NUMERICAL MODELING OF PREFABRICATED VERTICAL DRAIN

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ABSTRACT

Finite Element Method (FEM) analysis incorporated with the proposed matching schemes were performed on unit cells and, full scale Prefabricated Vertical Drain (PVD) improved ground. Interface element was introduced to simulate the vertical drain with finite permeability to take well resistance into account. Based on equivalent discharge rate under confined flow condition, an equivalent horizontal permeability was determined to consider smear effect. For axi-symmetric unit cell, the numerical results were compared with the theoretical solutions. Excellent agreements were found and the applicability of the proposed matching schemes was identified. On the other hand, the numerical results of two-layered unit cell were also compared with the theoretical solutions. Excellent comparisons confirmed the applicability of the proposed matching schemes in the multi-layered PVD improved ground. Further, the proposed matching schemes were employed to convert actual radial flow to two-dimensional (2-D) plane strain flow based on the equivalent average degree of consolidation and discharge capacity of the vertical drain. Well resistance was automatically considered by interface elements, which possesses equivalent discharge capacity to vertical drain in axi-symmetric case.

INTRODUCTION

The classical consolidation equation developed by Barron (1948) are well known on soil improvement by vertical drainage system, later modified and developed by a number of authors (e.g. Yoshikuni and Nakanodo, 1974; Hansbo, 1979, 1981; Onoue, 1988a). The result of advanced theoretical analysis, taking into account well resistance and smear effect (e.g. Onoue, 1988b), showed that the results obtained agree with the simple analytical solution presented by Hansbo (1979, 1981). However, Hansbo's solution is based on the homogeneous unit cell theory and most soft ground is multi-layer.

Most of FEM analyses were carried out to obtain results using open consolidation boundary or drainage element. The open consolidation boundary condition at which excess pore pressure is zero during consolidation process cannot be applied to full-scale analyses under well resistance condition. On the other hand, drainage element produces large amount of elements and it may exceed the limitation of maximum number of elements, nodal points, or integration points.

Since PVD has a limited discharge capacity, the effect of well resistance vary with the permeability of surrounding soils, the discharge capacity and the length of drainage path of PVD. Consequently, the well resistance may affect the distribution of excess pore pressure with depth and distance from vertical drain during the consolidation. It is necessary to consider well resistance and smear effect for the consolidation rate of PVD improved ground with finite permeability. The advanced theoretical solutions can consider the above problem but had a difficulty in mathematical calculation for routine analysis.

Under embankment loading and with vertical drains, the consolidation behavior of soft soil deposits with vertical drainage system has been predicted by classical theory (unit cell theory) or 2-D numerical procedures. Due to the characteristics of stress and strain under embankment loading, it is required to convert the radial flow in the actual condition to the equivalent two-dimensional (2-D) plane strain flow. Thus, many attempts have been made to incorporate the actual three-dimensional (3-D) radial flow with two-dimensional (2-D) plane strain flow (Sekiguchi, et al., 1986; Hird, et al., 1992, 1995; Bergado, et al., 1993a,b, 1998; Bergado and Long, 1993).

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NUMERICAL MODELING OF VERTICAL DRAIN IN UNIT CELL ANALYSIS

General

In this study, the interface element in PLAXIS FEM program was introduced to simulate vertical drains. Imposing a specified cross sectional area and permeability of vertical drain to the interface element, the well resistance can be simulated. Meanwhile, the effect of smear was considered by the equivalent permeability of surrounding soils. The proposed matching scheme using interface element was employed in which the characteristics of consolidation of axi-symmetric unit cell were converted to those of 2-D plane strain unit cell. Comparative FEM analyses using interface element were then performed in axi-symmetric and plane strain unit cells to evaluate the well resistance and smear effect in single-layered and two-layered soils.

To verify the performance of interface element for vertical drain in FEM analysis, the overall average degree of consolidation, U_h, in terms of settlement were evaluated during the consolidation process. The FEM numerical procedures were verified by comparing the numerical results with the solutions of Zeng and Xie (1989) and Onoue (1988).

Geometry and Soil Parameters

To model the performance of a unit cell, a 40 *kPa* traction load, was applied to the upper boundary under free strain condition. Linear elastic soil model is employed for the numerical analysis in which Young's modulus, horizontal consolidation coefficient, and permeability of soils were kept constant. The geometry of unit cells for different analysis purposes are illustrated in Figs. 1(a) to (f). The associated parameters used for analysis are listed in Tables 1 (a) and (b).

Verification of Interface Element for Vertical Drain Simulation

As shown in Figs.1 (a) to (c), the comparison of two simulation schemes of PVD were made, namely: interface element and open consolidation boundary condition, to verify the validity of interface element for the simulation of vertical drain. The interface element possessed high vertical permeability (k_w = 1.395x10^2 m/day) to neglect the well resistance and were compared with open the consolidation boundary condition on which the excess pore pressure was specified to be zero during the consolidation process. As shown in Fig. 2, the consolidation characteristics of interface elements coincided with that of open consolidation boundary condition. It implies that the interface element behaves as a drainage channel to dissipate the excess pore water during the consolidation process.

Table 1 (a) Geometry for Unit Cell Analysis

Height (m)	r_e (m)	r_s (m)	r_m (m)	r_w (m)	Loading (kPa)	t_i (m)
20	0.75	0.06	0.03	0.025	40	0.06

Table 1(b) Model Parameter for Unit Cell Analysis

Soil model	E' (kPa)	K_o	γ_t (kN/m^3)	γ_d (kN/m^3)	k_h (m/day)	k_v (m/day)
Linear elastic	10,000	0.7	14.5	8.75	8.64E-04	8.64E-10

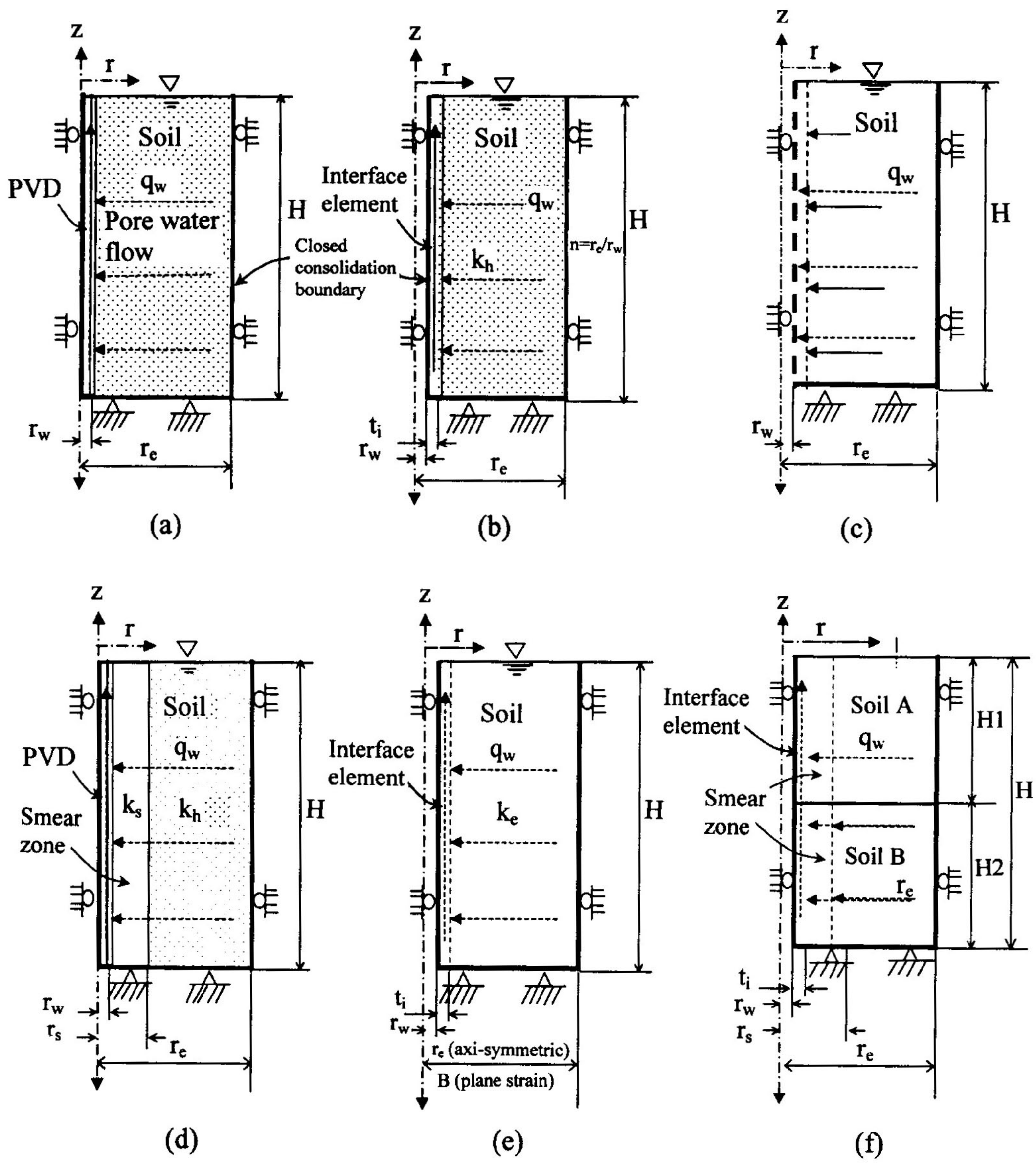

Fig. 1 Schematic Expressions of Axi-Symmetric Unit Cell For Different Types of Analysis, Unit Cell with (a) PVD (b) Interface Element (c) Open Consolidation Boundary (d) PVD and Smear Zone (e) Interface Element and Equivalent Zone (f) Two-Layered System

Well Resistance in Axi-Symmetric Unit Cell Analysis

Since the thickness of PVD is relatively small compared with its spacing, the interface element was envisaged as the soil element possessing the properties similar to the adjacent soil except permeability. In the analysis, the interface element was used to simulate well resistance in vertical drain with finite permeability.

As shown in Fig. 1(b), the coefficient of permeability of PVD is commonly expressed in term of discharge capacity of vertical drain, q_w, with hydraulic gradient equal to unity as $k_w = q_w / \pi r_w^2$. In which, $r_w = (b+t)/4$, is the equivalent radius of vertical drain and b and t are the width and thickness of vertical drain, respectively.

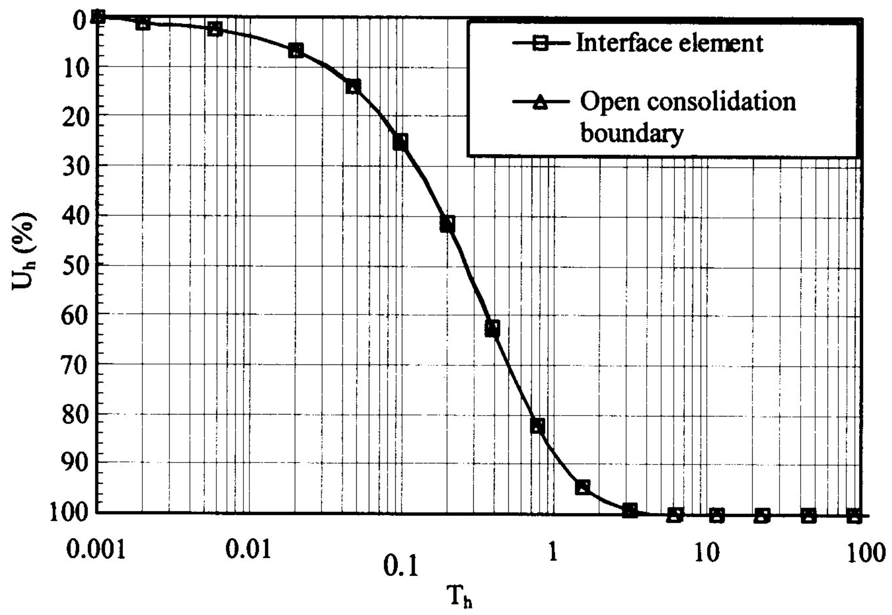

Fig. 2 Comparison of Overall Average Consolidation Rate of Axi-Symmetric Unit Cell between Interface Element and Open Consolidation Boundary

Jamiolkowski et al. (1983) indicated that the radial consolidation rate is controlled by the horizontal coefficient of consolidation, C_h, and radius of influence zone, r_e $(= d_e/2)$, but also by the ratio of (q_w/k_h) where k_h is the horizontal permeability of undisturbed soil. It was also proposed that the ratio, $(q_w/k_h) < 500\ m^2$, may play a very important part in increasing the time required to achieve a specific degree of consolidation. On the other hand, for the sand drain, where $(q_w/k_h) >$ 2000~3000 m^2, the impact of finite well permeability on the consolidation rate is negligible.

Mesri and Lo (1991) proposed the governing equation for vertical flow within the vertical drain in terms of excess pore water pressure at soil-drain interface. Based on Mesri's equation, a well resistance factor is defined as $\pi(k_w/k_h)(r_w/l_m)^2$ and is an index for the magnitude of pore water pressure. Eventually, the well resistance factor can be expressed as follows:

$$R = q_w / k_h l_m{}^2 \tag{1}$$

The analysis of field performance of vertical drains in the soft clay deposits indicated that well resistance is negligible when R is greater than 5. The minimum discharge capacity, $q_{w(min)}$, of vertical drains required for negligible well resistance is $5k_h l_m^2$. The most typical value of $q_{w(min)}$ can range from 2 to 80 m^3/year.

In FEM analysis, the value of q_w was imposed to the vertical drain and the corresponding well resistance was simulated by specifying a vertical permeability, k_w, to the interface element. As shown in

Table 2 Permeability of Vertical Drain

q_w (m^3/yr)	10	20	50	100	157	400	630	1000	10000
k_w (m/day)	14.0	27.9	69.8	139.5	219	558.1	879.1	1395.3	13953
Hydraulic gradient = 1 and r_w = 0.025 m									

Table 2, taking equivalent discharge capacity into account, the permeability of the interface element was varied with respect to the discharge capacity of the vertical drain. Comparisons between FEM analysis results and Zeng's solutions are presented in Fig. 3 for $q_w = 100\ m^3/year$. It can be seen that the agreement is excellent for $U_h < 40\%$ and a slight underestimation of degree of consolidation is observed from the FEM analysis result for $U_h > 40\%$. Figure 4 displays the well resistance effect on U_h for various discharge capacities ($q_w = 1000 \sim 10\ m^3/year$).

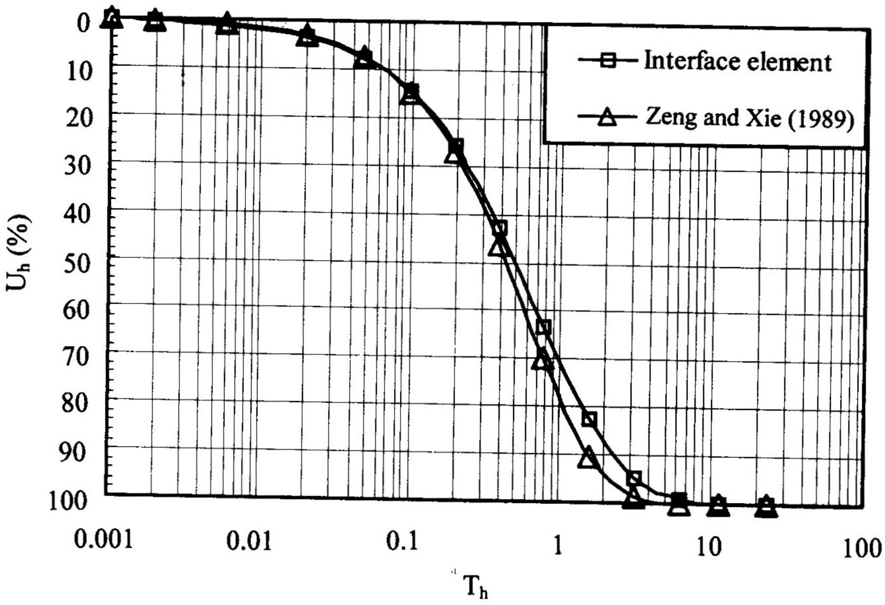

Fig. 3 Overall Average Consolidation Rate of Axi-Symmetric Unit Cell in Case of k_h=8.64E-4 m/day, H=20m and n=30, q_w=100 m^3/yr

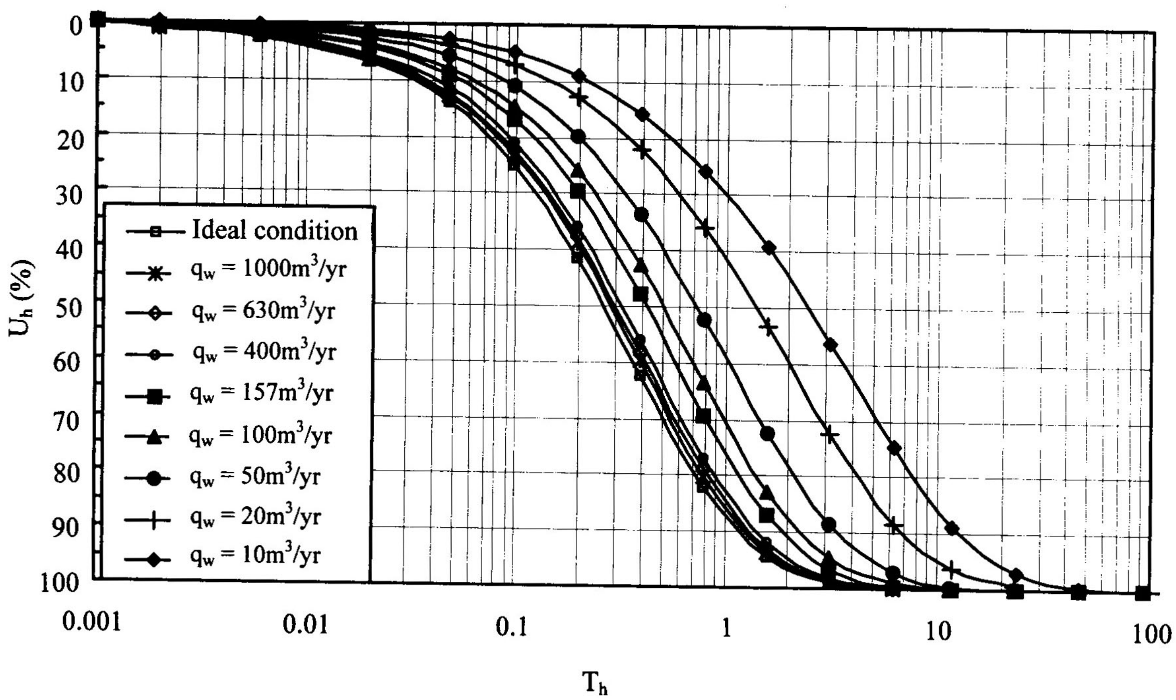

Fig. 4 Well Resistance Effect on Overall Average Consolidation Rate of Axi-Symmetric Unit Cell in Case of k_h=8.64E-4 m/day, H=20m and n=30 (q_w=10 m^3/yr ~ 1000)

Table 3 Equivalent Horizontal Permeability of Smear Effect for Axis-Symmetric Unit Cell Analysis

k_h/k_s	1	2	4	10
k_e (m/day)	8.64E-04	6.87E-04	4.88E-04	2.61E-04
k_s (m/day)	8.64E-04	4.32E-04	2.16E-04	8.64E-05
k_h (m/day) = 8.64E-04				
r_w (m)	r_m (m)	r_s (m)	r_e (m)	
0.025	0.03	0.06	0.75	

Well Resistance and Smear Effect in Axi-Symmetric Unit Cell Analysis

As a result of the installation of vertical drains, the surrounding soils of vertical drains might be considerably disturbed. The diameter of smeared zone varies with the shape of mandrel and anchor plate and with installation method. Bergado et al. (1993a,b) have verified the smear effect radius to be $r_s = 2r_m$, for the reconstituted Bangkok soft clay in which, r_m is the radius of a circle with an area equal to the cross sectional area of the mandrel. The permeability of surrounding soils within the smeared zone, k_s, can be equivalent to k_v determined by oedometer tests, which was proposed by Hansbo (1987) and verified by Bergado et al. (1993a,b). The effects of smear can be simulated in FEM analysis by equivalent horizontal permeability of surrounding soils, k_e, as shown in Figs. 1(d) and (e). Considering the continuity of discharge rate and excess pore water pressure of radial flow from undisturbed zone into smear zone and from smear zone into drain well, the equivalent horizontal permeability of the surrounding soils can be given by:

$$k_e = \frac{k_h k_s \, ln(r_e/r_w)}{k_s \, ln(r_e/r_s) + k_h \, ln(r_s/r_w)} = \frac{(k_h) ln(r_e/r_w)}{ln(r_e/r_s) + (k_h/k_s) ln(r_s/r_w)} \tag{2}$$

As listed in Table 3, the calculated equivalent horizontal permeability of soils was used to consider the smear effect. Figure 5 shows the comparison of FEM result with Zeng's solution which indicate that the FEM analysis with interface element slightly overestimates the degree of consolidation for $U_h < 60\%$, whereas it slightly underestimates for $U_h > 60\%$. In addition, Fig. 6 displays the effect of well resistance with the range of (k_h/k_s) values from 1 to 10.

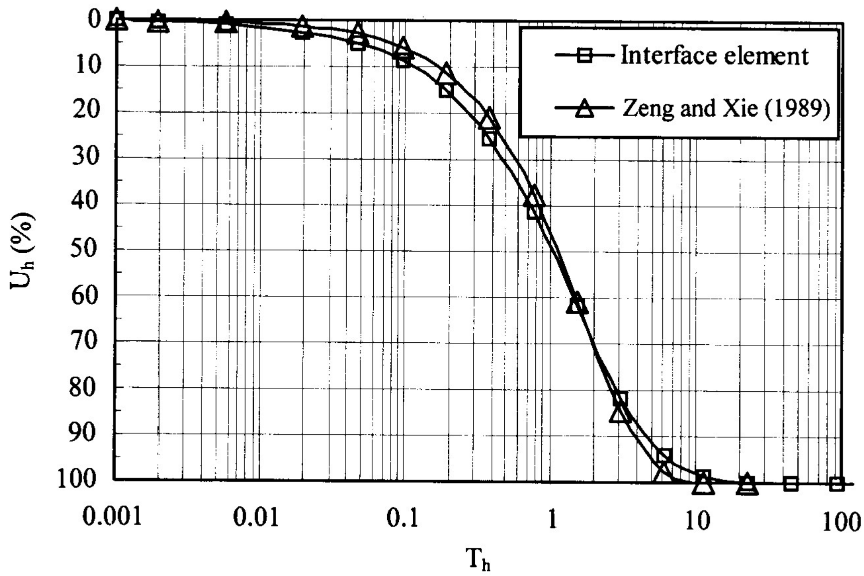

Fig. 5(a) Overall Average Consolidation Rate of Axi-Symmetric Unit Cell in Case of k_h=8.64E-4 m/day, H=20m and n=30, k_h/k_s=10

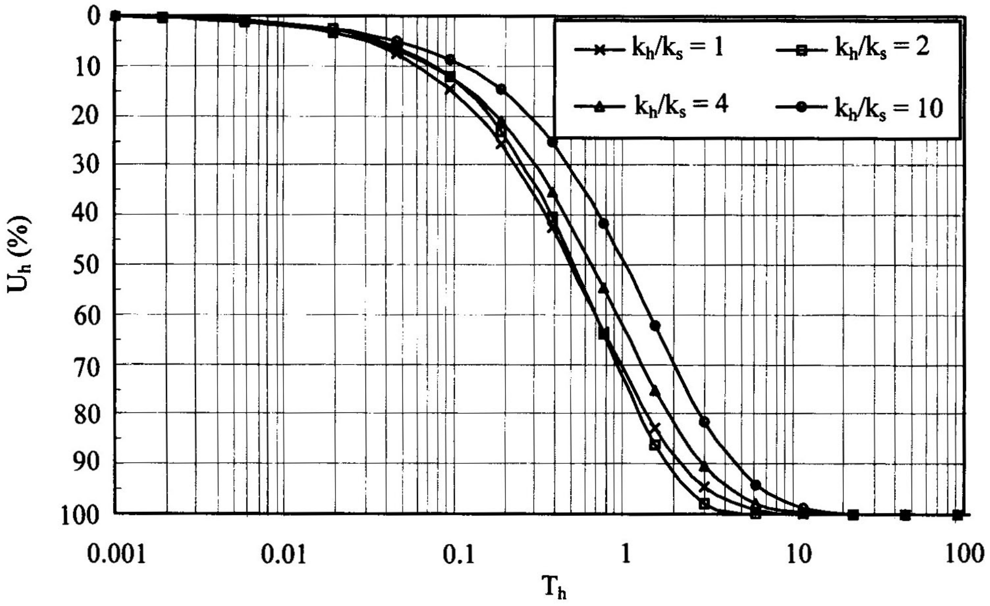

Fig. 6 Overall Average Consolidation Rate of Axi-Symmetric Unit Cell in Case of k_h=8.64E-4 m/day, H=20m and n=30, k_h/k_s=2 ~10

Conversion of Axi-symmetric Unit Cell to Plane Strain Unit Cell

In reality, the pore water flows from the surrounding soil into the vertical drain in a pattern of radial flow. However, in FEM analysis, the pore water flow in plane strain unit cell is considered as 2-D plane flow. Therefore, it is necessary to establish a scheme for converting radial flow of axi-symmetric unit cell to 2-D plane flow of continuous drainage wall systems of plane strain unit cell as shown in Figs. 7(a) to (d). For a square pattern, B (= $r_e\sqrt{\pi}/2 = S/2$), is the half width of plane strain unit cell and S is the spacing of vertical drain.

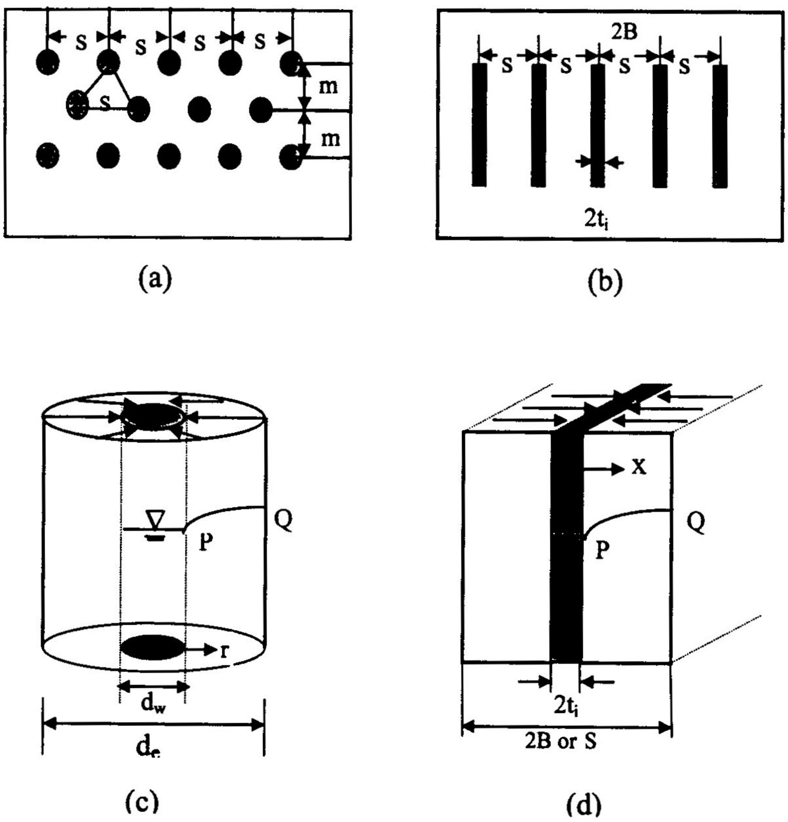

Fig. 7 Conversion of Axi-Symmetric Radial Flow to 2-D Plane Strain Flow (a) PVD Installation Layout (b) PVD in 2-D Plane Strain Model (c) Axi-Symmetric Radial Flow (d) PVD in 2-D Plane Strain Flow

In FEM analysis, the convertion scheme for well resistance can be achieved by using interface element. The equivalent permeability of soils can be formulated for smear effect by equating the average consolidation rate of plane strain and axi-symmetric unit cells as follows:

$$k_{hpl} = \frac{\pi}{6\left(ln(n/s) + (k_{hax}/k_{sax})ln(s) - 0.75\right)} k_{hax} \tag{3}$$

where:

k_{hpl} = Horizontal permeability of undisturbed zone in plane strain unit cell
k_{hax} = Horizontal permeability of undisturbed zone in axis-symmetric unit cell
k_{sax} = Horizontal permeability of smear zone in axis-symmetric unit cell
n = r_e/r_w = Influence ratio
s = r_s/r_w = Smear ratio

As shown in Figs. 1(d) and (e), for both axi-symmetric and plane strain unit cells, the discharge capacity of interface element in the plane strain unit cell should be equivalent to that of axi-symmetric unit cell. For square configuration of vertical drain, the following expression can be obtained:

$$t_{ipl} = \pi r_w^2 / m = \left(q_w / 2mk_{wpl}\right) \tag{4}$$

where:

t_{ipl} = Virtual thickness of interface element in plane strain unit cell $(= \alpha \times l_e)$
M = Row spacing in actual case ($m = S$ for square configuration)
S = Drain spacing in actual case
k_{wpl} = Vertical permeability of interface element in plane strain unit cell
α = Virtual thickness factor (0.01 < α < 1.0)
l_e = Average element size in finite element mesh $\left(= \sqrt{\frac{(X_{max} - X_{min})(Y_{max} - Y_{min})}{n_c}}\right)$

The X_{max}, X_{min}, Y_{max} and Y_{min} are the dimensions of outer geometry of finite element mesh and n_c is the number related to the global coarseness of the finite element mesh (n_c = 25 ~ 400 for different global coarseness). In finite element program, the virtual thickness of interface element, t_i, is defined as the virtual thickness factor, α, times the average element size, l_e. The average element size was determined by the global coarseness setting for the mesh generation.

Based on the equality of the average degree of consolidation at every elapsed time and depth, the proposed matching scheme was applied in FEM analysis using interface element. The well resistance was automatically considered in interface element for axi-symmetric and plane strain unit cells by the equivalent discharge capacity of interface element to that of vertical drain. Consequently, the parameters of axi-symmetric were converted to those of plane strain unit cell, as shown Table 4. As presented in Fig. 8, the agreements of overall average consolidation rate were excellent.

Multi-layered Axi-Symmetric Unit Cell with Well Resistance

In general, natural soft ground is multi-layered. Taking well resistance into consideration, Onoue (1988) proposed rigorous solution for multi-layered soils. However, the solution is mathematically complex. As shown in Fig. 1(f), FEM analysis with interface element considering well resistance in two-layered unit cell was compared with Onoue's solution and layer-thickness-weighted single layer system.

The selected parameters are shown in Table 5. The horizontal coefficient of consolidation for the equivalent single layer system was determined by layer-thickness-weighted coefficient of consolidation whereas the horizontal degree of consolidation was calculated by Zeng's equation. The results of FEM analyses with interface element generally coincide with Onoue's solution, as shown in Fig. 9. On the other hand, the result of layer-thickness-weighted single layer system deviates from the comparisons. This indicates the effectiveness of FEM analyses with interface element in multi-layered soil profile.

Table 4 Conversion of Permeability of Axi-Symmetric Radial Flow to Permeability of Plane Strain Flow with Smear Effect for Unit Cell Analysis

General	k_h/k_s	1	4	10
	Spacing S (m)	1.2		
	Height H (m)	10		
	Configuration	Square		
Axi-symmetric unit cell	k_{hax} (m/day)	8.64E-04		
	k_{sax} (m/day)	8.64E-04	2.16E-04	8.64E-05
	q_w (m^3/yr)	20		
	k_w (m/day)	27.91		
	r_w (m)	0.025		
	r_e (m)	0.677		
	n (r_e / r_w)	27.1		
	r_m (m)	0.03		
	r_s (m)	0.06		
	s (r_s / r_w)	2.4		
	t_{iax} (m)	0.06		
Plane strain unit cell	k_{hpl} (m/day)	1.77E-04	8.74E-05	4.34E-05
	q_w (m^3/yr)	20		
	k_w (m/day)	0.76		
	B (m)	0.6		
	m (m)	1.2		
	t_{ipl} (m)	0.06		

Table 5 Input Parameters for Two-Layered Unit Cell (H_1/H)=0.75, $H=H_1+H_2$ (a) Geometry and Engineering Properties (b) Discharge Properties of Vertical Drain

Layers	K_h (m/day)	E' (kPa)	γ_d (kN/m^3)	γ_t (kN/m^3)	r_e (m)	r_w (m)
First layers (H_1=1.5m)	8.64E-04	10000	8.8	14.5	0.125	0.025
Second layers (H_2=0.5m)	2.16E-02					

(a)

Layers	q_w (m^3/yr)	k_w (m/day)	t'_i (m)	k'_w (m/day)	k_{eh} (m/day)	C_{eh} (m^2/day)
First layers (H_1=1.5m)	80	112.1	0.018	18.633	1.12E-02	11.64
Second layers (H_2=0.5m)						

(b)

1. t'_i, k'_w = Modified values based on equal discharge capacity
2. k_{eh}, C_{eh} = Permeability and coefficient of consolidation for layer-thickness-weighted single layer system, respectively

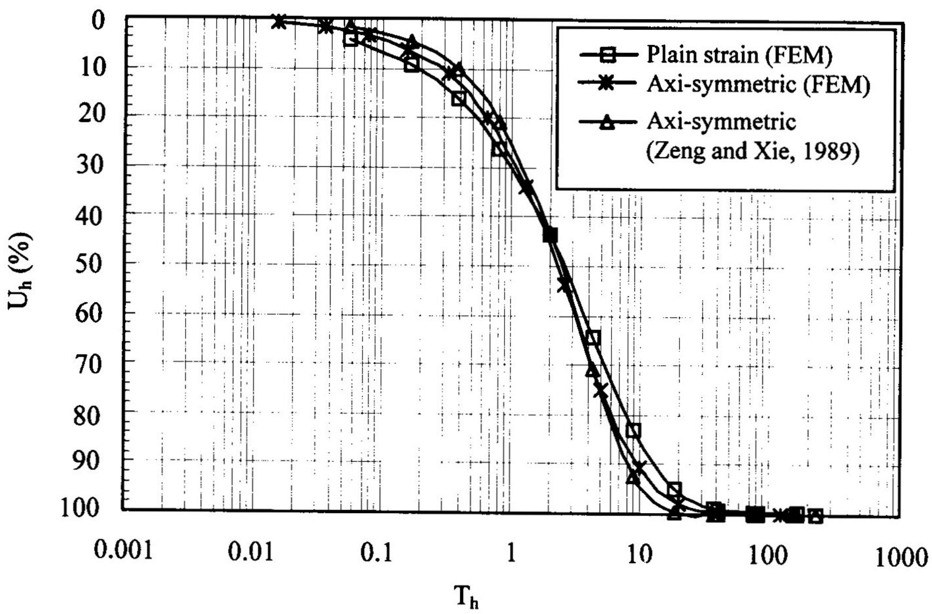

Fig. 8 Conversion of Axi-Symmetric Unit Cell to 2-D Plane Strain Unit Cell in Case of q_w=20 m^3/yr, k_h=8.64E-4 m/day, H=10m, s=2.4 and n=27, k_h/k_s=10

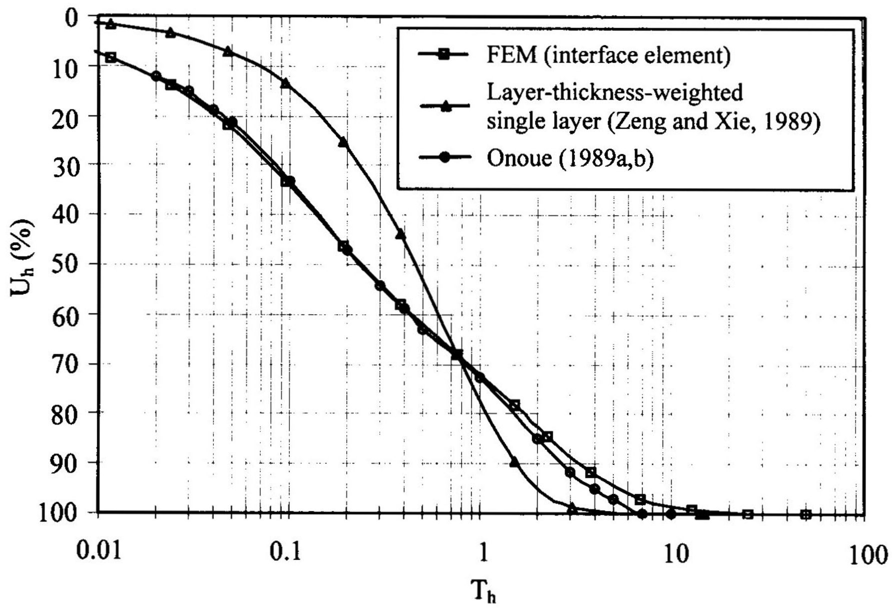

Fig. 9 Comparison of Overall Average Consolidation rate of Two-Layered Unit Cell in Case of H_1/H=0.5 and k_{h2}/k_{h1}=25

NUMERICAL MODELING OF VERTICAL DRAIN IN FULL SCALE ANALYSIS

The proposed matching method was applied to the full-scale test embankment on PVD improved ground for the Second Bangkok International Airport (SBIA) project and the effectiveness of the proposed matching method was verified in practical application.

Project Description and Site Condition

The site of the SBIA at Nong Ngu Hao (NNH) is underlain by soft clay strata with low strength and high compressibility. The use of PVD with surcharge increased the bearing capacity and reduced the compressibility of soft ground. In this study, test embankment TS3 with 4.2 m high fill was analyzed. The foundation soils were improved by PVD placed in a square pattern with spacing of 1.0 m and length of 12 m.

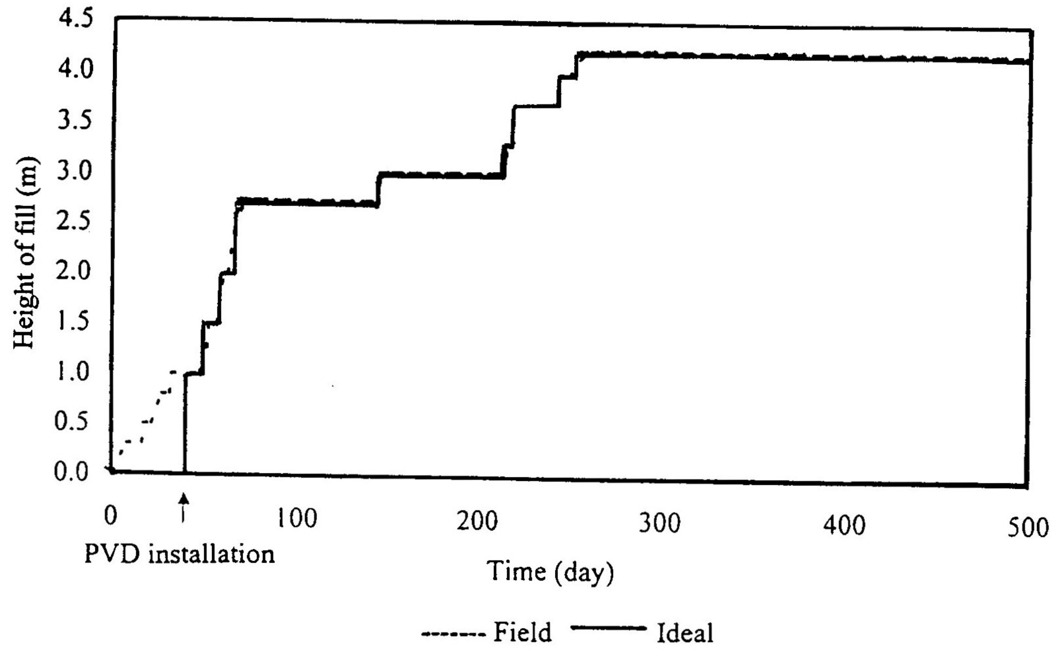

Fig. 10 Idealised Construction Sequence of Test Embankment

Table 6 Conversion of Permeability of Axi-Symmetric Radial Flow to Permeability of Plane Strain Flow with Smear Effect for Full Scale Analysis

General	k_h/k_s	10	15	5
	Spacing (m)	1		
	H (m)	12		
	Configuration	Square		
Axi-symmetric radial flow	Soil type	Crust	Very soft clay	Soft clay
	k_{hax} (m/day)	2.59E-03	1.01E-03	8.15E-03
	k_{sax} (m/day)	2.59E-04	6.73E-05	1.63E-03
	q_w (m^3/yr)	20		
	k_w (m/day)	27.91		
	r_w (m)	0.025		
	r_e (m)	0.564		
	n (r_e / r_w)	22.6		
	r_m(m)	0.048		
	r_s(m)	0.096		
	s (r_s / r_w)	3.84		
	t_{iax} (m)	0.06		
Plane strain flow	Soil type	Crust	Very soft clay	Soft clay
	k_{hpl} (m/day)	9.37E-05	2.49E-05	5.51E-04
	q_w (m^3/yr)	20		
	k_w (m/day)	0.76		
	B (m)	0.5		
	m(m)	1		
	t_{ipl} (m)	0.06		

The construction stages are illustrated in Fig. 10. In FEM analysis, hydrostatic pore pressure was employed as initial pore water pressure and initial effective stress was generated by K_o calculation procedure.

Soil Model Parameters and Drainage Parameters

Soil properties for the test site has been evaluated from previous reports (Bergado, et al., 1995; Bergado, et al., 1998). As listed in Table 6, the equivalent horizontal permeability of soils, k_{hpl}, was calculated by the proposed matching scheme and the different k_h / k_s ratios were determined by the strengths of different soil layers to match instrumentation data. In addition, the soil model parameters and the engineering properties of PVD are summarized in Tables 7 and 8, respectively.

Modeling of PVD Improved Ground

As shown in Table 9, well resistance factors, R and L, for soft clay and very soft clay layers were, respectively, calculated based on hydrostatic initial pore water pressure and single homogeneous layer.

The prescribed boundary conditions and the 2-D plane strain geometrical model were generated as shown in Fig. 11. The 6-node triangular element was adopted in the analysis. The element provides second order interpolation function for displacement and its stiffness matrix is evaluated by numerical integration using 3 integration points. Finite element mesh was refined locally in the PVD improved zone to increase the accuracy of numerical solution and the number of elements was 1,146 in the finite element dicretization. The following conditions were considered in the FEM analysis:

Table 7 Input Soil Model Parameters for Full Scale Analysis
(a) Soft Soil Model (b) Mohr-Coulomb Model

Depth (m)	c' (kpa)	ϕ' (degree)	λ^*	κ^*	K_o	k_h (m/day)	k_v (m/day)	γ_t (kN/m^3)	γ_d (kN/m^3)	OCR
0 ~ 2 crust	30	28	0.130	0.013	0.70	2.59E-03	2.59E-03	16.0	9.41	7.00
2 ~ 4 very soft clay	10	23	0.239	0.024	0.65	1.01E-03	5.90E-04	14.2	7.10	3.00
4 ~ 6 very soft clay	10	23	0.239	0.024	0.65	1.01E-03	5.90E-04	14.2	7.10	2.50
6 ~ 8 very soft clay	10	23	0.239	0.024	0.65	1.01E-03	5.90E-04	14.2	7.10	1.75
8 ~ 12 soft clay	15	25	0.195	0.020	0.63	8.15E-03	2.60E-04	14.7	8.17	1.35
12 ~ 16 medium clay	20	30	0.152	0.015	0.63	2.10E-04	5.00E-04	15.6	9.75	1.35
16 ~ 22 stiff clay	20	30	0.130	0.013	0.63	5.00E-05	3.00E-01	18.0	13.85	1.35

(a)

Material	c' (kPa)	ϕ' (degree)	K_o	E' (kN/m^2)	k_h (m/day)	k_v (m/day)	γ_t (kN/m^3)	γ_d (kN/m^3)
Sand blanket	10	35	0.50	7000	8.64E+00	8.64E+00	19.0	17.00
Backfill	10	30	0.50	7000	8.64E+00	8.64E+00	19.0	17.00

(b)

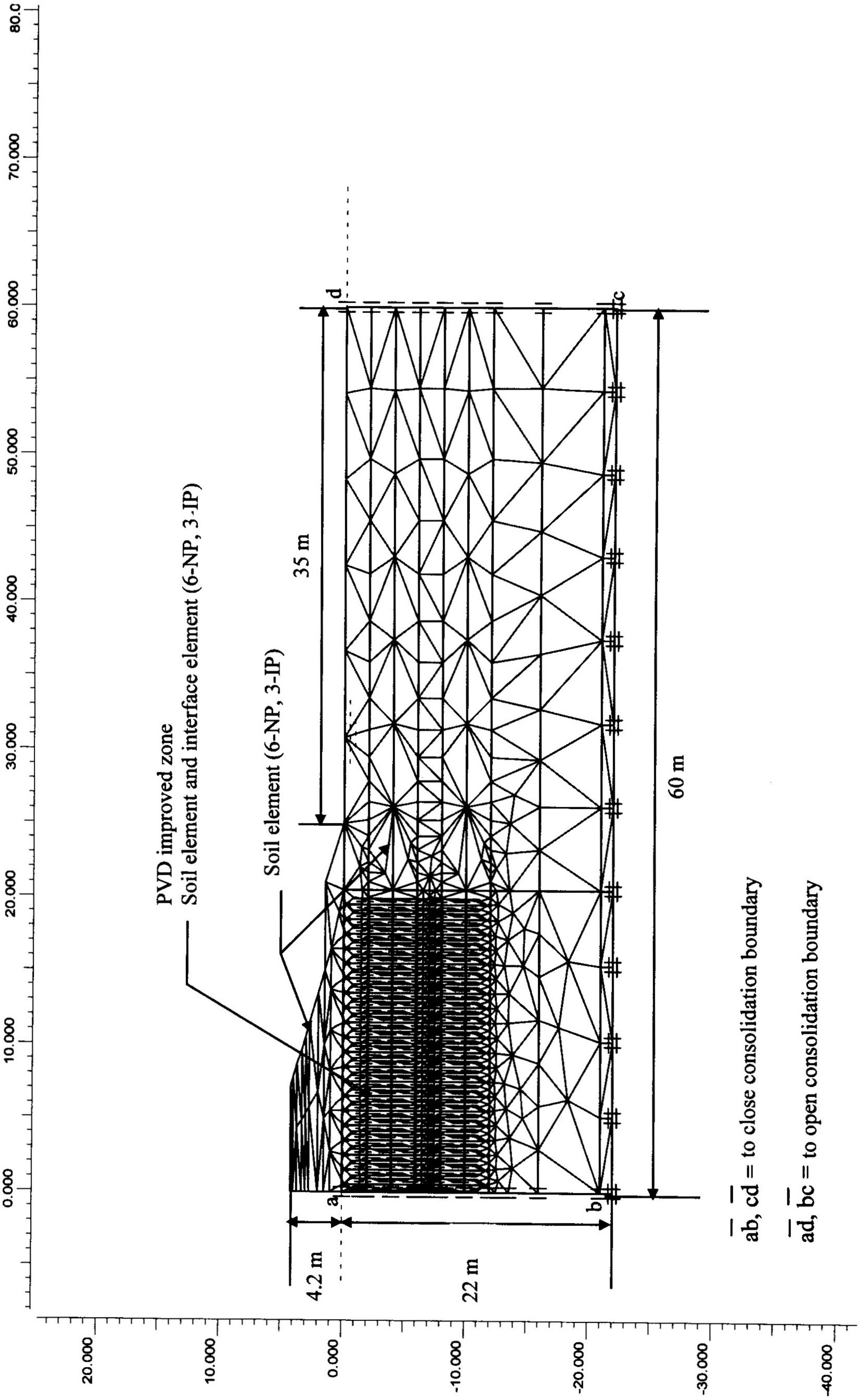

Fig. 11 Finite Element Mesh of Test Embankment and PVD Improved Ground

Table 8 Properties of Vertical Drain (a) Physical Properties (b) Strength Properties (c) Discharge Capacity

Width b (mm)	Thickness t (mm)	Core		Filter			
		Material	Form	Material	Form	Permeability (cm/s)	Pore size (μm)
100	3	Poly-prophylene	Grooved (38 nos.)	Poly-ethylene	Thermally spun-bonded non-woven	6.50E-04	75 for O_{90}

(a)

Grab tensile strength (kPa)	Trapezoidal shear strength (kPa)	Puncture resistance (kPa)	Burst strength (kPa)
0.99	0.34	0.27	1382

(b)

Discharge capacity (m^3/yr)			
Straight	Free bending 20% compression	Twisted condition (45°) 20% compression	One clamped condition 20% compression
2115	1270	1105	570

(c)

Table 9 Well Resistance Factor of Soft Clay and Very Soft Clay for Full Scale Analysis

Soft clay								
l_m(m) = 12 k_h(m/day) = 8.15E-03 r_w (m) = 0.025								
q_w (m^3/yr)	400	570	800	1000	2150	6000	10000	
k_w (m/day)	558.1	795.3	1116	1395	3000	8372	13953	
$R=\frac{q_w}{k_h l_m^2}$	0.9	1.3	1.9	2.3	5.0	14.0	23.3	Mesri and Lo (1991)
$\frac{q_w}{k_h}$	134	192	269	336	723	2017	3362	Hansbo (1979)
$L=\frac{8k_h}{\pi^2 k_w}\left(\frac{l_m}{r_w}\right)^2$	2.7	1.9	1.4	1.1	0.5	0.2	0.1	Yoshikuni (1974)
Very soft clay								
l_m (m) = 12 k_h (m/day) =1.01E-03 r_w (m) = 0.025								
q_w (m^3/yr)	100	265	400	570	800	1000	2000	
k_w (m/day)	139.5	369.8	558.1	795.3	1116	1395	2791	
$R=\frac{q_w}{k_h l_m^2}$	1.9	5.0	7.5	10.7	15.1	18.8	37.7	Mesri and Lo (1991)
$\frac{q_w}{k_h}$	271	719	1085	1546	2170	2713	5425	Hansbo (1979)
$L=\frac{8k_h}{\pi^2 k_w}\left(\frac{l_m}{r_w}\right)^2$	1.4	0.5	0.3	0.2	0.2	0.1	0.1	Yoshikuni (1974)

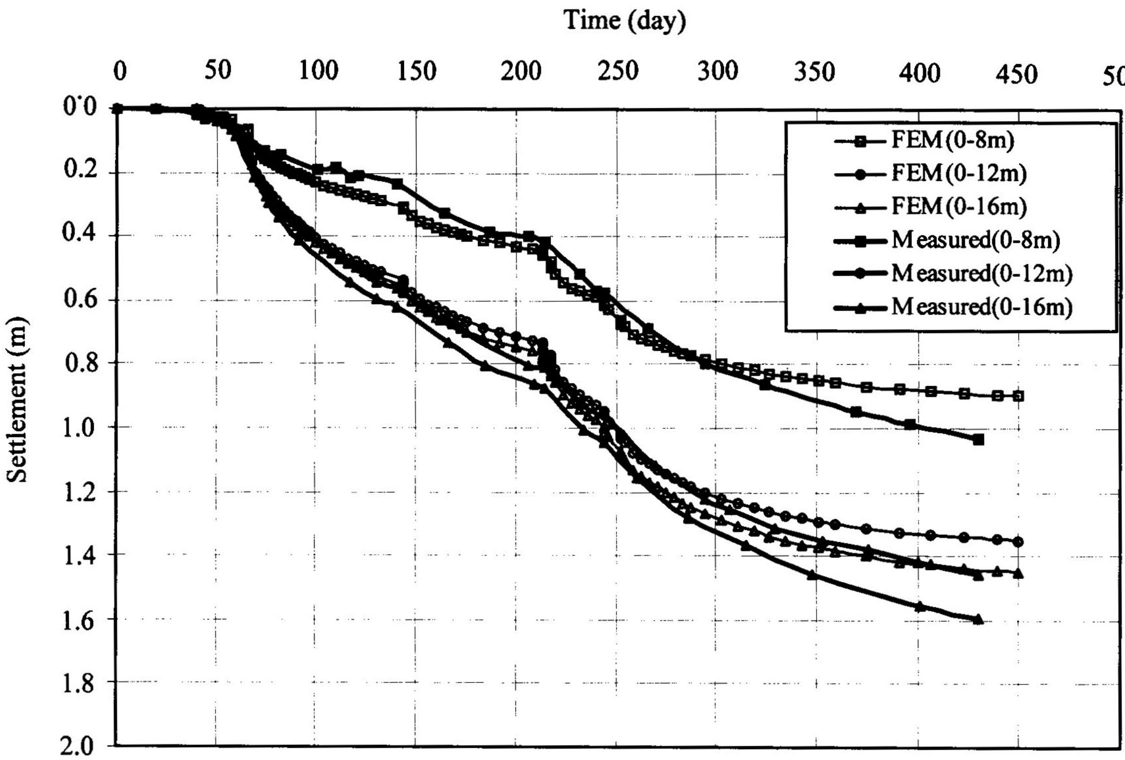

Fig. 12(a) Comparison of Settlement Rate of PVD Improved Ground between Numerical Analysis and Field Measurement with Well Resistance and Smear Effect

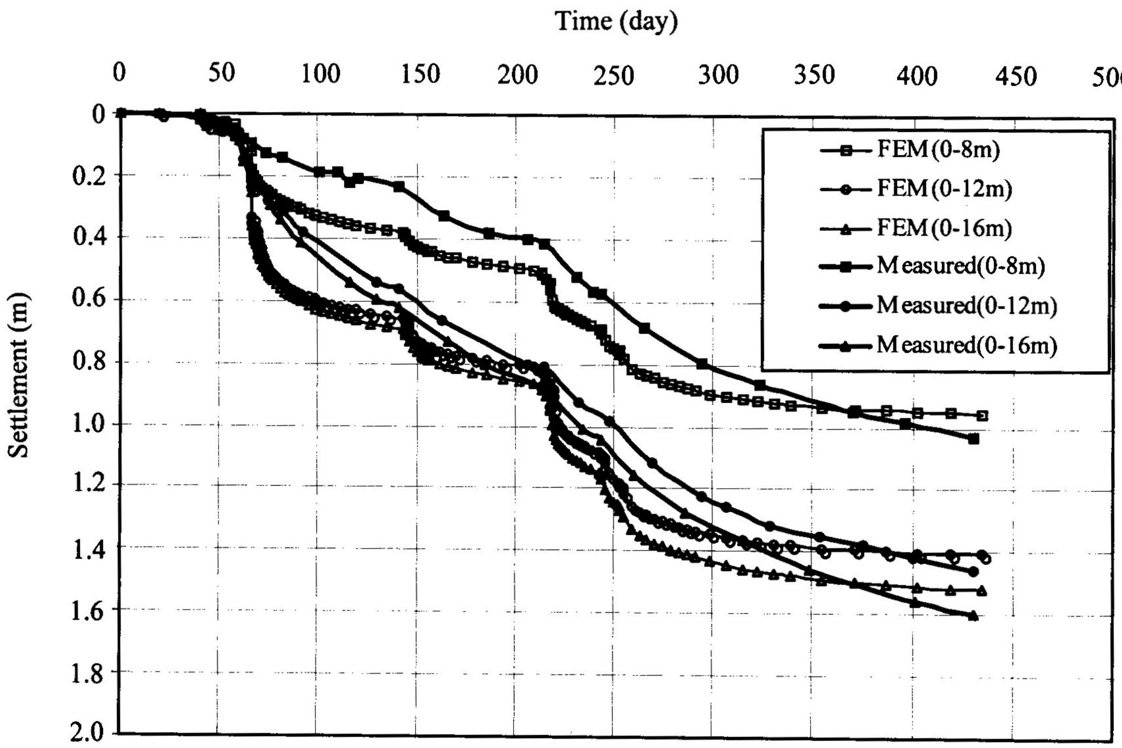

Fig. 12(b) Comparison of Settlement Rate of PVD Improved Ground between Numerical Analysis and Field Measurement with Smear Effect

(1) Coupled consolidation analysis was performed under 2-D plane strain condition.
(2) Vertical closed consolidation boundary was specified at the center of embankment and at 60.0m from the center of the embankment.
(3) Opened consolidation boundary was specified at ground surface and at the sand layer, 22m below the ground surface.
(4) Clay layers were simulated by Soft Soil Model while backfill material and sand blanket by Mohr-Coulomb Model.

As shown in Fig. 12(a), the consolidation rate of PVD improved ground considering well resistance and smear effect resulted in much better agreement with the measured data than that neglecting the well resistance (Fig. 12(b)). The significant influence of well resistance on consolidation behavior of PVD improved ground is also indicated.

CONCLUSIONS AND COMMENTS

In this study, finite element analyses using the interface element were performed to simulate vertical drain in axi-symmetric unit cell, plane strain unit cell, two-layered unit cell, and full scale test embankment improved by PVD. The following conclusions could be drawn:

(1) In the proposed matching schemes, the interface element with finite permeability was employed to consider the well resistance and the smear effect was introduced by an equivalent horizontal permeability of soils. The FEM calculation results show excellent agreement with Zeng's theoretical solution.
(2) The proposed matching schemes were applied to the conversion of actual radial flow to 2-D plane strain flow by equating the average degree of consolidation of two flow modes. The calculation results of plane strain unit cell show excellent agreement with those of axi-symmetric unit cell.
(3) The proposed matching schemes were applied to two-layered unit cell and compared with the layer-thickness-weighted single homogeneous soils system and Onoue's theoretical solutions. The calculation results of proposed matching schemes agree well with Onoue's solution while those of the layer-thickness-weighted single homogeneous soils system is too rough to apply for precise prediction analysis.
(4) FEM analyses incorporated with the proposed matching schemes were performed on full-scale test embankment improved by PVD with surcharge loading. The calculation results show that the well resistance was a crucial factor in the simulation of consolidation process. Consequently, the proposed matching schemes for smear effect and well resistance was verified to be applicable in engineering practice.

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