NUMERICAL MODELING OF FLOATING PREFABRICATED VERTICAL DRAINS IN LAYERED SOIL

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Abstract

This paper presents a comparison of field measurements and a numerical model of settlements based on the construction of an embankment on soft soil for the Cirebon Power Plant Project in Indonesia, where prefabricated vertical drains (PVDs) were installed. In the numerical model, floating PVDs in two soil layers for two- and one-way drainage conditions are examined in order to determine the optimum penetration depth. In this study, good agreement between the field measurements of the settlements and the numerical prediction could be achieved. An interesting result of this study is that the differences in the stiffness and/or the permeability in the unimproved area below the PVD tip have a significant influence on the optimum penetration depth (L/H) in the two-soil-layer condition. The numerical study showed that it is possible to use floating PVDs in single drainage conditions if the second layer is stiffer and/or more permeable than the first layer.

Keywords

two soil layers, floating prefabricated vertical drain, double and single drainage, numerical model, soft clay, consolidation

1 INTRODUCTION

Soft soil deposits such as soft clays, organic soils, and peats are generally characterized by a low shear strength, a high compressibility, and a low coefficient of permeability, which makes them a difficult soil for engineering. Soft soil deposits can be found throughout the world, including many parts of Indonesia, which possesses one of the longest coastlines in the world, with many of them having soft soil deposits. The total area of soft soil deposits in Indonesia is around 20 million hectares, i.e., 10% of Indonesia's total land area, which is mostly located in the coastal areas [1]. There are soft clays and peats with varying depth, shown as black areas in figure 1.

Ground-improvement techniques play an important role in extending the infrastructure across the country in difficult soils. Vertical drains combined with preloading have become common practice and are among the most effective procedures for ground improvement, accelerating the consolidation process and decreasing the time to reach final settlements. The installation of vertical drains reduces the drainage path and speeds up the excess pore-water pressure dissipation generated during the application of surcharge loads in saturated, fine-grained soils, thereby resulting in the faster development of settlements and a more rapid gain of strength due to consolidation.

It seems that almost all published numerical and analytical studies of soil consolidation with floating PVDs considered a homogeneous soil layer and a two-way drainage condition [2-11], which means that none of those studies focused on evaluating the effects of inhomogeneous soil layering in two- and one-way drainage conditions.

In this study the effects of floating PVDs in two soil layers for two- and one-way drainage conditions are numerically investigated in order to determine the optimum penetration depth. The results from this study can be used for similar cases where the sub-soil condition consists of more than one soil layer with similar mechanical and hydraulical properties.

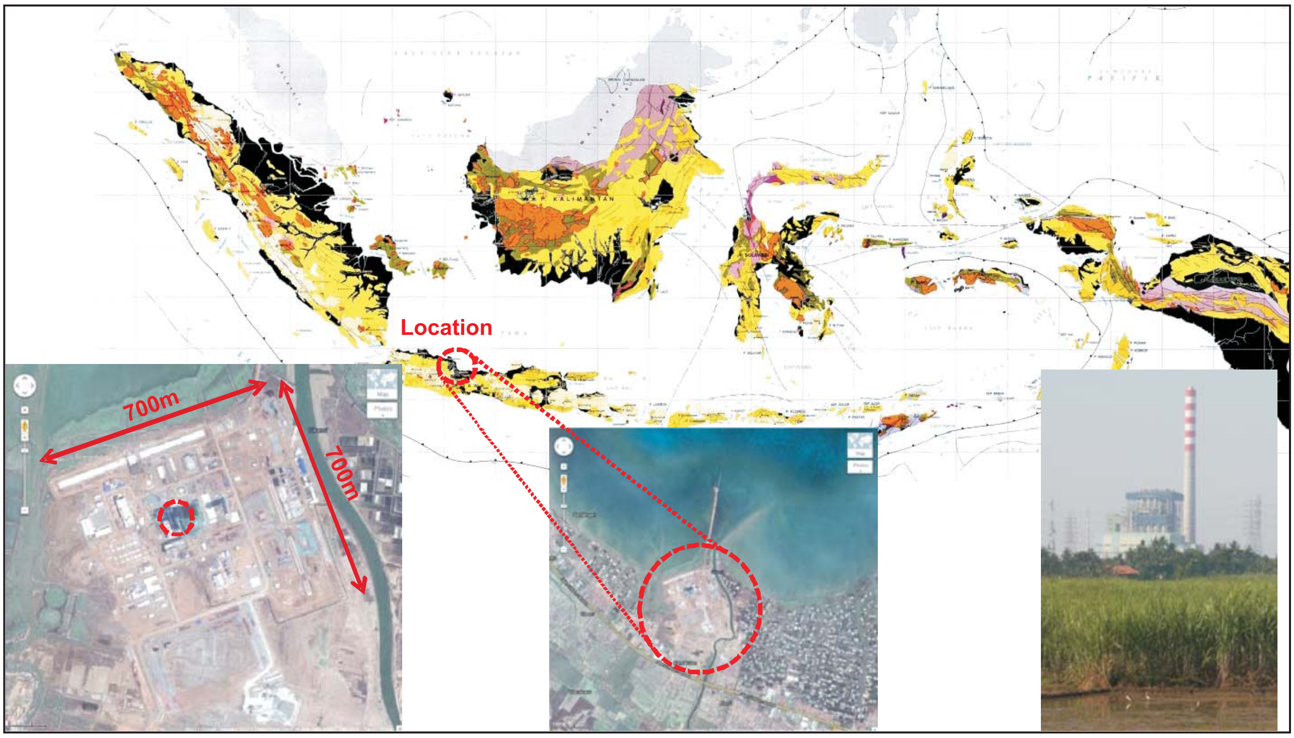

Figure 1. Soft soil areas in Indonesia and the location of the Cirebon Power Plant.

2 SITE DESCRIPTION AND GROUND CONDITION

The Cirebon Power Plant site is located on the north coastal plain of Java, near Kanci Village, which is approximately 20 kilometres to the south-east of Cirebon city and around 290 kilometres to the east of Jakarta city. The site is bounded by the Java Sea to the north, the Kanci River to the east, and the Waruduwur River to the west. The area of the single-unit 660MW coal-fired power station covers around 50 hectares. The topography of the plant site comprises a relatively flat and low-lying area with an average elevation of around +0.5 meters above mean sea level. The coast of the Cirebon area has a tidal range between 0.5 to 1.3 meters [12]. An overview of the soft soil areas in Indonesia and the location of the Cirebon Power Plant are shown in figure 1.

In order to establish a horizontal platform and to keep the site above flood level and always dry during the life time of the plant, the entire plant site area was reclaimed to reach a final elevation of +2.50 meters above mean sea level. The average thickness of the land fill is about 4 meters, including a 1.0 meter sand blanket, a 2.0 meter embankment, and 1.0 meter additional surcharge [13, 14].

The formation of the northern coast of Java, some on the North East Sumatra, and the other coastal areas of Indonesia, are normally Holocene soft clay deposits and quite similar to parts of the coasts of Singapore, Malaysia, Thailand, and in the other South East Asia countries [15, 16]. Based on the result of the soil investigation [17, 18, 14], the condition of the subsurface soils in the site area can be classified into three distinct soil layers: on top is a 6 meter very soft clay layer followed by a 6 meter soft-to-medium clay layer, which is underlain by a dense sand or a silty sand layer as the bearing strata. The ground-water table is located close to the ground surface.

To speed up the consolidation process of the top 12 meters of soft clay, PVDs together with 4.0 meters of filling material were installed, which can be considered to be a good solution in terms of cost and time efficiency. The drains were installed to a depth of 12 meters until reaching the dense soil layer with a 1.5 meter centre-to-centre spacing in a triangular grid pattern. The settlement plate and the drains were installed after the construction of a 1.0 meter sand blanket as the working area. A settlement analysis due to the areal fill was carried out around the centre of the fill [13]. The subsoil conditions, embankment thickness, PVD layout and the location of the settlement plate are shown in figure 2.

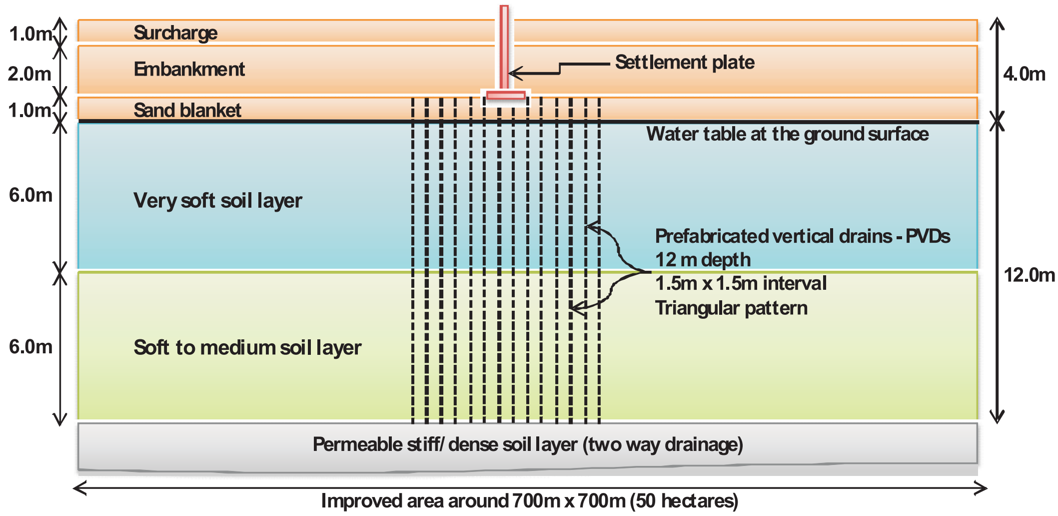

Figure 2. Subsoil and embankment condition, PVD configuration, and location of the settlement plate.

3 NUMERICAL MODEL

A Numerical model using the commercial finite-element software PLAXIS 2D 2010 was used to analyse this case study [19]. Axisymmetric conditions were choosen to simulate a unit-cell condition with a single drain at the center of the fill area. The total number of elements (15-noded triangles) in this model is 1343. The soil and the embankment were modelled using the Hardening Soil model, the advanced soil model in Plaxis for simulating both soft and stiff soils [20, 19]. Four different cases are considered in the numerical simulation: without improvement, with PVD improvement but ignoring smear effects, with PVD improvement considering the effects of smear caused by PVD installation and partial penetration of PVDs. The results from this numerical model were compared with data measured in the field. Figure 3 shows the geometry of the unit cell and the finite-element mesh in the axisymmetric condition for both full and floating PVDs.

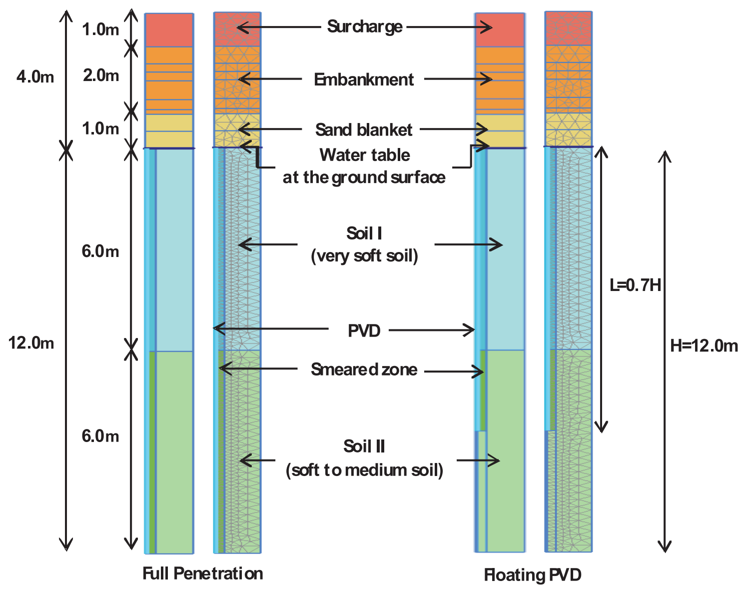

Figure 3. Geometry of unit cell and finite-element mesh for full penetration and floating PVD.

The drains were installed to a depth of 12 and 8.4 meters (L) for full and partial penetration, respectively, with a 1.5 meter spacing (S) in a triangular grid pattern. The soft clay layer to be improved was 12 meters thick (H). The equivalent influence zone diameter (the unit-cell diameter, d_e) is 1.575 meter, calculated based on the principle of equal area (d_e=1.05 · S). The equivalent drain diameter (d_w) is 66 mm, calculated based on the equal drainage perimeter assumption proposed by Hansbo [21] $d_w = 2(a \cdot b/\pi)$, where a = 100 mm and b = 4 mm are the width and thickness of the drain. Chai and Miura [22] suggested that the equivalent smeared zone diameter (d_s) can be estimated as $d_s = 3 \cdot d_m$, where d_m = 120 mm is the equivalent mandrel or anchor diameter.

The horizontal and vertical soil permeability are assumed to be the same ($k_h = k_v$), which is probably slightly unrealistic, but as no further information was available and the problem is considered to be governed by k_h, with the exception of floating PVDs, this assumption has been made. The ratio of the horizontal permeability in the undisturbed soil zone to the permeability in the smeared zone (k_h/k_s) is 2 and the well resistance is not taken into account because the drain-discharge capacity (q_w) is assumed to be large enough. The sand blanket is free draining and the bottom boundary is set to be open because a permeable soil layer is below the soft clay layer.

Hardening soil model parameters for the soil and the embankment used in the model are summarized in table 1. These parameters are based on the geotechnical report for this project and it is obvious that the values used for effective cohesion are rather optimistic for this type of soil. However, as the ultimate limit-state conditions are not considered, it can be argued that this assumption has no serious consequences for the results discussed in this study and thus the values given in the geotechnical report have been kept. In addition, one would expect the soil to exhibit creep behaviour, but this would be more relevant in the long-term assessment of settlements, which is not the topic of this investigation, although it is acknowledged that some creep may occur within the time frame analysed, but it is argued that due to the installation of the PVDs consolidation is prevailing. The calculation phases to simulate the stages of construction are shown in table 2.

Table 1. Soil and embankment properties.

HS Model Parameters	Drainage Condition	Thickness	$\gamma_{unat}/\gamma_{sat}$	$E_{50}^{ref} = E_{eod}^{ref}$	E_{ur}^{ref}	m(power)	c'_{ref}	φ'	U'_{ur}	p_{ref}	K_0^{nc}	R_f	$k_h = k_v$
		m	kN/m^2	kN/m^2	kN/m^2	-	kN/m^2	°	-	kN/m^3	-	-	m/s
Soil Layer I	Undrained	6	15/16	1000	3000	0.9	12	24	0.2	100	0.593	0.9	1.9×10^{-9}
Soil Layer II	Undrained	6	17/18	3000	9000	0.7	1	28	0.2	100	0.530	0.9	5.0×10^{-9}
Embankment	Drained	4	18/20	20000	60000	0.5	10	30	0.2	100	0.500	0.9	1.0×10^{-7}

Table 2. Stages of embankment construction of the Cirebon Power Plant.

No	Stage of Construction	Date	Days	2007 (November, December) – 2008 (January, Feb, March, April, May, June, July, August, Sept)
1	Site clearing and preparation	16 November – 25 November 2007	10	
2	0.5m Sand Blanket (+0.5m)	26 November – 27 November 2007	2	
3	Consolidation	28 November – 29 November 2007	2	
4	0.5m Sand Blanket (+1.0m)	30 November 2007	1	
5	Consolidation	01 December – 05 December 2007	5	Preparation of PVD installation
6	PVD+Smear Installation	06 December – 08 December 2007	3	
7	Consolidation	09 December – 10 December 2007	2	Settlement plate installation at +1.0m
8	0.15m Embankment (+1.15m)	11 December 2007	1	
9	0.3m Embankment (+1.45m)	12 December 2007	1	Start reading of settlement plate
10	0.55m Embankment (+2.0m)	13 December 2007	1	
11	Consolidation	14 December - 16 December 2007	3	
12	0.25m Embankment (+2.25m)	17 December 2007	1	
13	Consolidation	18 December 2007	1	
14	0.25m Embankment (+2.5m)	19 December 2007	1	
15	Consolidation	20 December – 27 December 2007	8	Christmas holiday
16	0.5m Embankment (+3.0m)	28 December 2007	1	
17	Consolidation	29 December – 04 January 2008	7	New year holiday
18	1.0m Surcharge (+4.0m)	05 January 2008	1	
19	119 days consolidation	06 January – 03 may 2008	119	Last day of measured
20	Final Consolidation	04 May – 23 September 2008	141	

The excess pore-pressure distribution along the 12 meters of soft clay layers after the construction of the 4.0 meter fill material is visualized in Figure 4. The development of the settlements and the excess pore pressures obtained from the numerical model is shown in figure 5 for all four conditions. As expected, the installation of the PVD significantly decreased the consolidation time, whereas considering the smear effects has the opposite effect and, therefore, in order to arrive at realistic predictions, this effect has to be taken into account.

The settlement plate was installed and measurements started after the installation of the 1.0 meter sand blanket and the drains, so no settlement readings were taken for this stage of the construction. The settlements obtained from the numerical prediction and measured in the field are compared in figure 6. It can be seen that a good agreement between the field measurement and the numerical prediction could be achieved, for both full and partial penetration (L/H=0.7) of the PVD when taking the smear effect into account. It is clear that the length of the drain can be reduced by up to 30% without significantly affecting the consolidation process for double drainage—two soil-layer conditions when the second layer is stiffer and has a higher permeability than the first layer.

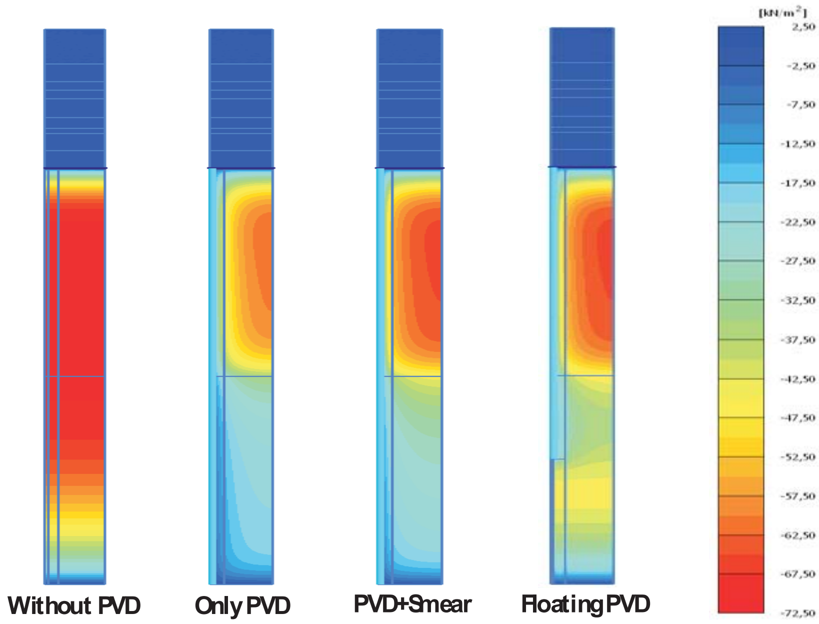

Figure 4. Excess pore-pressure distribution after the placement of 4.0 meter fill material.

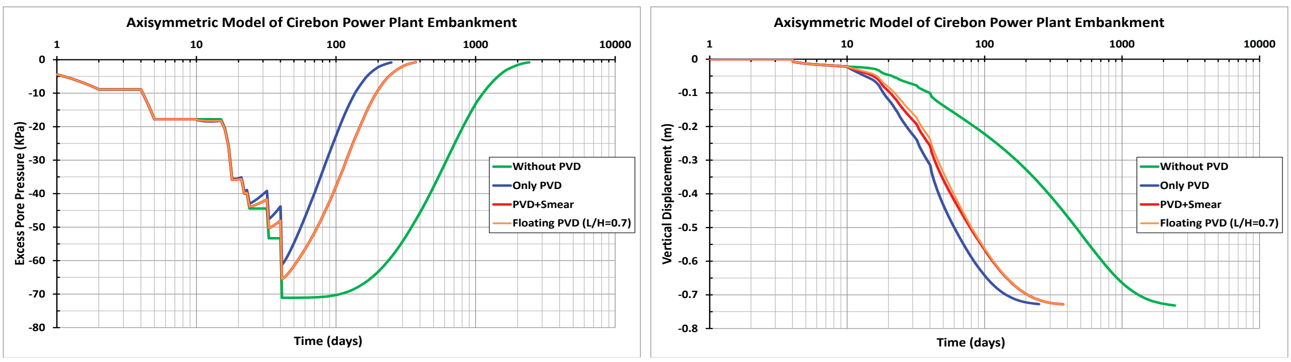

Figure 5. Excess pore-pressure and consolidation curves for all conditions.

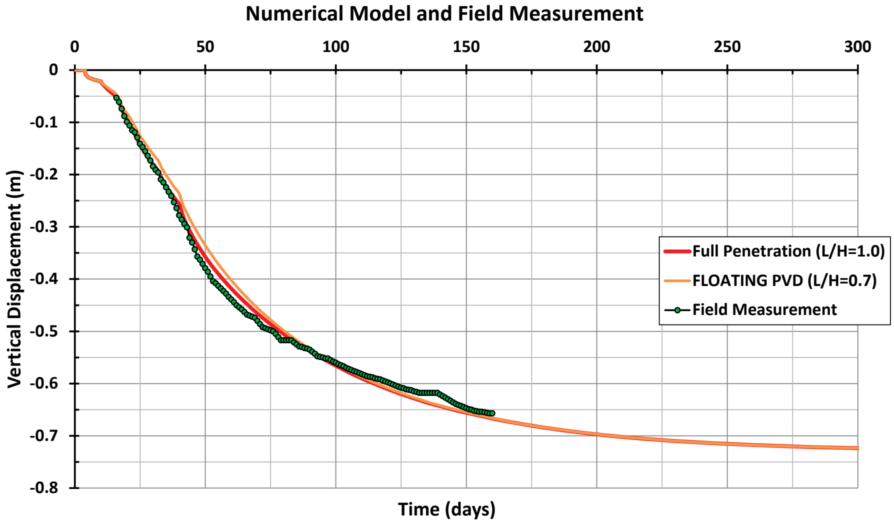

Figure 6. Comparison of settlements between the numerical prediction and field measurements.

4 FLOATING PVD IN TWO SOIL LAYERS

In this section, three different cases will be numerically investigated to look at the influence of floating PVDs on consolidation in a two-soil-layer condition. Figure 7 shows the three conditions analysed: first, a homogeneous soil layer, second, two soil layers where the lower layer is stiffer and more permeable than the upper layer, and third, the situation when the upper layer is stiffer and more permeable than the lower layer. The influence of the stiffness and the permeability will also be evaluated. Finally, the double and single drainage conditions will be examined for the above three cases. The results from this model will be evaluated in order to determine the optimum penetration depth (*L/H*), without significantly affecting the consolidation process. Table 3 summarizes all the analysed combinations.

4.1 DOUBLE DRAINAGE CONDITION

In this section, the effect of floating PVDs in a double drainage, two-soil-layers condition, on consolidation is numerically investigated. Here, the bottom boundary is open for flow. The result from this model will be evaluated so as to determine the optimum penetration depth (*L/H*), without significantly affecting the consolidation process.

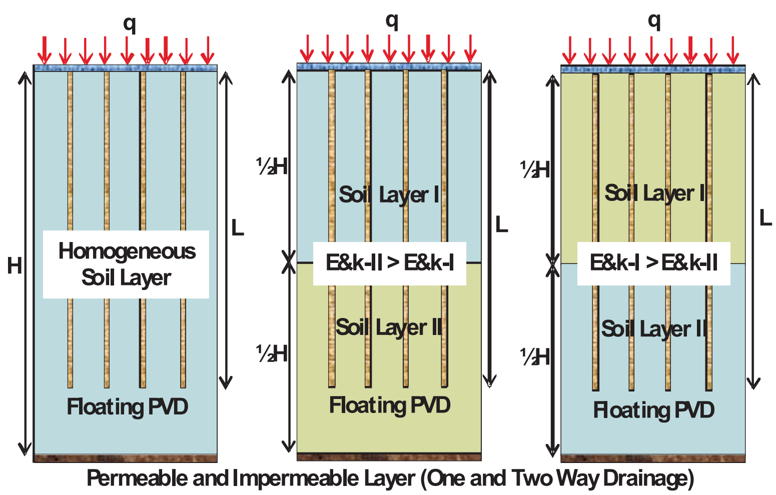

Figure 7. Illustration of three different cases of floating PVDs in two soil layers for one- and two-way drainage.

Table 3. Combination of cases for modelling floating PVDs in two soil layers for one- and two-way drainage conditions.

Model		Soil Layer I			Soil Layer II			Remarks
		$E_{50}^{ref} = E_{oed}^{ref}$	E_{ur}^{ref}	$k_h = k_v$	$E_{50}^{ref} = E_{oed}^{ref}$	E_{ur}^{ref}	$k_h = k_v$	
		kN/m^2	kN/m^2	m/s	kN/m^2	kN/m^2	m/s	
I		***1000***	***3000***	***1.9x10^{-9}***	***1000***	***3000***	***1.9x10^{-9}***	Homogeneous soil layer
II	A	1000	3000	1.9x10^{-9}	1000	3000	***5.0x10^{-9}***	Value of soil permeability in layer II is higher than layer I
II	B	1000	3000	1.9x10^{-9}	***3000***	***9000***	1.9x10^{-9}	Value of soil stiffness in layer II is higher than layer I
II	C	1000	3000	1.9x10^{-9}	***3000***	***9000***	***5.0x10^{-9}***	Value of soil stiffness and permeability in layer II are higher than layer I
III	A	1000	3000	***5.0x10^{-9}***	1000	3000	1.9x10^{-9}	Value of soil permeability in layer I is higher than layer II
III	B	***3000***	***9000***	1.9x10^{-9}	1000	3000	1.9x10^{-9}	Value of soil stiffness in layer I is higher than layer II
III	C	***3000***	***9000***	***5.0x10^{-9}***	1000	3000	1.9x10^{-9}	Value of soil stiffness and permeability in layer I are higher than layer II

The excess pore-pressure distributions for homogeneous and two soil layers are visualized in Figure 8. As expected, excess pore-pressure dissipation in the soil layer that has a high stiffness and permeability is faster than in the soil layer having a low stiffness and permeability. For the floating PVD conditions it is clear that the vertical flow is predominant in the unimproved area under the PVD tip, which has an influence on the consolidation time.

The settlement curves from the numerical model for PVD installation with varying the depth of penetration are shown in figures 9 and 10. It is clear that for a homogeneous layer (model 1), the drain length can be reduced by up to 20% without significantly affecting the consolidation process (*L*/*H* = 0.8). This result corresponds to the report of Indraratna and Rujikiatkamjorn [7]. For the two-soil-layer condition where the second layer is stiffer and more permeable than the first layer (model 2; IIA, IIB, IIC), the drain length can be shortened by 30–40% without affecting the consolidation process (*L*/*H* = 0.7 – 0.6) significantly. In contrast, for the two-soil-layer condition where the first layer is stiffer and more permeable than the second layer (model 3; IIIA, IIIB, IIIC), the drain length can be reduced by only 10–20% without significantly affecting the consolidation process (*L*/*H* = 0.9 – 0.8). It is interesting to note that the differences in stiffness and permeability in the two-soil-layer condition have an influence on the optimum penetration depth (*L*/*H*), especially in the unimproved area below the PVD tip.

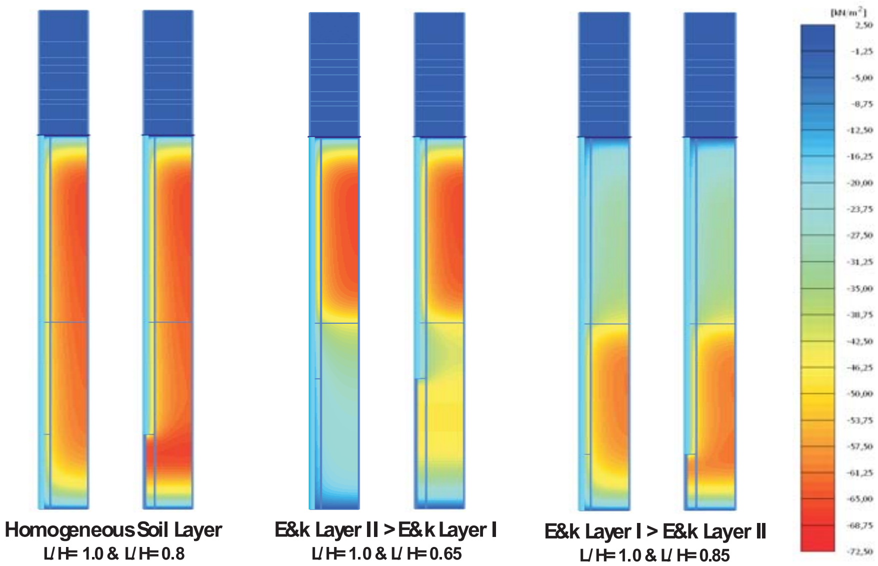

Figure 8. Excess pore-pressure distribution for homogeneous and two soil layers for double drainage conditions.

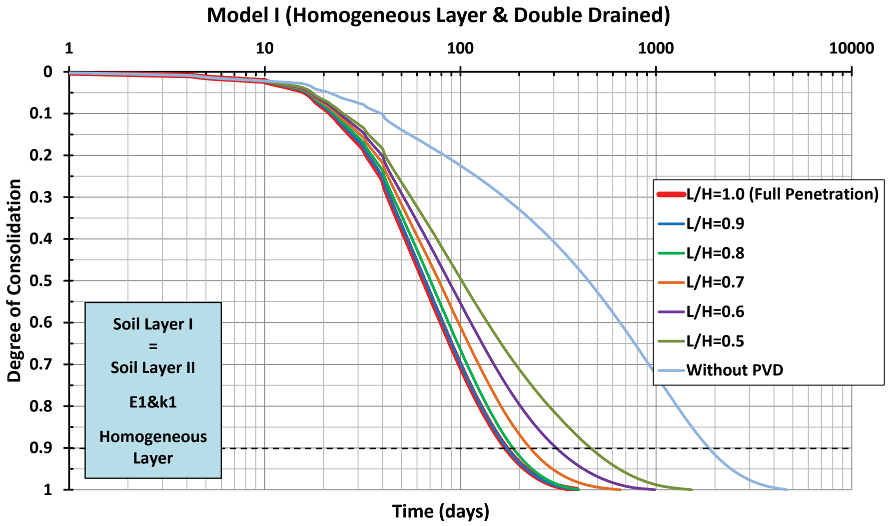

Figure 9. Settlement curves for homogeneous and double drainage conditions for varying PVD penetration depth.

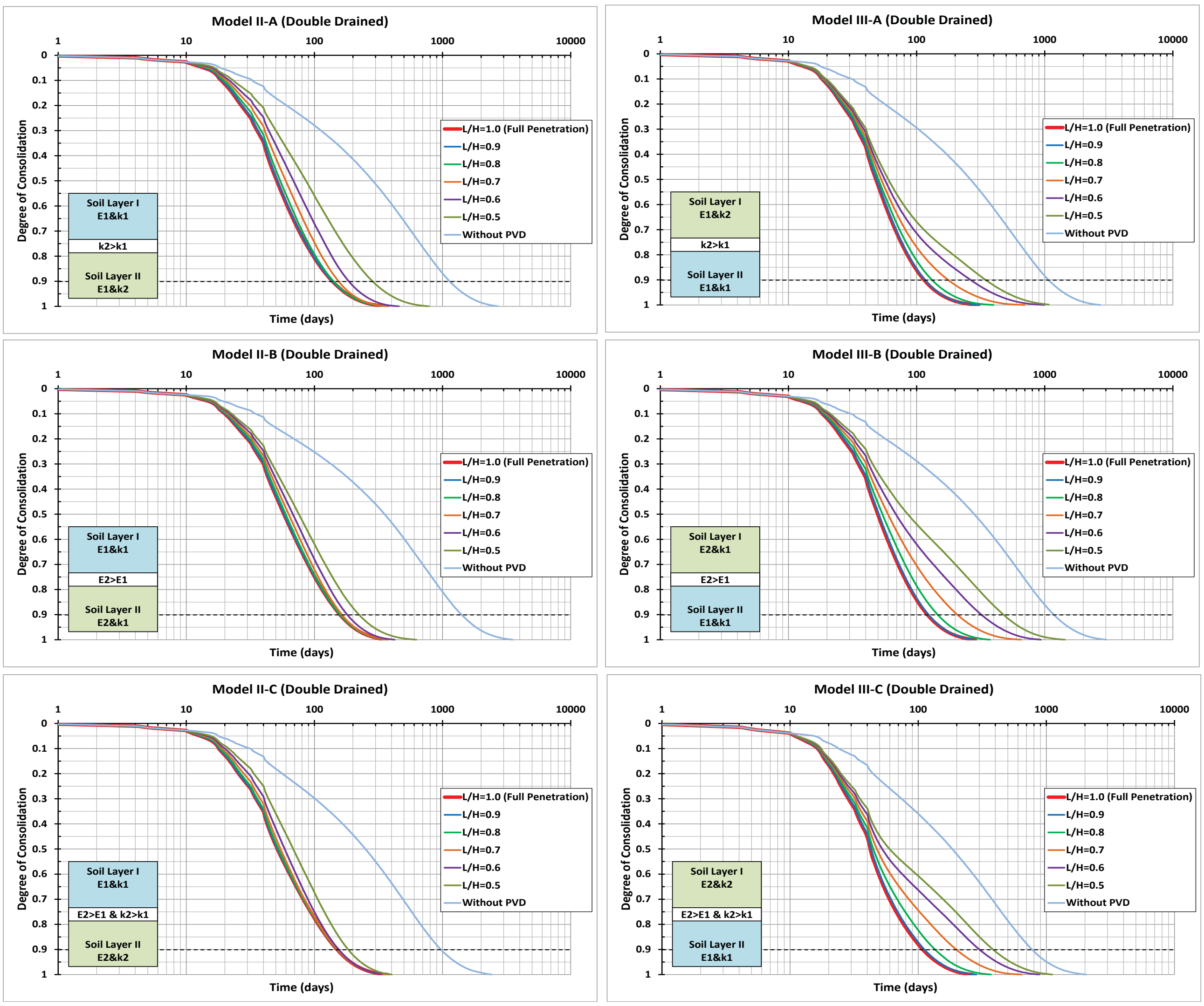

Figure 10. Settlement curves for two soil layers and double drainage conditions for varying PVD penetration depth.

4.2 SINGLE DRAINAGE CONDITION

In this section the effect of floating PVDs in single drainage, two-soil-layer conditions, on consolidation is numerically investigated. Here, no flow across the bottom boundary is allowed.

The excess pore-pressure distributions for the homogeneous and two-soil-layer conditions are shown in Figure 11. A similar picture as before is obtained, namely that the excess pore-water dissipation in the soil layer with a high stiffness and permeability is faster than in the soil layer with a low stiffness and permeability.

The settlement curves from the numerical model for a PVD installation with a varying depth of penetration are shown in figures 12 and 13. It is clear that for a homogeneous layer (model 1), the drain length can only be reduced by up to 10% without significantly affecting the consolidation process (*L/H* = 0.9). This is in line with Chai et al. [10], who suggested not choosing floating PVDs in one-way drainage conditions. For the two-soil-layer condition where the second layer is more stiff and permeable than the first layer (model 2; IIA, IIB, IIC), the drain length can be shortened by 15–25% without seriously affecting the consolidation process (*L/H* = 0.85 – 0.75). In contrast, for the two-soil-layer condition

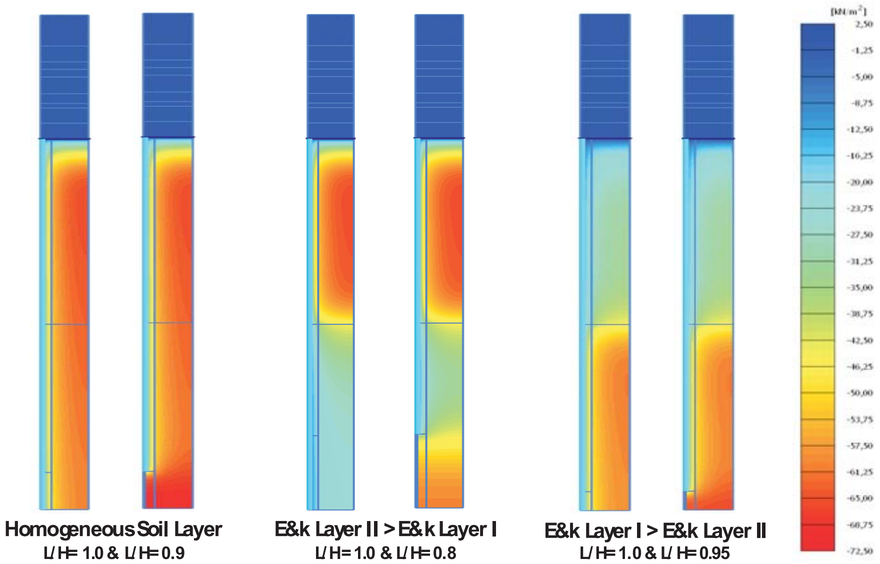

Figure 11. Excess pore-pressure distribution for homogeneous and two soil layers for single drainage condition.

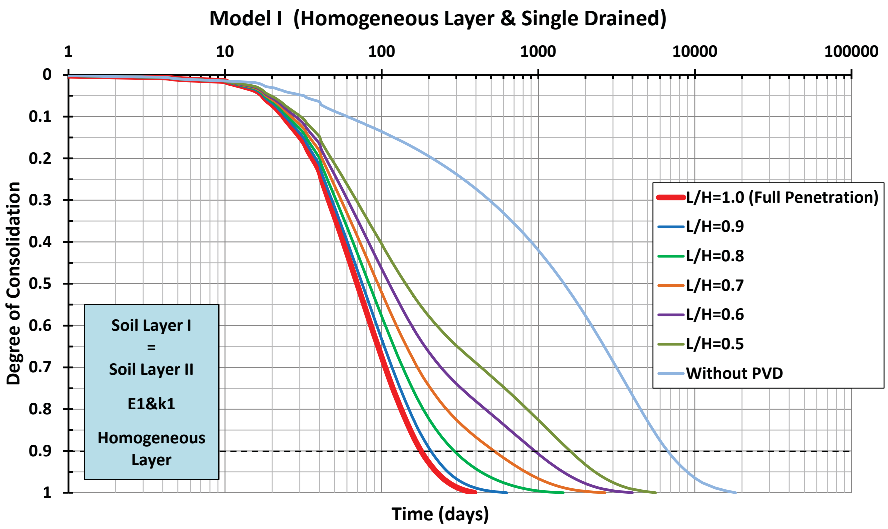

Figure 12. Settlement curves for homogeneous and single drainage conditions for varying PVD penetration depth.

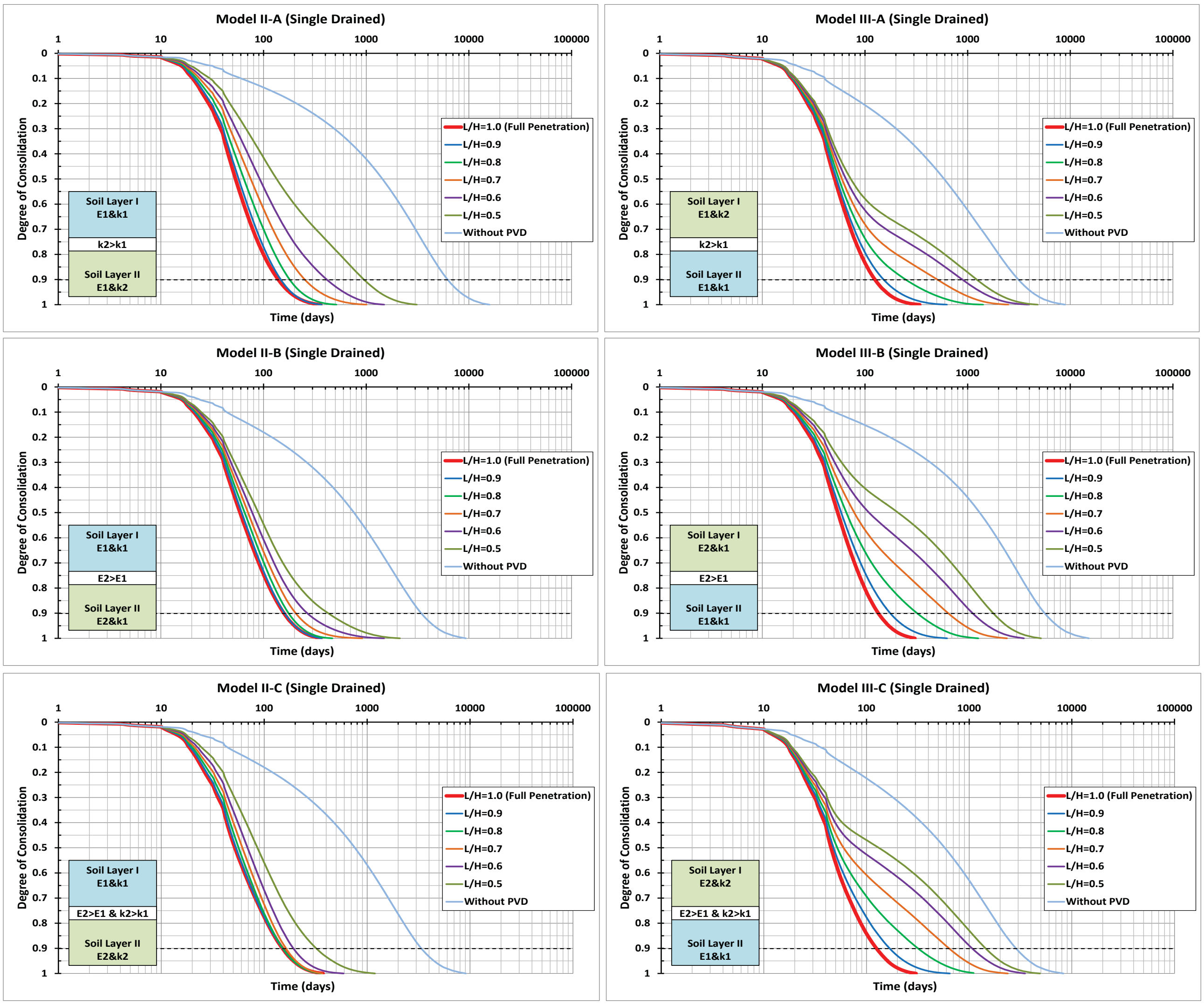

Figure 13. Settlement curves for two soil layers and single drainage condition for varying PVD penetration depth.

where the first layer is stiffer and more permeable than the second layer (model 3; IIIA, IIIB, IIIC), the drain length can only be reduced by about 10% without affecting the consolidation process (L/H = 1.0–0.9). Based on this numerical study it can be concluded that for single drainage conditions, only model 2, i.e., if the second layer is stiffer and more permeable than the first layer, can the use of floating PVDs be recommended.

5 CONCLUSIONS

Numerical results from a study of floating PVDs in two soil layers for double and single drainage conditions were examined to determine the optimum penetration depth for the PVDs. It is interesting to note that the differences in stiffness and permeability in the two-soil-layer condition, especially in the unimproved area below the PVD tip, have an influence on the optimum penetration depth (L/H) in order to achieve the same consolidation time.

It was found in this study that for double drainage conditions in a homogeneous soil layer (model 1), the drain length can be reduced by up to 20% without significantly affecting the consolidation process (L/H = 0.8). For a two-soil-layer condition where the second layer is stiffer and more permeable than the first layer (model 2; IIA, IIB, IIC), the drain length can be shortened by 30–40% (L/H = 0.7–0.6). In contrast, for a two-soil-layer condition where first layer is stiffer and more permeable than the second layer (model 3; IIIA, IIIB, IIIC), the drain length can be reduced by only 10–20% (L/H=0.9–0.8). For single drainage conditions it is possible to use a floating PVD only if the second layer is stiffer and/or more permeable than the first layer.

This study has shown that a good agreement between field measurements and numerical predictions for settlements in both full and partial penetration conditions can be achieved. For the presented case study the drain length could be reduced by up to 30% without significantly affecting the consolidation process (L/H = 0.7).

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