well as equivalent vertical permeability ($K_{ev}$) using back-calculated coefficient of horizontal consolidation ($C_h$). The simulation results indicated that the settlements and excess pore pressures obtained from axi-symmetric and equivalent vertical flows were similar at the same ratio of horizontal permeability at undisturbed zone to horizontal permeability at smear zone ($K_h/K_s$). The back-calculated $C_h$ values were 1.93, 2.23, 4.17 and 4.38 $m^2$/yr as well as the corresponding $K_h/K_s$ values were 3, 2.7, 1.4, and 1.1, for PVD, Vacuum-PVD, Thermo-PVD and Thermo-Vacuum PVD, respectively. The $C_h$ values increased while the $K_h/K_s$ values decreased corresponding to PVD, Vacuum-PVD, Thermo-PVD, and Thermo-Vacuum PVD, respectively.

**KEYWORD**: Prefabricated vertical drains (PVDs), equivalent vertical permeability ($K_{ev}$), heat and surcharge preloading, numerical simulation.

## 1. INTRODUCTION

Prefabricated vertical drains (PVDs) with preloading is a method of soft ground improvement which is environmental friendly compared to other methods because of the use of green technology such as geosynthetics. Popular advantages of this method are low costs and simplicity due to no need for heavy construction machines. The PVD soft ground improvement method is combined with surcharging method by inserting the PVDs into the soft ground and take advantage of the higher horizontal hydraulic conductivity than the vertical conductivity to shorten consolidation time. Thus, the pore water squeezed out during the process of consolidation caused by the hydraulic gradients, created by the surcharge preloading, can flow toward the drain in the horizontal direction, and then flow freely along the drain vertically towards the permeable drainage layers. Usually, a surcharge load equal to or greater than the expected loading is applied at the soil surface to generate the necessary hydraulic gradient needed for vertical drainage through the PVDs. Applications of PVD method are widely used in soft ground improvement (Bergado et al., 1996a; Chai et al., 2001; Shen et al., 2005; Chu and Yan, 2005; Abuel-Naga et al., 2006; Rowe and Taechakumthorn, 2008; Liu and Chu, 2009; Liu et al., 2009; Indraratna et al., 2009; Pothiraksanon et al., 2010). However, these methods still has some disadvantages such as long consolidation time and possible instability problem of the surcharge embankment that limits the height and slope of the embankment. To mitigate these disadvantages, PVDs with embankment preloading can be combined with vacuum pressure. The vacuum consolidation was first proposed by Kjellman (1952). The studies of vacuum induced consolidation continued up to the present (Holtz, 1975; Choa, 1989; Cognon et al., 1994; Bergado et al., 1998; Tang and Shang, 2000; Mohamedelhassan and Shang, 2002; Indraratna et al., 2004, 2005, 2009, 2010; Chai et al., 2005a, b, 2006a, b, 2007, 2008; Bergado et al., 1996, 2006; Rujikiatkamjorn et al., 2007, 2008; Walker and Indraratna, 2006, 2009; Saowapakpiboon et al., 2008a, 2008b, 2009, 2010). Vacuum consolidation preloads the soil by reducing the pore pressure while maintaining constant total stress instead of increasing the total stress. The effective stress is increased due to the reduced (less atmospheric) pressure in the soil mass. The net effect is equivalent to an additional surcharge to ensure early attainment of the required settlement and increased shear strength resulting in increased embankment stability with subsequent rapid improvement in the soft clay foundation.

Moreover, the applicability of using the thermal treatment up to 90°C combining with PVD called Thermo-PVD as ground improvement technique was first proposed by Abuel-Naga et al. (2006). The Thermo-PVD works by reducing the effect of the smear zone and, consequently, faster rate of consolidation can be achieved due to the elevated temperature. Thus, the thermally induced increase in permeability of clays around a heat source in the smear zone can offset the effect of disturbance due to the PVD installation. The effect of temperature on the coefficient of the hydraulic permeability was also studied previously (e.g. Towhata et al., 1993a, 1993b; Habibagahi, 1977; Morinl and Silva, 1984; Houston and Lin, 1987; Burghignoli et al., 1995, 2000; Delage et al., 2000; Trani et al., 2010) who reported that normally consolidated saturated or lightly overconsolidated clay with applied heat up to 90°C under full drainage condition resulted in the increase in the overconsolidation ratio, the increase in the hydraulic permeability, and the increase in the shear strength. Therefore, heating the natural soft clays with drainage, which are mainly normally consolidated or lightly overconsolidated, can improve its strength, reduce its deformation properties and reduce its consolidation period under the proposed surcharge load.

## 2. SIMULATIONS

ABAQUS software is a finite element program based on Biot consolidation theory can be employed to simulate the 2D drain analysis (Hibbitt et al., 2006). It is a general purpose finite element computer code which was on the windows platform. The experimental behavior of the reconstituted specimens with PVD, Vacuum-PVD, Thermo-PVD and Thermo-Vacuum-PVD, respectively, for their settlement and dissipation of excess pore water pressure were simulated utilizing the ABAQUS/standard program. The Modified Cam Clay (MCC) model has been used to simulate the reconstituted specimens with PVD, Vacuum-PVD, Thermo-PVD and Thermo-Vacuum-PVD, respectively. The complete description of the MCC model requires 5 parameters, namely; critical state friction constant ($M$), compression index ($\lambda$), unloading/reloading index or recompression index ($\kappa$), Poisson ratio ($\nu$) and critical state void ratio ($e_{cs}$), respectively, which can be obtained from the 1-D consolidation results of the reconstituted specimen as shown in Figure 1.

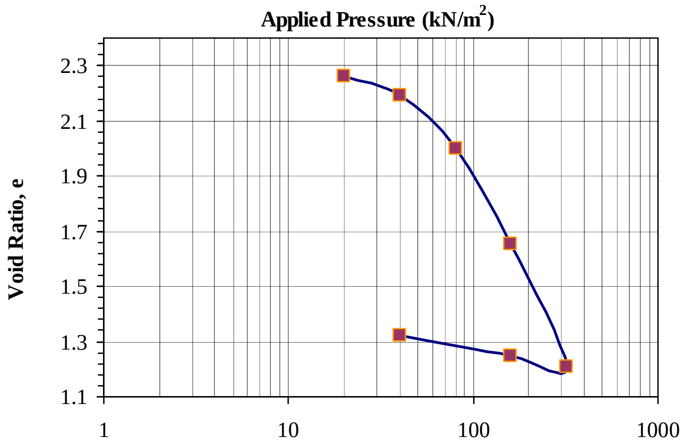


Figure 1 Relation between applied pressure and void ratio for reconstituted Bangkok clay

The two-dimensional axi-symmetric mesh was selected with horizontal ($K_h$) and vertical ($K_v$) permeability. A drainage element in finite element mesh was specified to simulate the drainage of PVD. Through the input of a specific cross sectional area and discharge capacity, $q_w$, or the horizontal permeability $K_h$ for the drainage element, the well resistance can be introduced to the analysis. Moreover, Chai et al. (2011) proposed a simple method of modeling the PVD improved ground using the equivalent vertical permeability, $K_{ev}$. In this method, $K_{ev}$ was derived by converting the expression of Carillo (1942) in one-dimensional drainage. The equivalent vertical permeability, $K_{ev}$, for radial consolidation was also applied in the simulation incorporating the effects of the smear and well-resistance. The PVD was simulated as a drain with equivalent diameter of 26.8 mm that equals to half of the actual equivalent diameter of the PVD. Due to the smear effect, Bergado et al. (1996b) indicated that the discharge capacity can be affected by $C_h$ and $K_h/K_s$. Bergado et al. (1996b) also indicated that the calculated $C_h$ values became almost independent of $q_w$ when the values of the latter exceed 100 $m^3$/yr. It could be seen further that the $C_h$ is sensitive to the ratio $K_h/K_s$, which accounted for the soil disturbance at the smeared zones, for all possible values of $q_w$. Consequently, the underestimation of smear effects and/or overestimation of the discharge capacity will lead to underestimation of the $C_h$ value. Shen et al. (2005) has also found that if the discharge capacity is equal or greater than 100 $m^3$/year, it has not much effect on the settlement behaviour. Moreover, Rujikiatkamjorn et al. (2008) and Indrarana et al. (2009) concluded that in a three-dimensional and two-dimensional multi-drain finite element analyses (ABAQUS), the predicted results from equivalent 2D (plane strain) and 3D analyses were similar.

Table 1 tabulates the parameters of PVD used in the simulation. As the simulation model, water flowed to the drain radial drainage and to the top vertical drainage. The bottom surface was made impervious similar to the laboratory test by node fixation. The effect of smear is very important for calculation of consolidation with PVD because the consolidation process is mainly affected by radial drainage. The CAX8RP (8-node biquadratic displacement, bilinear pore pressure, reduced integration) element in 2D axi-symmetric mesh was used in the simulation.

## 2.1 FEM simulation with horizontal (Kh) and vertical (Kv) permeability

For FEM simulation parameters with $K_h$ and $K_v$ used in the simulation of reconstituted specimens improved with PVD and Vacuum-PVD, as well as Thermo-PVD and Thermo-Vacuum-PVD are tabulated in Tables 2 and 3, respectively. Moreover, the parameters of reconstituted specimen improved with heat were adjusted with temperature based on experimental results of Abuel-Naga (2006) which indicated that the permeability of soil increases in the decrease in of the viscosity of the pore water. Hillel (1980) proposed the equation which related the decrease in the viscosity of water $\mu$ (in Pa.s) with the increase in temperature $T$ in °C as follows:

Table 1 PVD parameters for numerical simulation

| | | | |
|---|---|---|---|
| PVD size | | | |
| Width | $w$ | (m) | 0.0500 |
| Thickness | $t$ | (m) | 0.0035 |
| Diameter | $d_w$ | (m) | 0.0268 |
| Discharge capacity | $q_w$ | ($m^3$/year) | 100 |
| Mandrel | | | |
| Width | $t$ | (m) | 0.0182 |
| Thickness | $w$ | (m) | 0.0819 |
| Diameter | $d_m$ | (m) | 0.044 |
| Smeared zone | | | |
| Diameter | $d_s$=2 $d_m$ | (m) | 0.0871 |

Table 2 Simulation parameters with Kh and Kv in axi-symmetric flow condition of reconstituted specimen improved with PVD and Vacuum-PVD

| $H$ (m) | $e_0$ | $K_h$=$K_v$ (m/day) | $\kappa$ | $\nu$ | $\lambda$ | $M$ | $e_{cs}$ |
|---|---|---|---|---|---|---|---|
| 0.70 | 2.29 | 6.3E-05 | 0.055 | 0.3 | 0.569 | 0.8 | 4.51 |

Table 3 Simulation parameters with Kh and Kv in axi-symmetric flow condition of reconstituted specimen improved with Thermo-PVD and Thermo-Vacuum-PVD

| $H$ (m) | $e_0$ | $T$ (°C) | $K_h$=$K_v$ (m/day) | $\kappa$ | $\nu$ | $\lambda$ | $M$ | $e_{cs}$ |
|---|---|---|---|---|---|---|---|---|
| 0.70 | 2.29 | 25 | 6.3E-05 | 0.055 | 0.3 | 0.569 | 0.8 | 4.51 |
| 0.70 | 2.29 | 70 | 1.3E-05 | 0.058 | 0.3 | 0.569 | 0.8 | 4.51 |
| 0.70 | 2.29 | 90 | 1.9E-05 | 0.070 | 0.3 | 0.569 | 0.8 | 4.51 |

$$\mu(T) = -0.00046575 \ln(T) + 0.00239138 \tag{1}$$

In general, the intrinsic permeability describes the permeability of the porous skeleton regardless of the permeant fluid properties. It expresses the permeability based on the size of channels where the permeant fluid flows. Therefore, if the temperature induces changes in the diffused double layer thickness, the size of the flow channels can be affected. Consequently, the intrinsic permeability also shows changes with specimen temperature.

Based on the above discussions, the increase in the hydraulic conductivity could be attributed to the thermal evolution of the pore liquid properties. Therefore, the ratio between the hydraulic permeability at tested temperature $K(T)$ and at room temperature $K(T_o)$ can be estimated using Kozeny-Carman equation as follows:

$$\frac{K(T)}{K(T_o)} = \frac{\mu(T_o)\gamma_w(T)}{\mu(T)\gamma_w(T_o)} \tag{2}$$

where $\mu(T)$ and $\mu(T_o)$ are the pore water viscosity at tested and room temperature estimated by Eq. 1, respectively, and $\gamma_w(T)$ and $\gamma_w(T_o)$ are the pore water unit weight at tested and room temperature, respectively.

In the simulation model, a two-dimensional axi-symmetric mesh was used, with eleven elements in the x-direction (0.225 m wide) and eight elements in the z-direction (total height of 0.70 m) as shown in Figure 2 which consisted of 3 zones, namely; drain zone, smeared zone and undisturbed zone, respectively. The drain zone, smeared zone and undisturbed zone with eight elements in the z-direction and two elements, three elements and six elements, respectively, in the x-direction. The element chosen was a pore fluid/stress four-node axi-symmetric quadrilateral element with bilinear displacement and bilinear pore pressure. For the specimen improved with PVD and Thermo-PVD, a surcharge of 100 kPa was applied on the top and simulated as surface pressure as shown in Figure 2. For the specimen improved with Vacuum-PVD and Thermo-Vacuum-PVD, a surcharge of 50 kPa and vacuum pressure of 50 kPa were applied and simulated using finite element program in axi-symmetric condition as shown in Figure 3. On the bottom, the vertical and horizontal components of displacement were fixed ($u_x$=$u_z$=$0$), and on the right-hand side, the horizontal component of displacement was fixed ($u_x$= $0$) to simulate the frictionless interface between the soil and the rigid cell. The left-hand of the mesh was a symmetry line (no horizontal displacement). Note that the cell was not modeled in the analysis. Flow of pore water through the walls of the cell was not allowed. On the top surface a uniform downward pressure of 100 kPa was applied suddenly in a case of PVD and Thermo-PVD. Both uniform downward and upward pressures of 50 kPa were applied suddenly in a case of Vacuum-PVD and Thermo-Vacuum-PVD on the top surface. The top surface was permeable but the bottom surface was made impervious by node fixation. The purpose of the analysis was to predict the time dependency of the settlement pore water pressure in the soil mass after load application and to compare those with the predicted solution of Hansbo (1979) method.

### 2.2 FEM simulation with equivalent vertical permeability ($K_{ev}$)

For FEM simulation with improved zone by using equivalent vertical permeability, $K_{ev}$ which was proposed by Chai et al. (2001). The equivalent vertical permeability, $K_{ev}$ was derived by converting the expression of Carillo (1942) into one-dimensional drainage. This method proposed the equivalent vertical permeability, $K_{ev}$, expressed as follows:

$$K_{ev} = \left( 1 + \frac{2.5l^2}{\mu D_e^2} \frac{K_h}{K_v} \right) K_v \tag{3}$$

where:

$D_e$ = equivalent diameter of a unit PVD influence zone
$K_h$, $K_v$ = permeabilities of the reconstituted specimens in horizontal and vertical directions, respectively.
$l$ = drainage length of PVD improved zone
$\mu$ = factor of PVD geometry, smear effect and well-resistance from expression of Hansbo (1981) as follows:

$$\mu = ln(\frac{n}{s}) + \frac{K_h}{K_s} ln(s) - \frac{3}{4} + \frac{\pi 2l^2 K_h}{3q_w} \tag{4}$$

The parameters in simulation of reconstituted specimens improved with Vacuum-PVD, Thermo-PVD and Thermo-Vacuum-PVD are tabulated in Tables 4 and 5, respectively. Moreover, the parameters of reconstituted specimen improved with heat were adjusted with temperature based on experimental results of Abuel-Naga (2006). In the the simulation model, a two-dimensional axi-symmetric mesh was used, with eleven elements in the x-direction (0.225 m wide) and eight elements in the z-direction (total height of 0.70 m) as shown in Figure 4. The element chosen was a pore fluid/stress four-node axi-symmetric quadrilateral element with bilinear displacement and bilinear pore pressure. For the specimen improved with PVD and Thermo-PVD, a surcharge of 100 kPa was applied on the top and simulated as surface pressure as shown in Figure 4. For the specimen improved with Vacuum-PVD and Thermo-Vacuum-PVD, a surcharge of 50 kPa and vacuum pressure of 50 kPa were applied and simulated using finite element program in axi-symmetric condition as shown in Figure 5. On the bottom, the vertical and horizontal components of displacement were fixed ($u_x$=$u_z$=$0$), and on the right-hand side, the horizontal component of displacement was fixed ($u_x$= $0$) to simulate the frictionless interface between the soil and the rigid cell. The left-hand of the mesh was a symmetry line (no horizontal displacement). Note that the cell was not modeled in the analysis. Flow of pore water through the walls of the cell was not allowed. On the top surface a uniform downward pressure of 100 kPa was applied suddenly in a case of PVD and Thermo-PVD. Both uniform downward and upward pressures of 50 kPa were applied suddenly in a case of Vacuum-PVD and Thermo-Vacuum-PVD on the top surface. The top surface was permeable but the bottom surface was assumed impervious by node fixation. The purpose of the analysis was to predict the time dependency of the settlement pore water pressure in the soil mass after load application and to compare those with the predicted solution of Hansbo (1979) method.

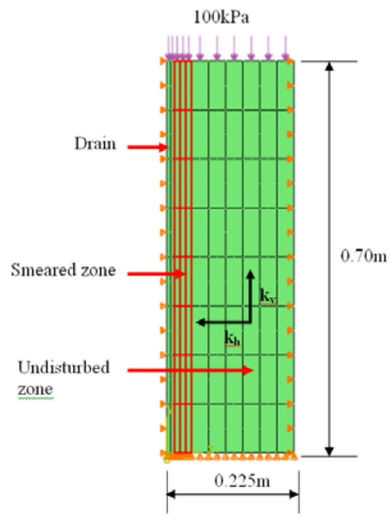


Figure 2 FEM simulation with Kh and Kv in axi-symmetric flow condition of reconstituted specimen with PVD and Thermo-PVD

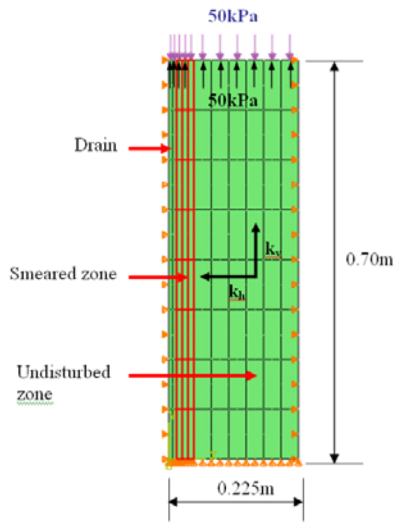


Figure 3 FEM simulation with Kh and Kv in axi-symmetric flow condition of reconstituted specimen with Vacuum-PVD and Thermo-Vacuum-PVD

Table 4 Simulation parameters with $K_{ev}$ in equivalent vertical flow condition of reconstituted specimen improved with PVD and Vacuum-PVD

| $H$ (m) | $e_0$ | $K_{ev}$ (m/day) | $\kappa$ | $\nu$ | $\lambda$ | $M$ | $e_{cs}$ |
|---|---|---|---|---|---|---|---|
| 0.70 | 2.29 | 2.7E-04 | 0.055 | 0.3 | 0.569 | 0.8 | 4.51 |

Table 5 Simulation parameters with $K_{ev}$ in equivalent vertical flow condition of reconstituted specimen improved with Thermo-PVD and Thermo-Vacuum-PVD

| $H$ (m) | $e_0$ | $T$ (°C) | $K_{ev}$ (m/day) | $\kappa$ | $\nu$ | $\lambda$ | $M$ | $e_{cs}$ |
|---|---|---|---|---|---|---|---|---|
| 0.70 | 2.29 | 25 | 2.7E-04 | 0.055 | 0.3 | 0.569 | 0.8 | 4.51 |
| 0.70 | 2.29 | 70 | 5.4E-04 | 0.058 | 0.3 | 0.569 | 0.8 | 4.51 |
| 0.70 | 2.29 | 90 | 8.1E-04 | 0.070 | 0.3 | 0.569 | 0.8 | 4.51 |

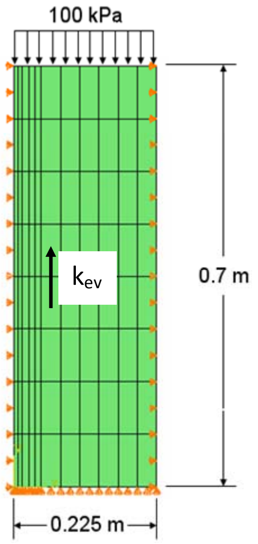


Figure 4 FEM simulation with Kev in equivalent vertical flow condition of reconstituted specimen with PVD and Thermo-PVD

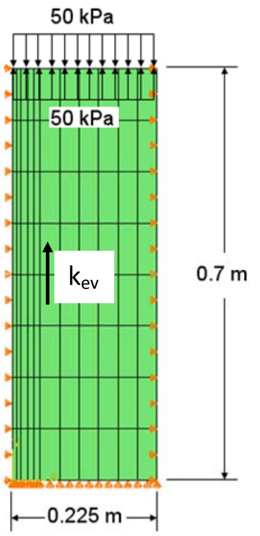


Figure 5 FEM simulation with Kev in axi-symmetric flow condition of reconstituted specimen improved with Vacuum-PVD and Thermo-Vacuum-PVD

## 3. SIMULATION RESULTS

### 3.1 Simulated settlement and excess pore pressure

For the reconstituted specimen with PVD, a surcharge of 100 kPa was applied on the top and simulated as surface pressure. For FEM simulation of PVD, the simulated settlement with $K_h$ and $K_v$ and with $K_{ev}$ are plotted in Figures 6 and 7, respectively, and compared with measured data by using back-calculated $C_h$. The $K_h/K_s$ from FEM simulation with smear and improved zones were the same and equal to 3 and the simulated settlement data matched with the measured data. In addition, the simulated excess pore pressures with $K_h$ and $K_v$ are plotted in Figure 8. The measured excess pore pressure had increased to maximum of 80 kPa after 47 days and decreased to about 10 kPa. The FEM simulated excess pore pressure had increased to maximum of 90 kPa after 47 days and decreased to about 15 kPa. The excess pore pressures were slightly overestimated by the FEM simulation with Kh and Kv. Moreover, the rates of dissipation from the measured data were faster than FEM simulation.

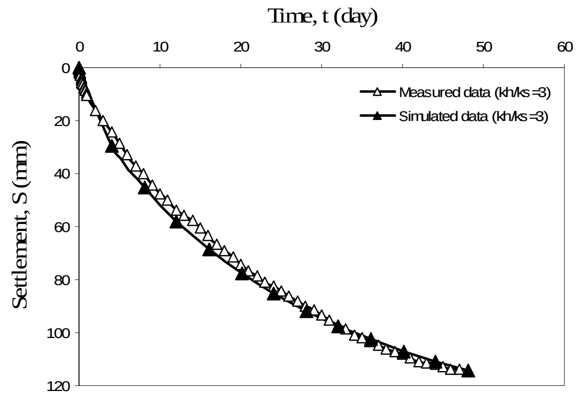


Figure 6 Comparison of settlement between measured data and simulated data with $K_h$ and $K_v$ in axi-symmetric flow condition of reconstituted specimen improved with PVD

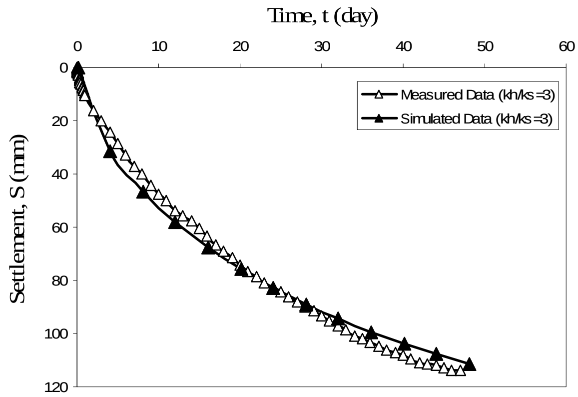


Figure 7 Comparison of settlement between measured data and simulated data with Kev in equivalent vertical flow condition of reconstituted specimen improved with PVD

For the reconstituted specimen with Vacuum-PVD, a surcharge of 50 kPa and a vacuum pressure of -50 kPa were applied at the top and simulated as surface pressure. For the FEM simulation of Vacuum-PVD, the simulated settlement data with $K_h$ and $K_v$ are plotted in Figure 9, and compared with measured data by using the back-calculated $C_h$. The $K_h/K_s$ from FEM simulation with smear and improved zones were the same and equal to 2.7 and simulated settlement curve matched with the measured data. In addition, the excess pore pressures obtained from FEM analysis with $K_h$ and $K_v$ are plotted in Figure 10. The maximum measured excess pore pressure in the smear zone had increased about 40 kPa, dissipated gradually after 7 days and decreased to about -35 kPa after 40 days. The FEM excess pore pressures in the smear zone had increased to maximum of 44 kPa, dissipated rapidly after 3 days and decreased to about -38 kPa after 40 days. Moreover, the maximum measured excess pore pressure in the undisturbed zone had increased about 39 kPa, dissipated gradually after 12 days and decreased to about -35 kPa after 40 days as same as the FEM excess pore pressure in the undisturbed zone had increased to maximum of 44 kPa, dissipated gradually after 14 days and decreased to about -30 kPa after 40 days.

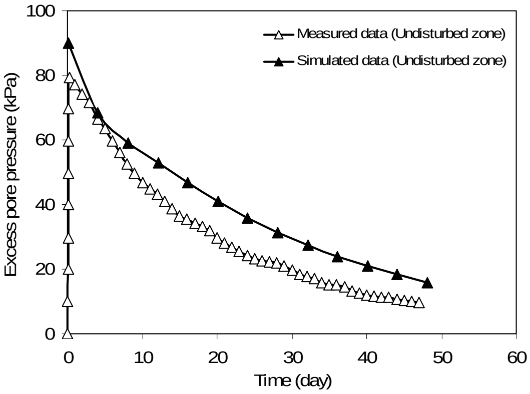


Figure 8 Comparison of excess pore pressure between measured data and simulated data with $K_h$ and $K_v$ in axi-symmetric flow condition of of reconstituted specimen improved with PVD

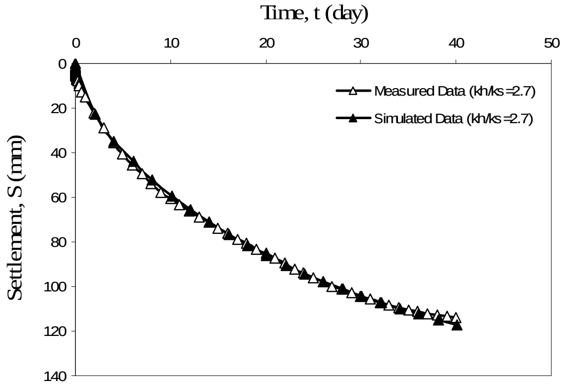


Figure 9 Comparison of settlement between measured data and simulated data with $K_h$ and $K_v$ in axi-symmetric flow condition of reconstituted specimen improved with Vacuum-PVD

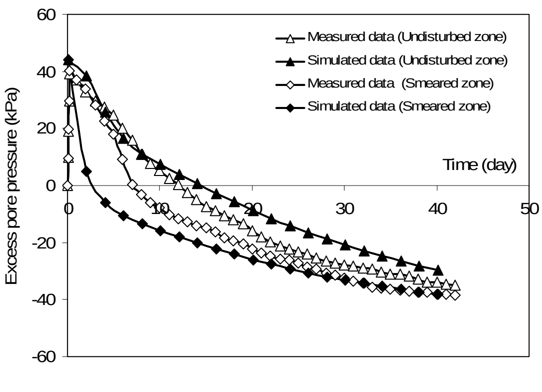


Figure 10 Comparison of excess pore pressure between measured data and simulated data with $K_h$ and $K_v$ in axi-symmetric flow condition of reconstituted specimen improved with Vacuum-PVD

The vacuum preloading generated negative (suction) excess pore pressures equivalent to the applied vacuum pressure. This behavior is similar to the results obtained by Indraratna et al. (2005) where the assumption of constant vacuum pressure distribution over the soil surface and linearly decreasing vacuum pressure along the drain length were indicated. Moreover, Chai et al. (2007) showed that the measured and simulated excess pore pressure and vacuum pressure varied with time. Figures 11 and 12 show the excess pore pressures along the height of the reconstituted specimen improved with Vacuum-PVD at the undisturbed and smeared zone with durations of 10, 20, 30 and 40 days. The excess pore pressures at the smeared zone reduced non-linearly with depth faster than the corresponding values in the undisturbed zone as expected.

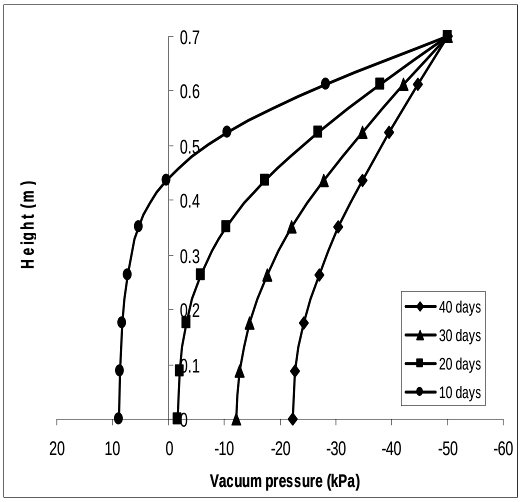


Figure 11 Simulation of excess pore pressures in the undisturbed zone of the reconstituted specimen improved with Vacuum-PVD with durations of 10, 20, 30, and 40 days

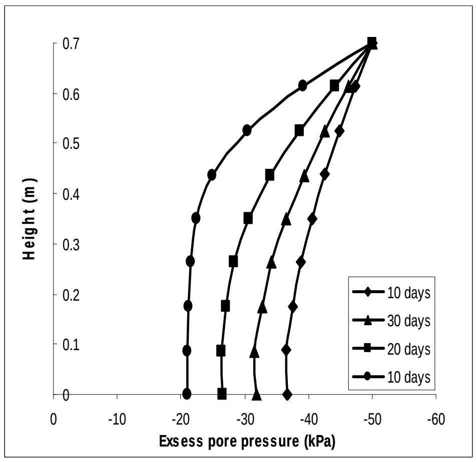


Figure 12 Simulation of excess pore pressures in the smear zone of the reconstituted specimen improved with Vacuum-PVD with durations of 10, 20, 30, and 40 days

The reconstituted specimen with Thermo-PVD, a surcharge of 100 kPa was applied at the top and simulated as surface pressure and applied the heat up to 90°C at PVD. For FEM simulation of Thermo-PVD, the simulated settlement with $K_h$ and $K_v$ are plotted in Figure 13, comparing the simulated data with measured data by using back-calculated $C_h$. The $K_h/K_s$ from FEM simulation with smear and improved zones were the same and equal to 1.4 and the simulated settlement curve matched with the measured data. In addition, the excess pore pressures obtained from FEM analysis with

$K_h$ and $K_v$ are plotted in Figure 14. The maximum measured excess pore pressure in the undisturbed zone had increased to 80 kPa and dissipated rapidly after 28 days to 1 kPa. Similarly, the FEM excess pore pressures in the undisturbed zone had increased to 80 kPa and dissipated rapidly after 28 days to 2 kPa. The permeability values in the smear zone increased at higher temperature and, consequently, the excess pore water pressures dissipated more rapidly (Pothiraksanon et al., 2008, 2010). The thermally induced excess pore pressures were generated because the thermal expansion coefficient of the pore water is approximately 15 times larger than the thermal expansion of the clay solid skeleton (Abuel-Naga, et al., 2007).

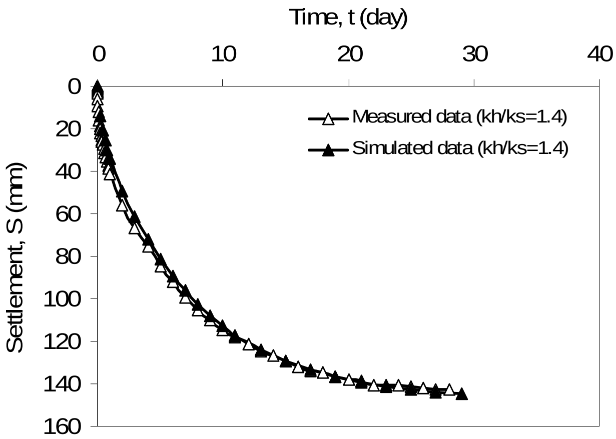


Figure 13 Comparison of settlement between measured data and simulated data with $K_h$ and $K_v$ in axi-symmetric flow condition of reconstituted specimen improved with Thermo-PVD

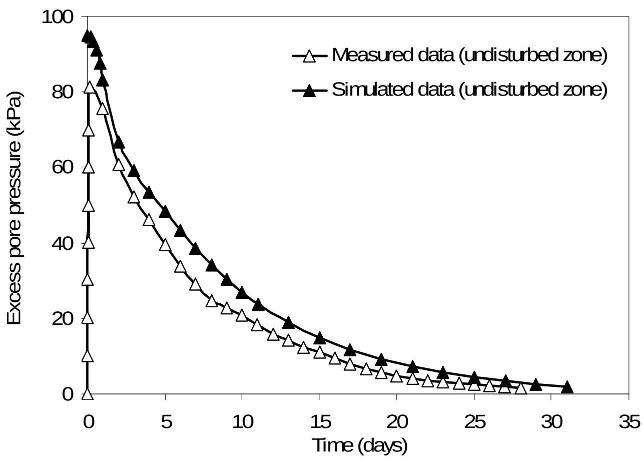


Figure 14 Comparison of excess pore pressure between measured data and simulated data with $K_h$ and $K_v$ in ax-symmetric flow condition of reconstituted specimen improved with Thermo-PVD

The reconstituted specimen with Thermo-Vacuum-PVD, a surcharge of 50 kPa and vacuum pressure of -50 kPa were applied at the top and simulated as surface pressure which applied the heat up to 90°C at PVD. For FEM simulation of Thermo-Vacuum-PVD, the simulated settlement with $K_h$ and $K_v$ are plotted in Figure 15 and compared with the measured data by using back-calculated $C_h$. The $K_h/K_s$ from FEM analysis with smear and improved zones were equal to 1.1 and yielded good agreement of the settlement curve compared with measured data. In addition, the excess pore pressures obtained from FEM simulation in the smear and improved zones are plotted together in Figure 16. The maximum measured excess pore pressure in the undisturbed zone had increased to 40 kPa, dissipated rapidly after 5 days and decreased to -43 kPa after 28 days.

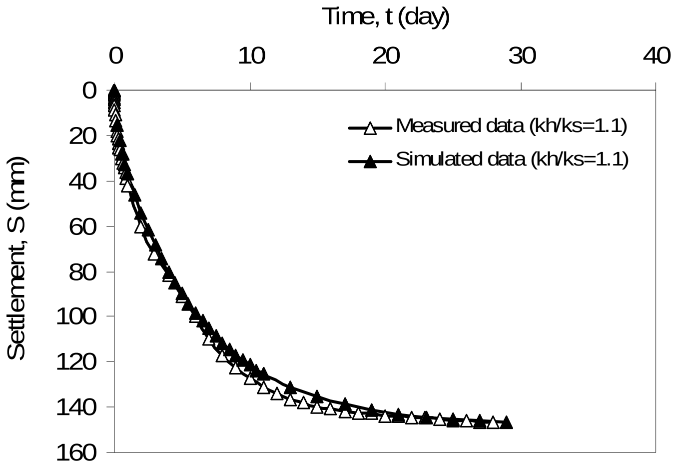


Figure15 Comparison of settlement between measured data and simulated data with $K_h$ and $K_v$ in axi-symmetric flow condition of reconstituted specimen improved with Thermo-Vacuum-PVD

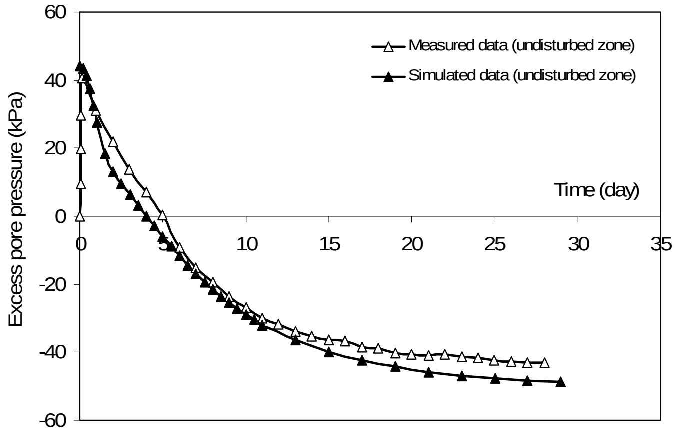


Figure 16 Comparison of excess pore pressure between measured data and simulated data with $K_h$ and $K_v$ in axi-symmetric flow condition of reconstituted specimen improved with Thermo-Vacuum-PVD

Similarly, the FEM excess pore pressure in the undisturbed zone had increased to maximum of 44 kPa, dissipated gradually after 4 days and decreased to about -49 kPa after 28 days. However, the FEM simulated excess pore pressures with $K_h$ and $K_v$ and with $K_{ev}$ in the undisturbed zone slightly overestimated the measured data.

The simulated ratio of horizontal permeability at undisturbed zone to horizontal permeability at smear zone ($K_h/K_s$) of reconstituted specimen improved with PVD, Vacuum-PVD, Thermo-PVD and Thermo-Vacuum-PVD, respectively are tabulated in Table 6. The summary of the measured and simulated settlement data of reconstituted specimens improved with PVD, Vacuum-PVD, Thermo-PVD and Thermo-Vacuum-PVD, are compared in Figure 17.

Table 6 Summary of changes in flow parameters of reconstituted specimens from numerical simulations

| Type of Specimen | $C_h$ (m$^2$/year) | $K_h/K_s$ |
|---|---|---|
| PVD | 1.93 | 3.00 |
| Vacuum-PVD | 2.23 | 2.70 |
| Thermo-PVD | 4.17 | 1.40 |
| Thermo-Vacuum-PVD | 4.38 | 1.10 |

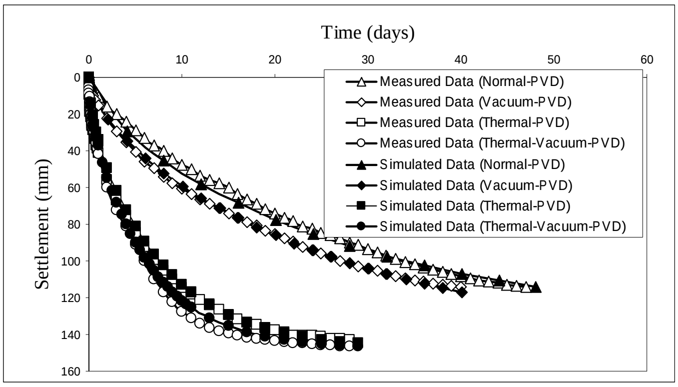


Figure 17 Summary of the measured and simulated settlement data of reconstituted specimens improved with PVD, Vaccum-PVD, Thermo-PVD, and Thermo-Vacuum-PVD

## 4. CONCLUSIONS

Based on the data and results of the analyses, the following conclusions can be made:

(1) The simulated settlements and excess pore pressures in axi-symmetric flow with $K_h$ and $K_v$ values were similar in equivalent vertical flow with Kev at the same $K_h/K_s$ values.

(2) The simulated ratio of horizontal permeability at undisturbed zone to horizontal permeability at smear zone ($K_h/K_s$) affected the predicted settlement.

(3) The simulated $C_h$ values were found to be 1.93, 2.23, 4.17 and 4.38 m$^2$/yr with $K_h/K_s$ values of 3, 2.7, 1.4, and 1.1, respectively, corresponding to PVD, Vacuum-PVD, Thermo-PVD and Thermo-Vacuum-PVD.

(4) The simulated $C_h$ values increased for reconstituted specimens improved with PVD, Vacuum-PVD, Thermo-PVD and Thermo-Vacuum-PVD.

(5) The corresponding $K_h/K_s$ values decreased for reconstituted specimens improved with PVD, PVD, Vacuum-PVD, Thermo-PVD and Thermo-Vacuum-PVD due to the corresponding increase permeabilities in the smear zone, $K_s$.

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