Numerical analysis of PVD-improved soft deposit considering soil disturbance and well resistance

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ABSTRACT

A simple equivalent plane strain model was proposed to estimate the consolidation behavior of prefabricated vertical drain (PVD)-improved ground. In this equivalent model, an equivalent horizontal permeability based on the matching of the total volume of water to be discharged in an axisymmetric model and the total changes in flow in a plane strain was proposed, while the geometry of the PVD was deduced from the balancing of the area ratio. The proposed equivalent horizontal permeability in the plane strain model not only considered the effects of the smear zone and the well resistance but also depended on the degree of radial consolidation of the PVD-improved soft deposit. The proposed method was applied in finite element method (FEM) to analyze consolidation behavior of a case history of embankment on the PVD-improved ground. The analysis results using the proposed method produced a good agreement with the observed field behaviors. The proposed method is recommended as a useful approach in engineering practice for consolidation analysis of the PVD-improved ground.

Keywords: numerical analysis; PVD; soft soil; soil disturbance; well resistance

1 INTRODUCTION

Prefabricated vertical drains (PVDs) combined with preloading are frequently used to accelerate the rate of consolidation and gain shear strength in soft soil. The prediction of consolidation behavior of soft ground is important in the design of PVD improvement. Numerical analysis, typically finite element method (FEM) is occasionally used owing to the complexes of construction sites such as construction process and non-uniform soil properties of subsoil. To simulate the performance of multiple vertical drains under an embankment, three dimensional (3-D) numerical analysis may be required, but a lot of cubic elements have to be employed (Tran and Mitachi 2008; Indraratna and Redana 2000). Therefore, a full scale 3-D simulation in numerical analysis is inconvenient and time-consuming or a powerful computer is required in the design stage. Therefore, a plane strain model is typically used to analyze the PVD-improved ground.

Various methods for modeling the PVD-improved subsoil in plane strain analysis were presented. In the first category, Hird et al. (1992) and Chai et al. (1995) formulated the degree of horizontal consolidation in the plane strain unit cell and matched it with the degree of radial consolidation in the axisymmetric model. A 1-D drainage element was used to model the effect of PVD in the plane strain analysis. In this way, the 1-D drainage element can express that the excess pore water pressure at PVD is equal to zero (u = 0). In the second category, Sekiguchi et al. (1986) formulated a quadrilateral macro-element to simulate the effect of PVD in the ground, in which the smear zone effect was neglected and the discharge capacity of PVD was assumed to be infinite. This method is exceptionally time-consuming and exceedingly inconvenient in engineering practice. In the third category, Chai et al. (2001) and Kim et al. (2018) modeled the PVD-improved ground as an unimproved one with equivalent vertical hydraulic conductivity. Although, this is a simple method to simulate the PVD-improved soil deposit, the concept is unrealistic with regard to the existence of PVD in the subsoil. As a fourth category, the PVD was modeled using a solid element with an equivalent hydraulic conductivity and an equivalent width, which was frequently applied in engineering practice because it is more realistic compared to the in-situ case and not excessively complex with regard to the simulation. This category can be approached by several methods such as Shinsha et al. (1982), Kim and Lee (1997), Indraratna and Redana (1997). Among of these methods, Indraratna and Redana (1997) considered effects of smear zone and well resistance of drain, only. But, when we consider the smear zone in a multi-drain finite element, it is exceedingly inconvenient and time-consuming with regard to implementation because the dimension of the drain and smear zone is exceedingly small for modeling. Therefore, a simple equivalent permeability considering effects of the smear zone and well resistance is necessary, especially in the consolidation analysis of the PVD-improved ground.

This paper provides an equivalent plane strain (2-D) model of the PVD-improved ground where the PVD is modeled using the finite element that belongs to the fourth category as mentioned above. An equivalent width of the PVD and an equivalent horizontal permeability of the subsoil in the plane strain model were proposed, in which effects of the smear zone and the well resistance were taken into account. The equivalent horizontal permeability of the proposed model depends on the degree of consolidation of the improved ground. A multi-drain finite element analysis was conducted to validate the proposed equivalent plane strain model. Verification of the proposed method was performed by comparing the settlement and the excess pore water pressure distribution with regard to the observed results of a case history of the embankment tests on the soft mucky clay of the Malaysian soft muar clay. The approaches of Indraratna and Redana (1997) and Kim and Lee (1997) were also applied and compared with regard to the proposed method.

2 FORMULATION OF A NOVEL EQUIVALENT 2-D MODEL

This paper provides an equivalent plane strain (2-D) model of the PVD-improved ground where the PVD is modeled using the solid elements, as shown in Figure 1.

2.1 Equivalent width of vertical drain

The equivalent width of the drains was deduced from the balancing of the area ratio. The equivalent width of the vertical drain in the equivalent plane strain model is then proposed as:

$$b_w = C\frac{d_w^2}{S} \tag{1}$$

$$\begin{cases} C = \dfrac{\pi}{4} \text{ with square pattern } (D_e = 1.13S) \\ C = \dfrac{\pi}{2\sqrt{3}} \text{ with triangle pattern } (D_e = 1.05S) \end{cases}$$

where d_w is the equivalent diameter of the drain in the axisymmetric model, which can be calculated by $d_w = (a+b)/2$ (Atkinson and Eldred 1981), where a and b are the dimensions of the PVD; the factor C is related to the PVD installation pattern (i.e., square pattern or triangle pattern), where D_e is diameter of the axisymmetric unit cell and S is a space between two adjacent PVDs.

2.2 Equivalent horizontal permeability

An equivalent horizontal permeability was obtained from the matching of the total volume of water to be discharged in an axisymmetric model and the total changes in flow in a plane strain. The equivalent horizontal permeability in the 2-D model is then proposed as:

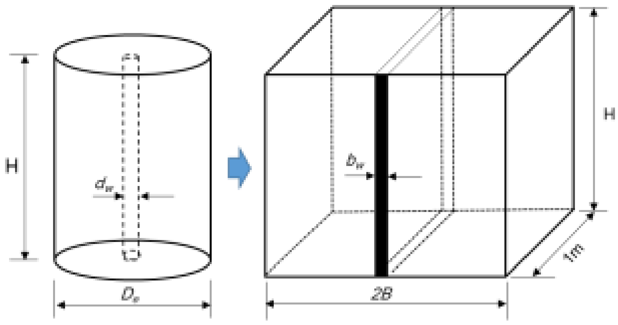

Fig. 1. Axisymmetric and equivalent 2-D plane strain model

$$k_{hp} = \frac{-\pi B \bar{U}_h k_h}{\mu \ln\left(1-\bar{U}_h\right)} \tag{2}$$

where B is haft of the width of the plane strain unit cell, k_h is horizontal permeability of natural soil, $\bar{U}_h$ is the average degree of radial consolidation which was defined in Hansbo's solution (Hansbo 1981) and μ is factors describing the effects of smear zone and well resistance of drains. Value μ can be simply gotten from Hansbo's solution, as follows:

$$\mu = \ln\frac{n}{s} + \frac{k_h}{k_s}\ln(s) - \frac{3}{4} + \pi\frac{2L^2 k_h}{3q_{wa}} \tag{3}$$

where $n = D_e/d_w$ (d_w is the equivalent diameter of the drain); $s = d_s/d_w$ (d_s is the equivalent diameter of the smear zone); k_s is the horizontal permeability of the smear zone; L is the drainage length and q_{wa} is the discharge capacity of PVD in the axisymmetric unit cell model (or in-situ case).

3 APPLICATION TO A TEST EMBANKMENT

To evaluate the proposed equivalent 2-D model, the proposed method is applied to the test embankments the soft muar clay in Malaysia. A multi-drain finite element model of the PVD-improved ground was conducted to evaluate the proposed method. Other approaches by Kim and Lee (1997) and Indraratna and Redana (1997) that also modeled the PVD by finite element, were applied and compared with the proposed method.

A series of trial embankments with muar clay were constructed in Malaysia (Indraratna and Redana 1997). Figure 2 shows the cross-section of the embankment on soft muar clay with PVD arrangement. The test embankment was 86 m wide and composed of compacted sandy clay that has a unit weight of 20 kN/m^3. The subsoil profiles at the test site consist of a weathered crust layer with 1.75 m thickness, which is underlain by approximately 3.75 m of soft clay layer. Below this soft clay layer lies an approximately 12.5 m thick layer of soft silt clay layer including the first soft silt clay with 2.5 m thickness and the second soft silt clay with 10 m thickness. Under soft silt clay layer is the medium dense to dense silt sand with 6 m thickness. PVDs were installed in a triangular pattern at a spacing of 1.3 m. The PVDs were installed completely into the soft clay layers with 18 m depth. The equivalent drain diameter was 70 mm (d_w = 70mm). The equivalent width in the plane strain was then calculated to be approximately 3.4 mm (b_w = 3.4 mm). For convenience, the equivalent width of the PVD in the plane strain can be chosen as 4 mm.

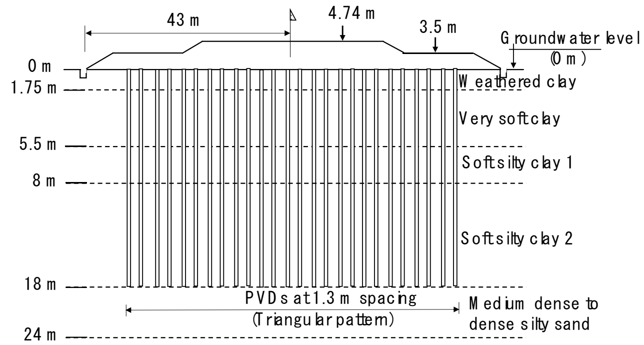

Fig. 2. Cross-section of test embankment on soft muar clay in Malaysia

Table 1 shows the initial permeability and the calculated equivalent horizontal permeability (at $\bar{U}_h = 50\%$) in the proposed method and other methods (Kim and Lee 1997; Indraratna and Redana 1997).

Table 1. Initial and calculated permeability of soft muar clay deposit

Layers	k_v (m/day)	k_{hp} (m/day) Present study	Indraratna and Redana (1997)	Kim and Lee (1997)
Weather Crust	2.59×10^{-4}	3.14×10^{-5}	1.67×10^{-4}	6.89×10^{-5}
Soft clay	2.33×10^{-4}	2.57×10^{-5}	1.36×10^{-4}	5.62×10^{-4}
Soft-silt clay 1	1.21×10^{-4}	1.56×10^{-5}	8.08×10^{-5}	1.03×10^{-4}
Soft-silt clay 2	5.18×10^{-5}	6.65×10^{-6}	3.39×10^{-5}	2.85×10^{-3}
Fill material	1	-	-	-

The geotechnical properties of the subsoil beneath the test embankment are shown in Table 2.

Table 2. Geotechnical properties of soft muar clay deposit in numerical analysis

Layers	γ_{sat} (kN/m^3)	e_0	C_k	λ^*	κ^*	OCR
Weather Crust	16.5	3.1	1.395	0.072	0.014	1.8
Soft clay	15	3.1	1.395	0.057	0.011	1.5
Soft-silt clay 1	15.5	3.06	1.377	0.043	0.008	1
Soft-silt clay 2	16	1.61	0.724	0.058	0.012	1
Fill material	20	-	-	-	-	-

In Table 2, γ_{sat} is saturated unit weight; e_o is initial void ratio; OCR is overconsolidation ratio; λ^* and κ^* are modified compression index and modified swelling index in Soft Soil model, respectively. C_k is permeability index. These properties were collected from Indraratna and Redana (1997).

The finite element mesh of the multi-drain plane strain model and its boundary condition with regard to the test embankment on the soft muar clay in Malaysia are shown as Figure 3.

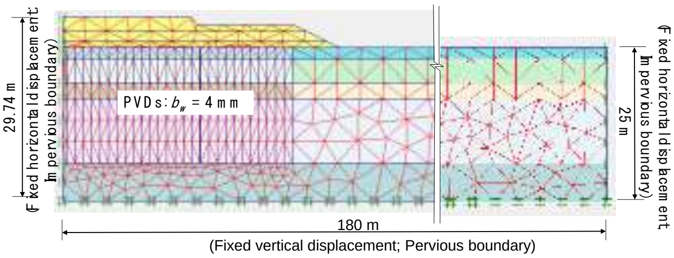

Fig. 3. Geometry and boundary condition in plane strain FEM of test embankment on soft muar clay in Malaysia

Figure 4 shows the loading schedule and the comparison of the settlement results between the proposed method and others. The settlement results in the proposed model were good agreement with the observed settlement in the field, while the results from Kim and Lee (1997) and Indraratna and Redana (1997) were overestimated with the observed data. It can be imaged that consolidation degree obtained from the proposed model is lower than that of other models during consolidation.

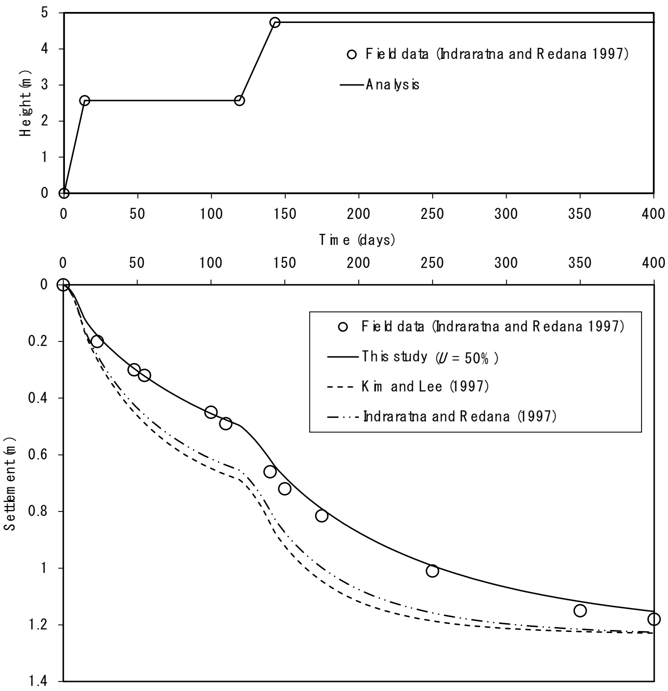

Fig. 4. Loading schedule and comparison of the settlement results of test embankment on soft muar clay in Malaysia

Figure 5 shows the comparison of the results of excess pore water pressure dissipation at 13.6 m depth. The results also indicated that the proposed method provides better agreement with excess pore water pressure dissipation than the other methods. Generally, the good results obtained from the proposed model could be explained that the effects of smear zone and the well resistance of PVD were considered. Meanwhile, these effects were ignored in the other methods. Moreover, the equivalent width of the drain (b_w) in Indraratna and Redana (1997) and Kim and Lee (1997) was assumed to equal to radius of the vertical drain. This is larger than b_w in the proposed model.

4 CONCLUSION

To predict the consolidation behavior of the PVD-improved ground, a simple equivalent 2-D plane strain model was proposed. The proposed method was applied to the test embankment on PVD-installed ground. The analyzed results using the proposed model provides a better agreement with the observed results of the case history, in comparing with the other methods. It is recommended that the proposed equivalent plane strain model can be used in engineering practice for consolidation analysis of the PVD-improved soft ground.

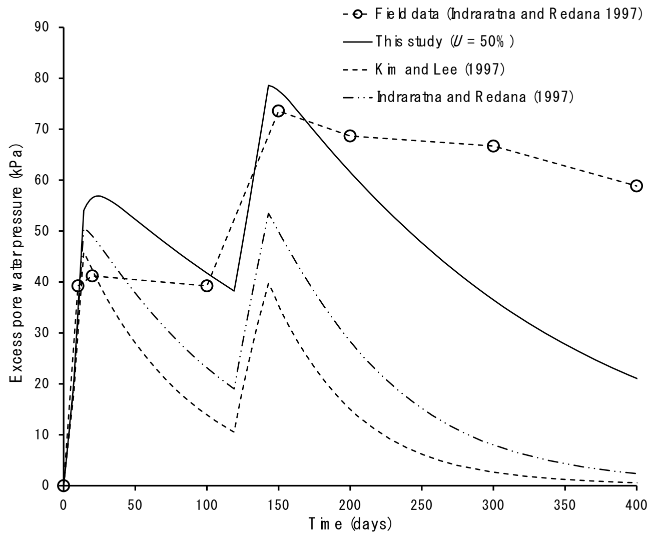

Fig. 5. Comparison of the excess pore water results at 13.6 m depth of test embankments on the soft muar clay in Malaysia

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