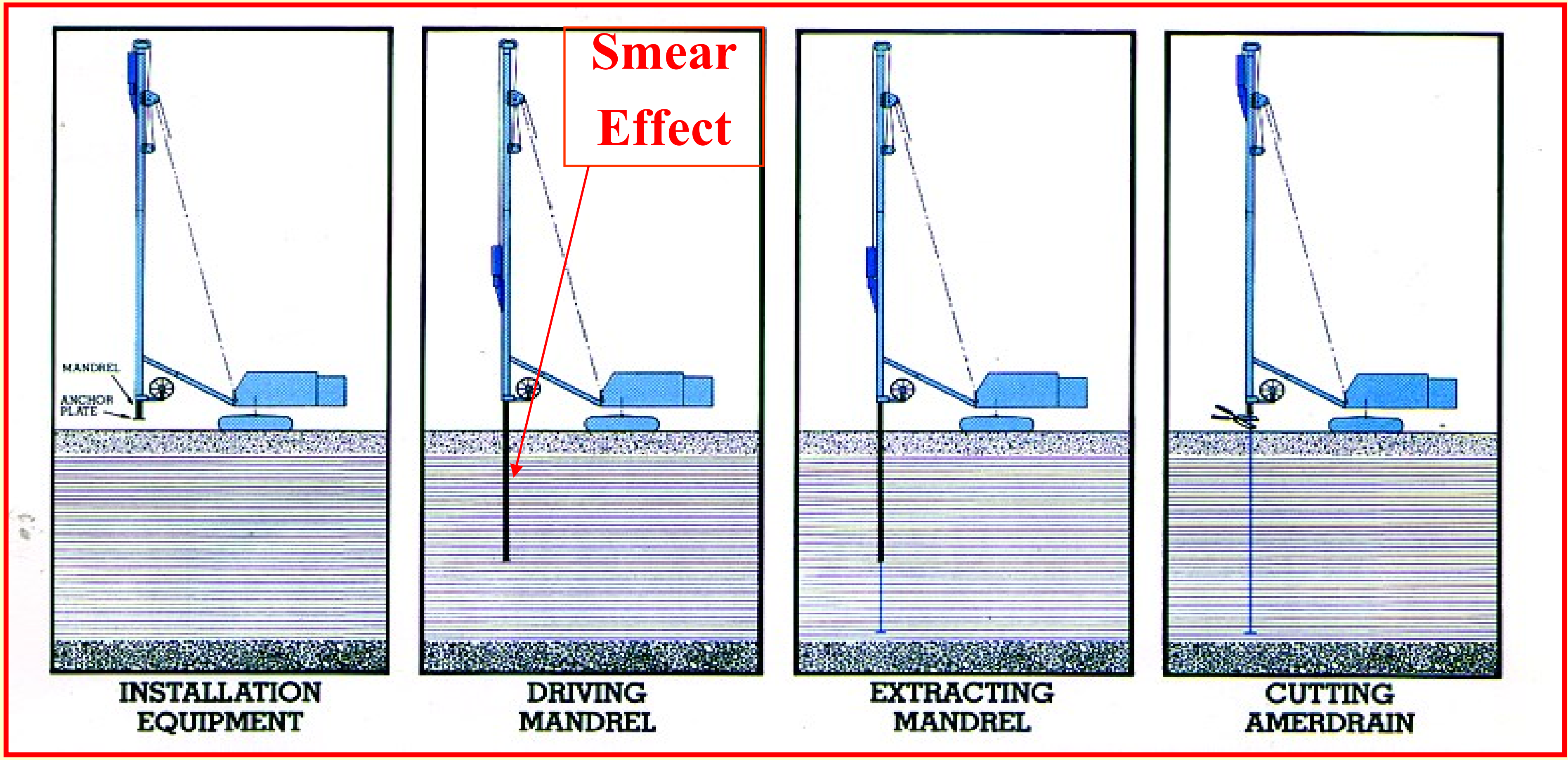
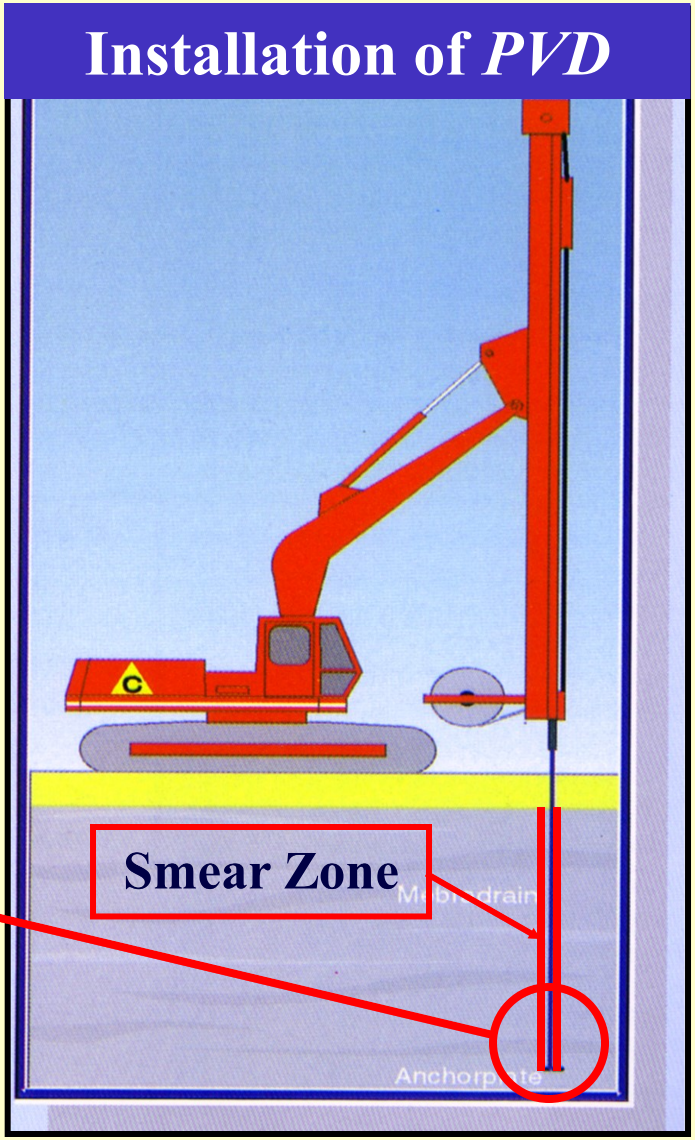
Numerical Analyses of *PVD* Improved Ground At Reference Section of Second Bangkok International Airport

KEY ISSUES IN NUMERICAL MODELING OF *PVD* IMPROVED GROUND

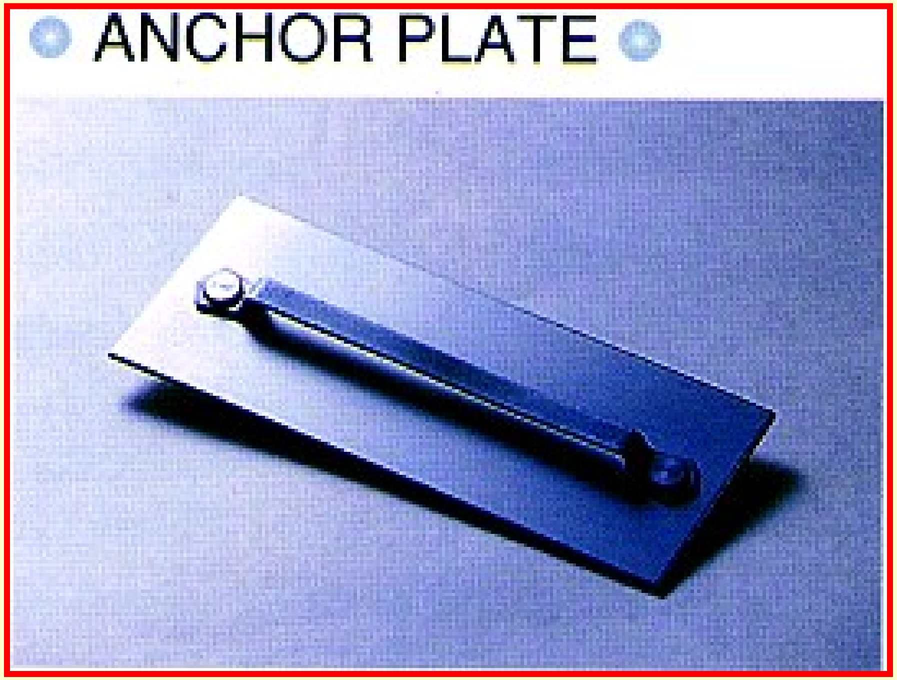
Smear Effect
(Severe Disturbance at the Mandrel~Soil Interface) Induced during the *PVD* Installation

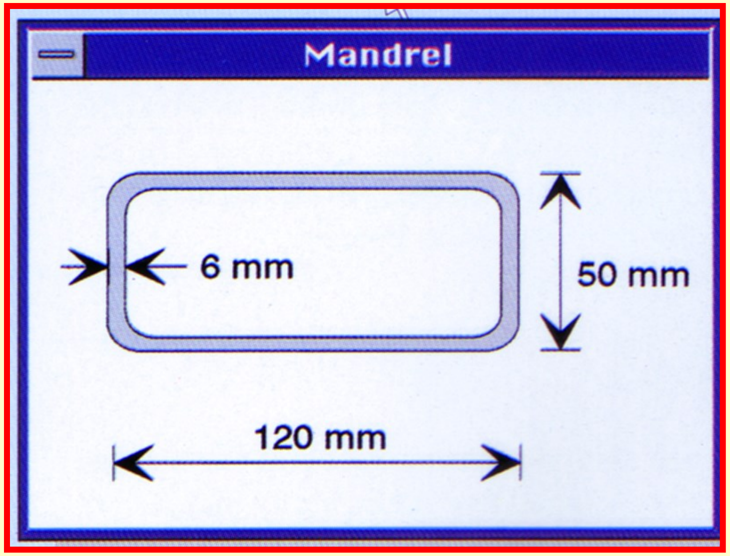


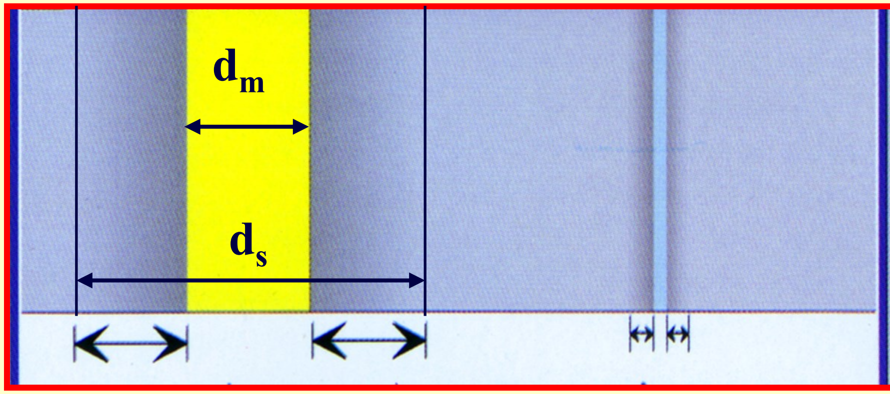
Smear Zone Caused by the Penetration of Mandrel with Anchor Plate



Estimation of Smear Zone of *PVD* Installation



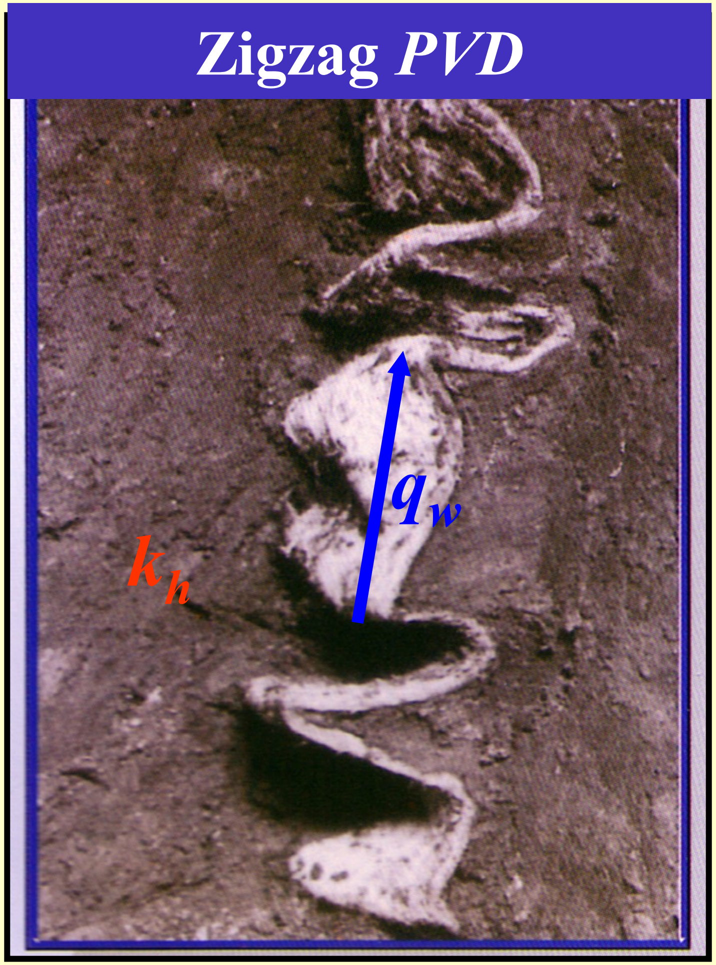




- $(1/4)\times\pi\times(d_m)^2 = 120mm \times 50mm$
- $d_s = (2.5 \sim 3)\ d_m$

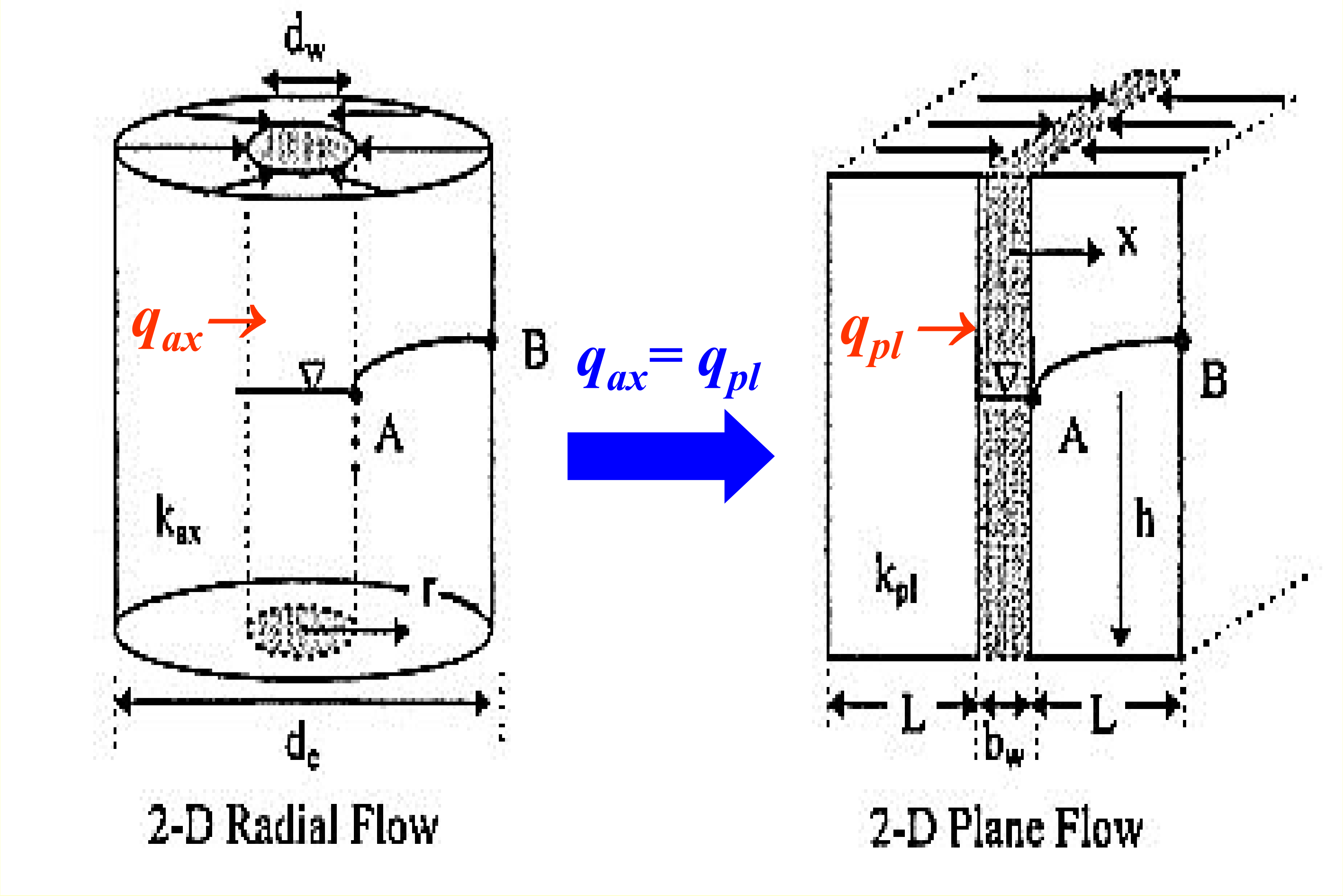
Well Resistance of Prefabricated Vertical Drain

- Deterioration of the drain filter
- Silt intrusion into the filter and enter the drainage channel
- Folding of the drain due to lateral movement



q_w=Discharge capacity of *PVD* $\rightarrow$ k_w

Conversion of 2-D Radial Flow into 2-D Plane Flow of *PVD* Improved Ground



$$2\text{-D radial flow} \quad q_{ax} = \frac{\pi\, k_{ax}(h_B{}^2 - h_A{}^2)}{\ln\left(\dfrac{d_e}{d_w}\right)}$$

- The total discharge capacity for the 2-D radial flow (axis-symmetric flow) and 2-D plane flow can be represented by:

$$2\text{-D plane flow} \quad q_{pl} = \frac{m\, k_{pl}(h_B{}^2 - h_A{}^2)}{L}$$

- Considering the condition of equal discharge rate and taking the same head boundaries at points A (h_A) and B (h_B) for both the axsi-symmetric (in-situ) flow and the 2-D plane flow :

$$q_{ax} = q_{pl}$$

- Permeability of soil to transform the axis-symmetric flow into 2-D plane flow :

$$k_{pl} = \frac{\pi L}{m \ln\left(\frac{d_e}{d_w}\right)} k_{ax}$$

SOME CONSIDERATIONS IN *PVD* NUMERICAL MODELING

- **Smear effect of *PVD*:**
  (1) continuity of discharge rate
  (2) distribution of excess pore water pressure

- **Well resistance of *PVD***
  (q_w=discharge capacity of *PVD* and k_w=vertical permeability of *PV*D)

- **Conversion of 2-D radial flow to 2-D plane flow**
  (equaling the average consolidation rate for both flow models)

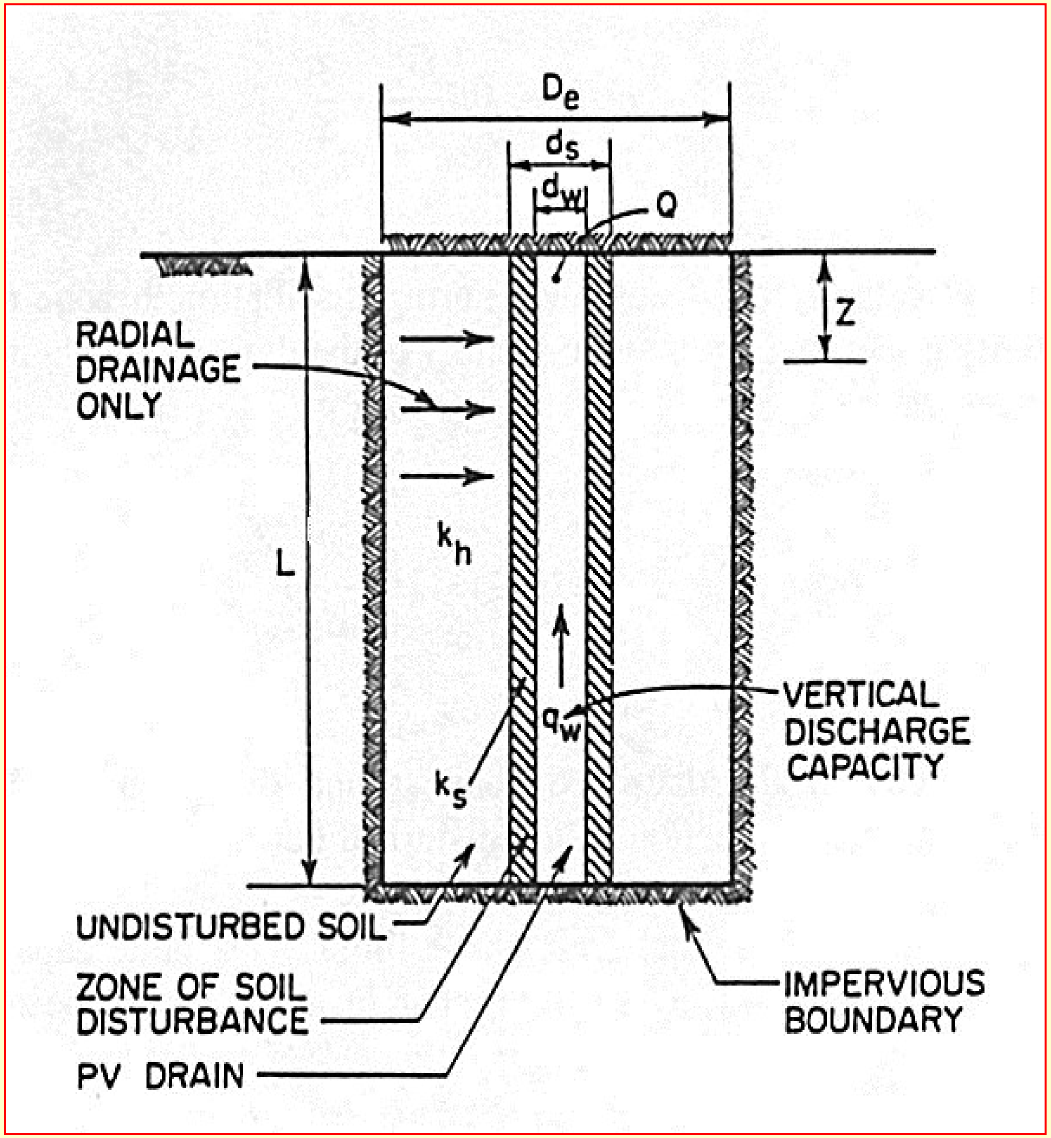
- **Simulation of *PVD* numerically**
  (1) drainage element with thin thickness
  (2) interface element

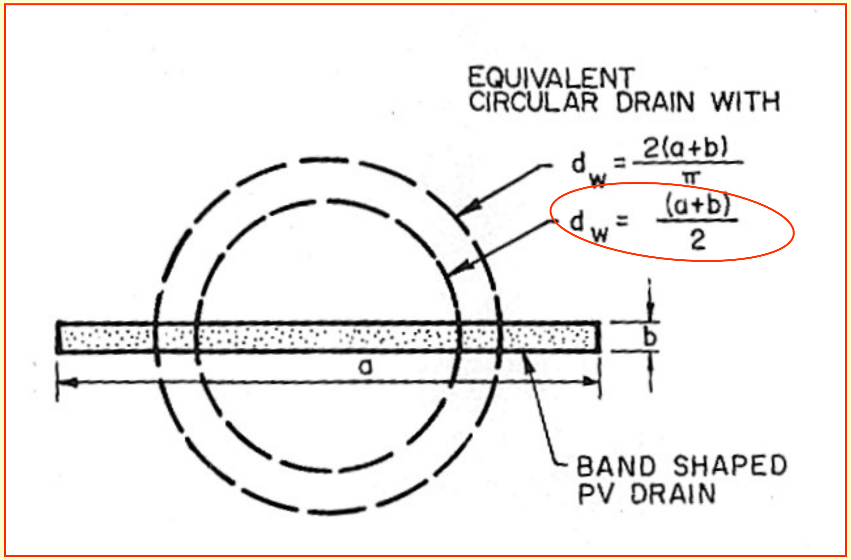
Comparison of Numerical Tools in *PVD* Modeling

Tools	Smear Effect	Well Resistance	Water Flow	*PVD* Drainage
Crisp	Equivalent permeability k_e	Finite permeability k_w	2-D plane flow	1. drainage element (with limit number) 2. negative pore pressure for vacuum simulation
Plaxis	k_e	k_w	2-D plane flow	1. drainage element (without limitation) 2. interface element
Flac^{3D}	k_e	k_w	3-D channel flow	1. drainage element (drainage well)

UNIT CELL THEORY OF VERTICAL DRAIN

Some Parameters Considered in Unit Cell Theory and Numerical Modeling of *PVD*





a= Width of *PVD*= 100 *mm*

b=Thickness of *PVD*=3 *mm*

Barron's Unit Cell Theory (1948)

Barron (1948) presented the first exhaustive solution to the problem of consolidation of a soil cylinder containing a central sand drain, and the solution of Barron under ideal conditions (i.e. no smear and no well resistance) on a saturated soil.

Yoshikuni's Unit Cell Theory (1974)

Yoshikuni, et al. (1974) presented a rigorous solution for the consolidation of isotropic and homogeneous soils by vertical drain well with finite permeability (well resistance).

Hansbo's Unit Cell Theory (1981)

Hansbo (1981) modified the equations developed by Barron (1948) based on the equal strain condition approach, and considered the effects of well resistance and smear, but neglected vertical drainage in the soil (the consolidation was contributed by radial flow due to vertical drain only).

Onoue's Unit Cell Theory (1988)

Onoue's (1988) presented a rigorous solution for consolidation by vertical drains taking well resistance and smear into account in the case of equal strain consolidation and considered vertical drainage (soil) and radial drainage (vertical drain) in the soil.

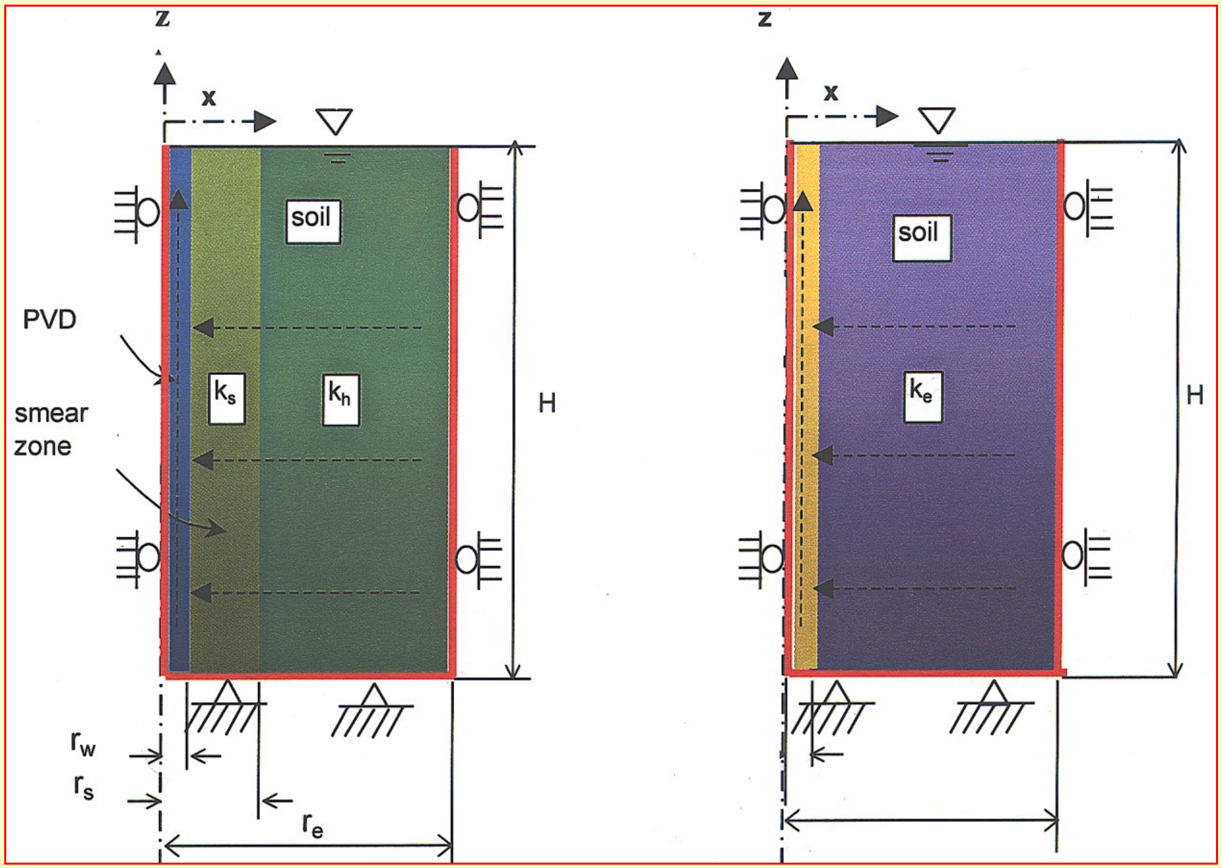
Zeng's Theory (1989)

Zeng, et al. (1989) proposed analytical solution for fully penetrating drains and partially penetrating drains and considered the effect of the smear and well resistance, but neglected the vertical drainage in soil (the consolidation was contributed by radial flow due to vertical drain only).

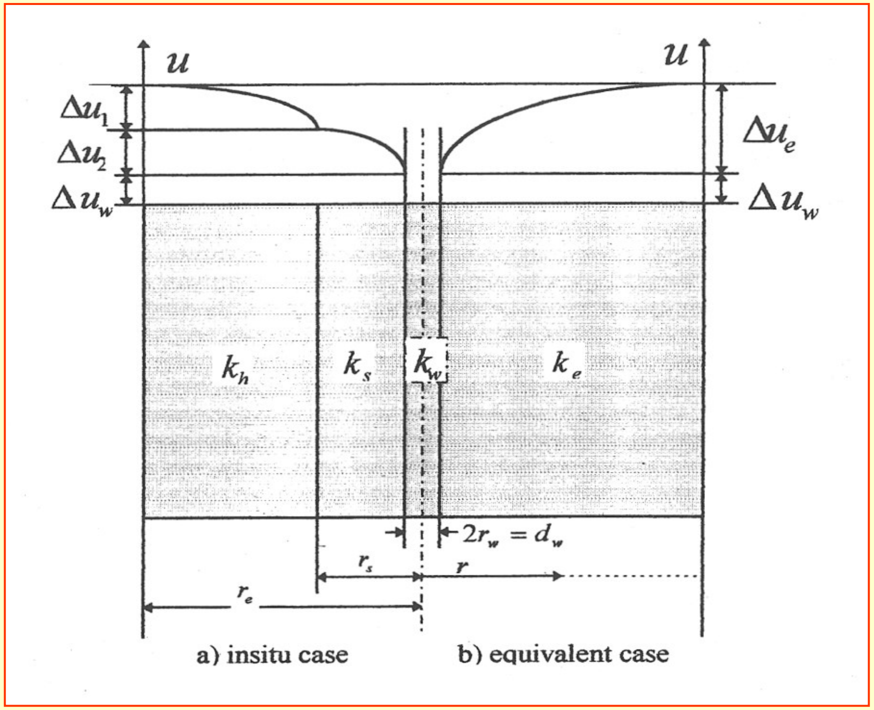
SMEAR EFFECT AND WELL RESISTANCE IN NUMERICAL MODELING OF *PVD*

Smear Effect

- In the analysis, the smear effect of *PVD* can be simulated by specifying an equivalent horizontal permeability, ($\boldsymbol{k_e}$), for both smear zone and undisturbed zone.



Considering the continuity of discharge rate and distribution of excess pore water pressure



$$q_1 = q_2 = q_e$$

$$\Delta u_e = \Delta u_1 + \Delta u_2$$

Equivalent horizontal permeability for smear effect

$$k_e = \frac{k_h k_s \ln\left(\frac{r_e}{r_w}\right)}{k_s \ln\left(\frac{r_e}{r_s}\right) + k_h \ln\left(\frac{r_s}{r_w}\right)}$$

Well Resistance

- In the analysis, to consider the finite permeability, and the corresponding well resistance is simulated by specifying permeability, (***k_w***), as follow:

$$q_w = k_w \times i \times \pi r_w^2$$

q_w=experimental or field observations=10~1500 m^3/year for confining pressure =50~300kPa

Approximate Method Used in This Study

(Chai and Miura, 1997a)

From a macro point of view, vertical drain increases the mass permeability in vertical direction. Therefore, it is possible to establish an equivalent vertical permeability (k_{ve}) which approximately represent :

- the vertical drainage of natural subsoil and
- the radial drainage due to *PVD*.

This method can be used to solve the numerical difficulty caused by thin thickness drainage element.

- Based on Terzaghi's theory, the average degree of consolidation for vertical flow (due to the drainage of soil):

$$U_v = 1 - \exp(-3.54 T_v)$$

- Using Hansbo's theory, the average degree of consolidation for radial flow (due to the drainage of *PVD*) :

$$U_h = 1 - \exp(-\frac{8}{\mu} T_h)$$

$$\mu = \ln\frac{n}{s} + \frac{k_h}{k_s}\ln s - \frac{3}{4} + \pi\frac{2 l_d^2 k_h}{3 q_w} \qquad n = \frac{d_e}{d_w} \quad , \quad s = \frac{d_s}{d_w}$$

- Using Scott's equation and combining the U_h and U_V to obtain the average degree of consolidation:

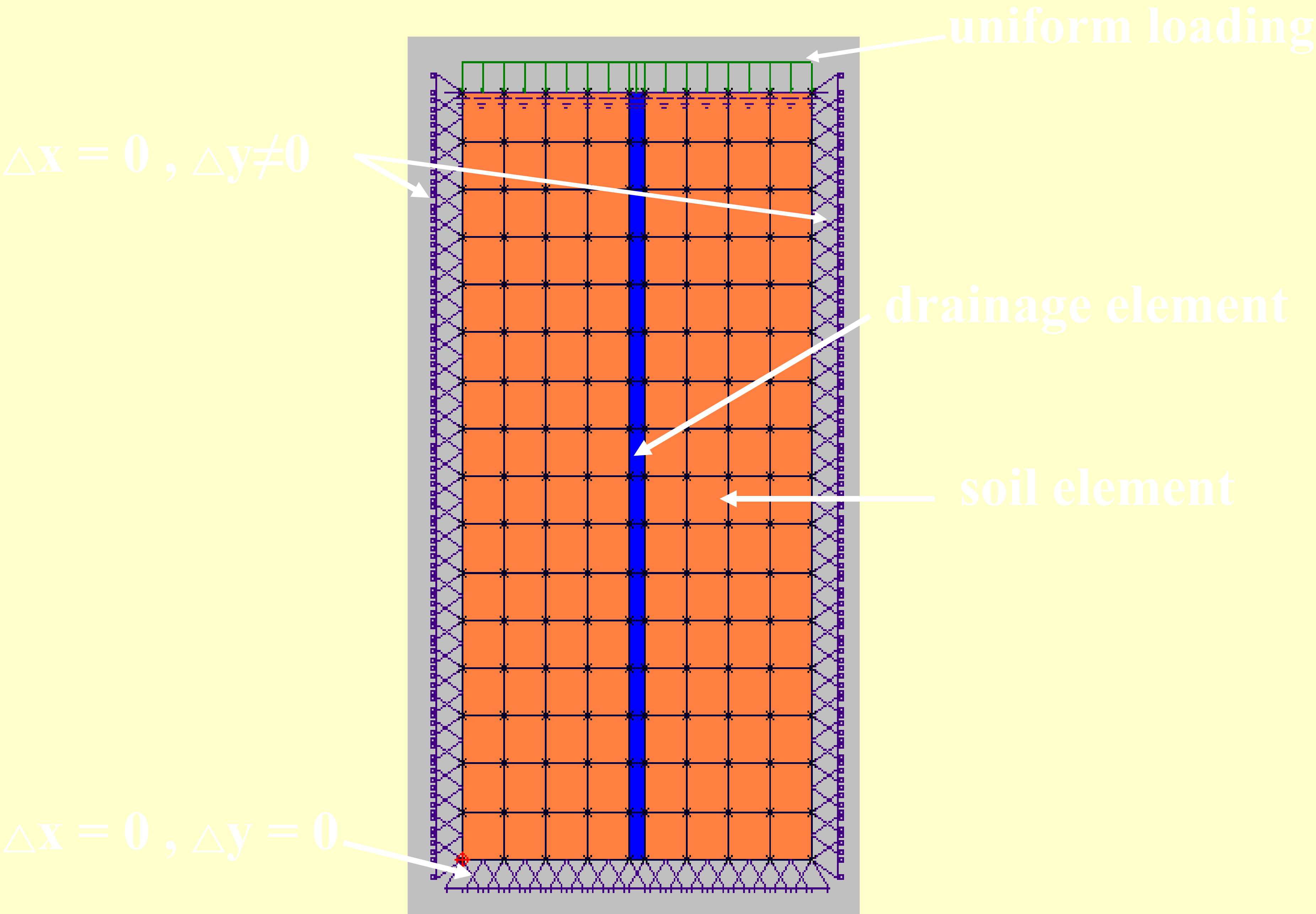
$$\overline{U} = 1 - (1 - U_h)(1 - U_v)$$

- Based on the Scott's assumption, an equivalent vertical permeability, k_{ve}, can be given as:

$$k_{ve} = \left(1 + \frac{2.26 l_d^2}{\mu d_e^2} \frac{k_h}{k_v}\right) k_v$$

NUMERICAL MODELING OF *PVD* IMPROVED UNIT CELL (Crisp Axis-symmetric Analysis)

Numerical Model of *PVD* Unit Cell



Soil Model Parameters for Unit Cell (Hansbo's solution)

Soil model	Loading (kPa)	E (kPa)	ν	γ_w (kN/m^3)	k_h (m/sec)	k_v (m/sec)
Isotropic Elastic	10	10000	0.3	10	1.0E-08	1.0E-16

Height (m)	L	M	C_h (m^2/s)	k_s (m/sec)	k_e (m/sec)	k_{ve} (m/sec)
20	0.5	13462	1.346E-05	2.0E-09	3.3E-09	8.6E-09

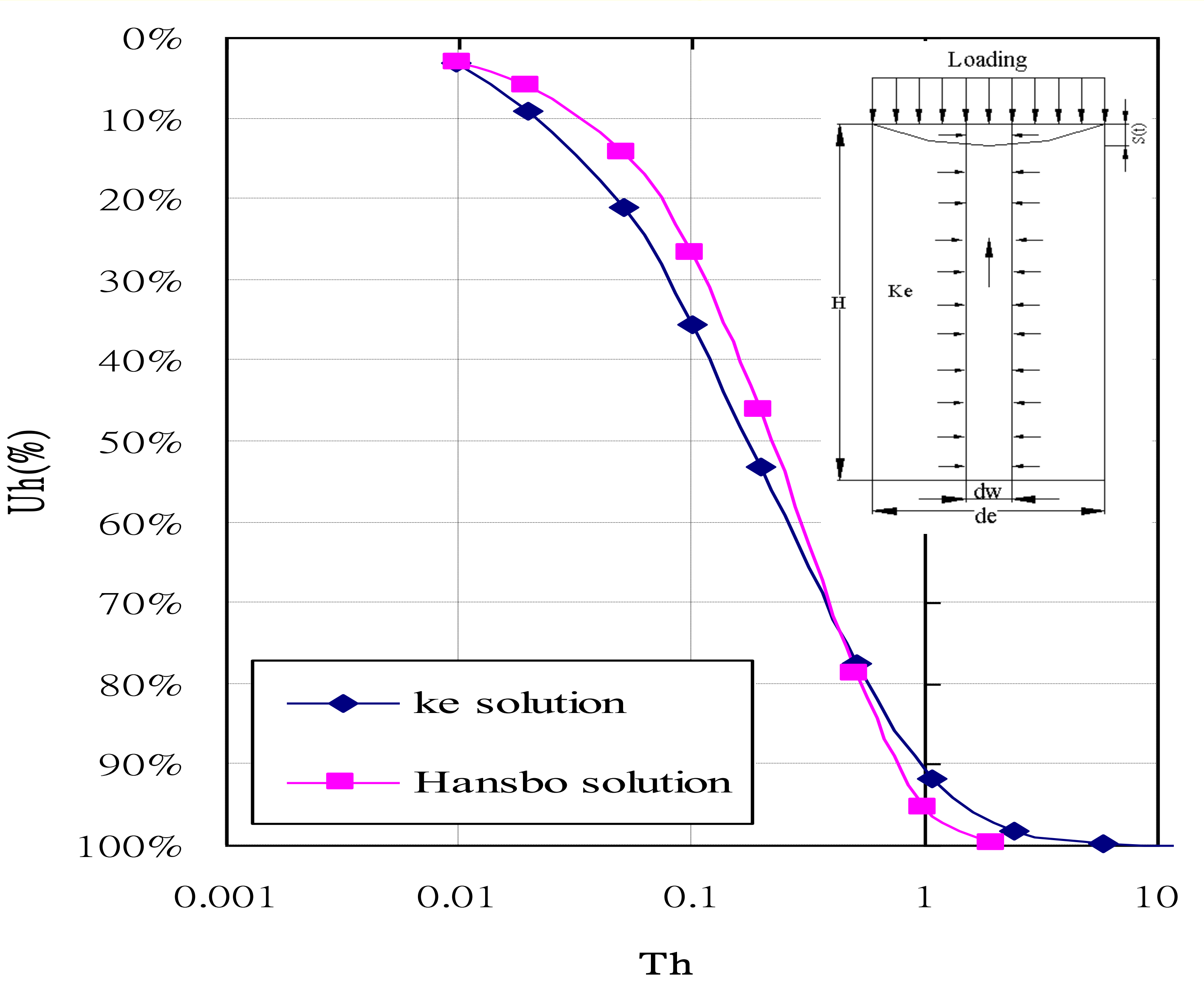
Non-dimensional coefficient of well resistance $L = \dfrac{8 k_h l_d^2}{\pi\, q_w}$

Constraint modulus $M = \dfrac{E(1-\nu)}{(1+\nu)(1-2\nu)}$

PVD Drainage Parameters for Unit Cell (Hansbo's solution)

Drain length l_d (m)	10
Spacing ratio $n = d_e/d_w$	25
Smear ratio = d_s/d_w	5
d_w (m)	0.4
d_e (m)	10
d_s (m)	2
q_w (m^3/s)	5.1E-06
k_w (m/s)	4.058E-05

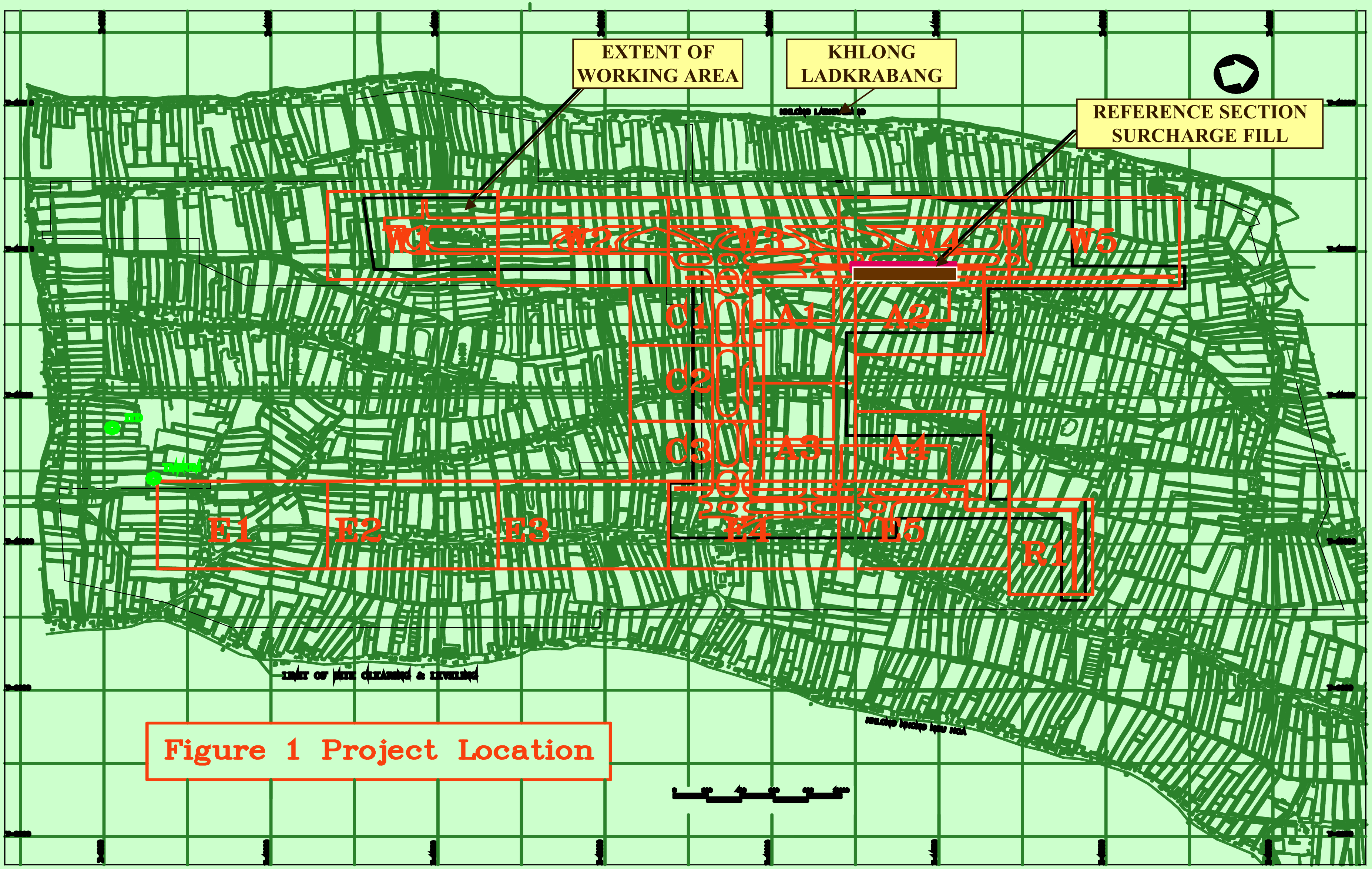
Comparisons between Numerical Results and Hansbo's Solutions of Horizontal Average Consolidation Rate



2-D NUMERICAL MODELING of *PVD* IMPROVED GROUND at REFERENCE SECTION

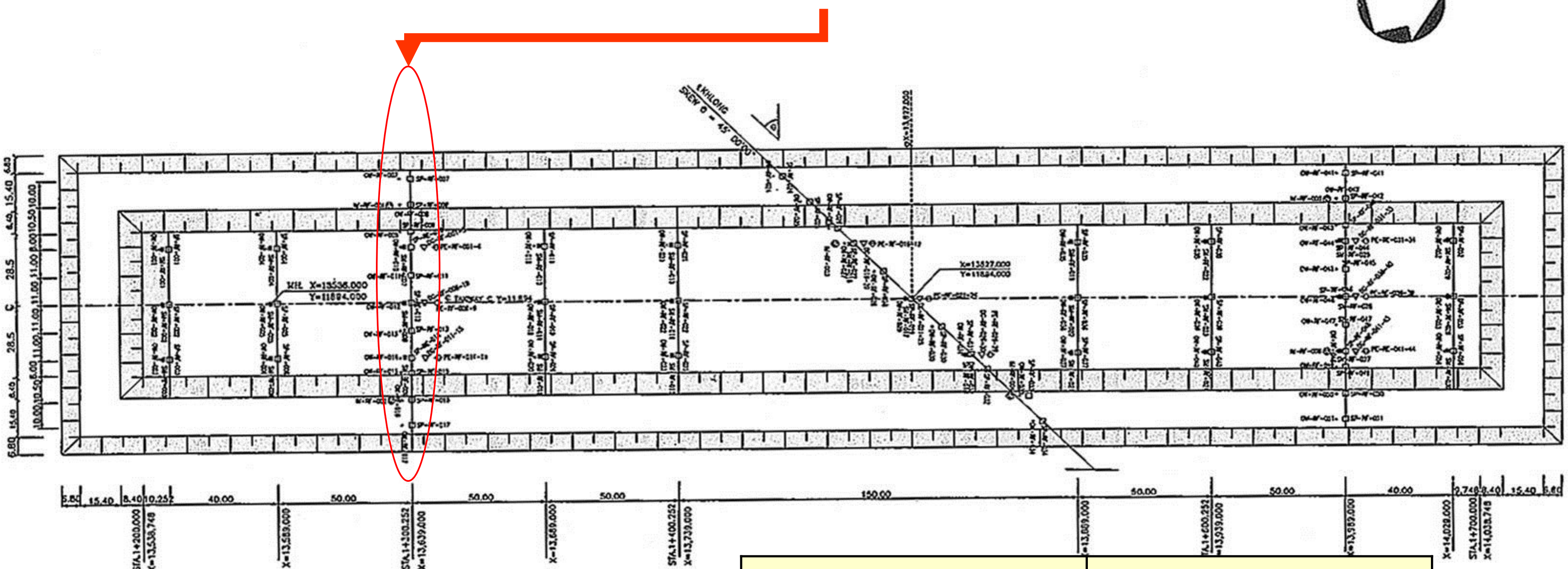
(Crisp Plane Flow Analysis)

Location of Reference Section



Location and Instrumentation at Reference Section

X=13639.0 , Y=11845.5-11942.5

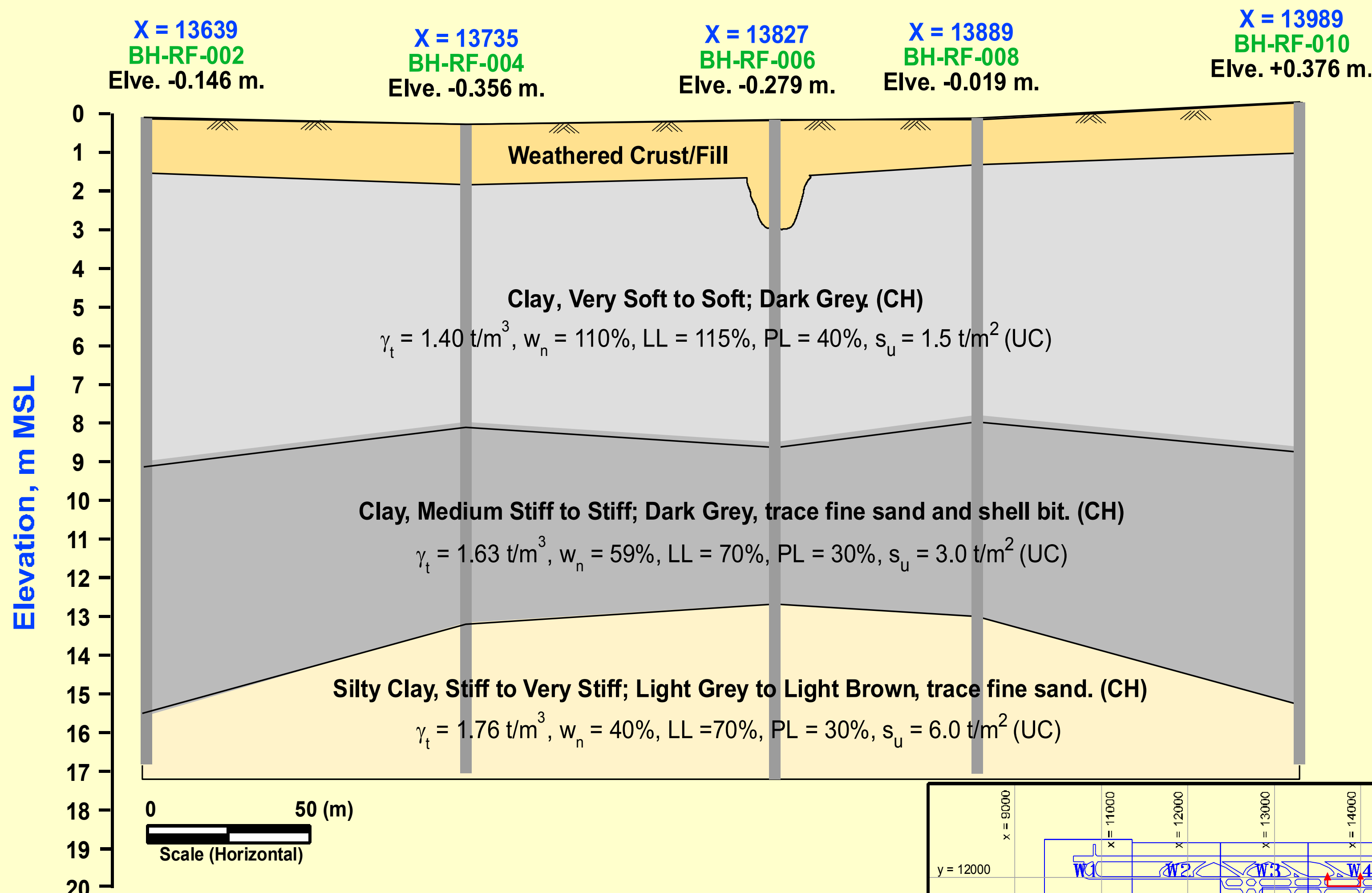


Legends

- ▽ DEEP SETTLEMENT GAUGE (DG)
- INCLINOMETER (IM)
- ELECTRICAL PIEZOMETER (PE)
- OBSERVATION WELL (OW)
- ☐ SURFACE SETTLEMENT PLATE (SP)
- SURFACE SETTLEMENT MONUMENT (SM)

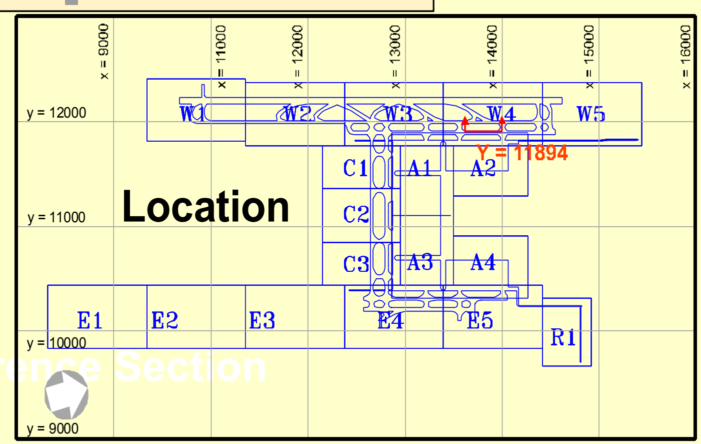
Type of Instrument	Quantity (No.)
Deep Settlement Gauge	45
Inclinometer	6
Electric Piezometer	36
Observation Well	54
Surface Settlement Plate	54

Subsoil Condition at Reference Section



Soil Description

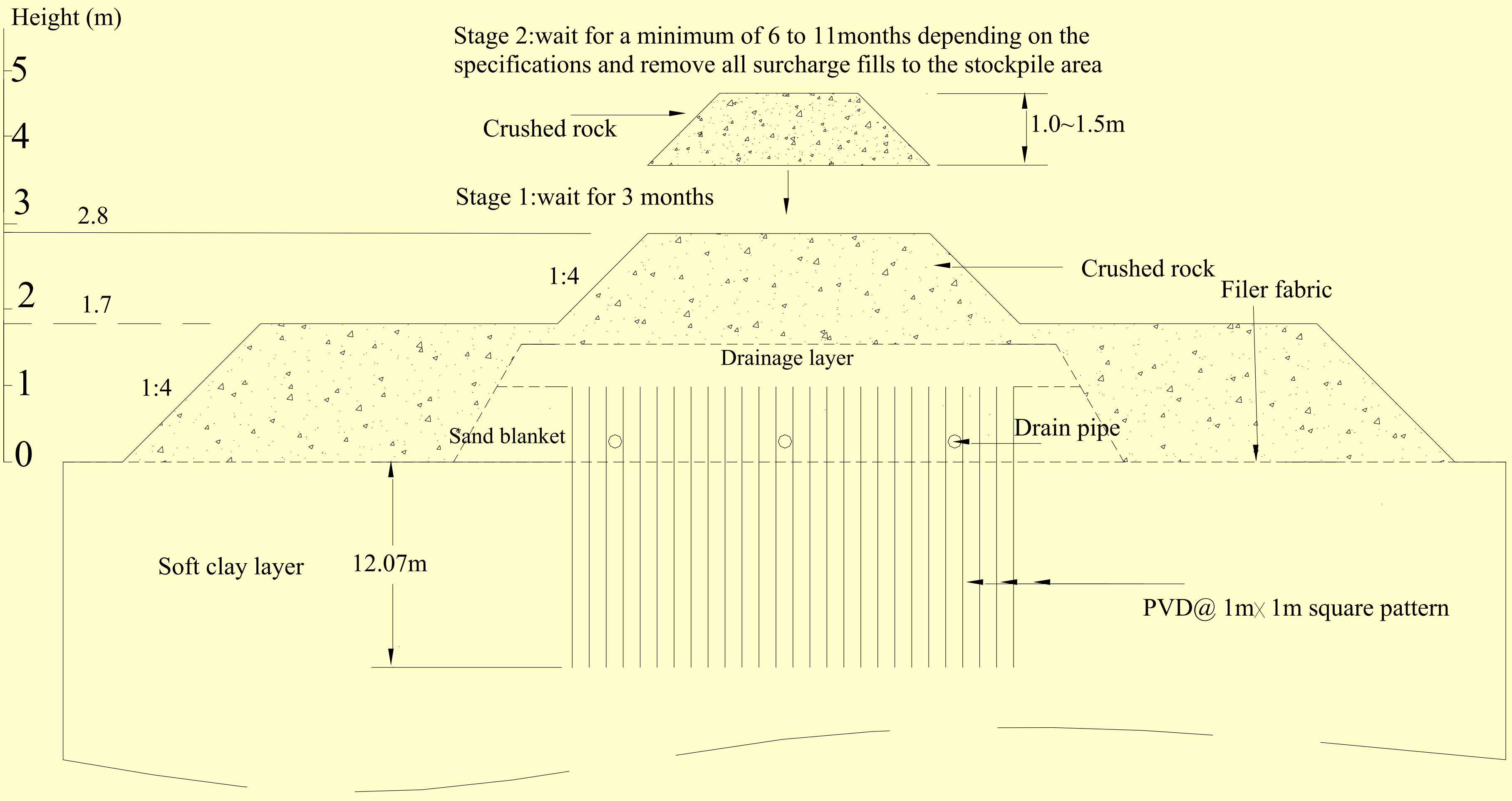
- Top Soil/Fill
- Very Soft to Soft Clay
- Medium Stiff to Stiff Clay
- Stiff to Very Stiff Silty Clay



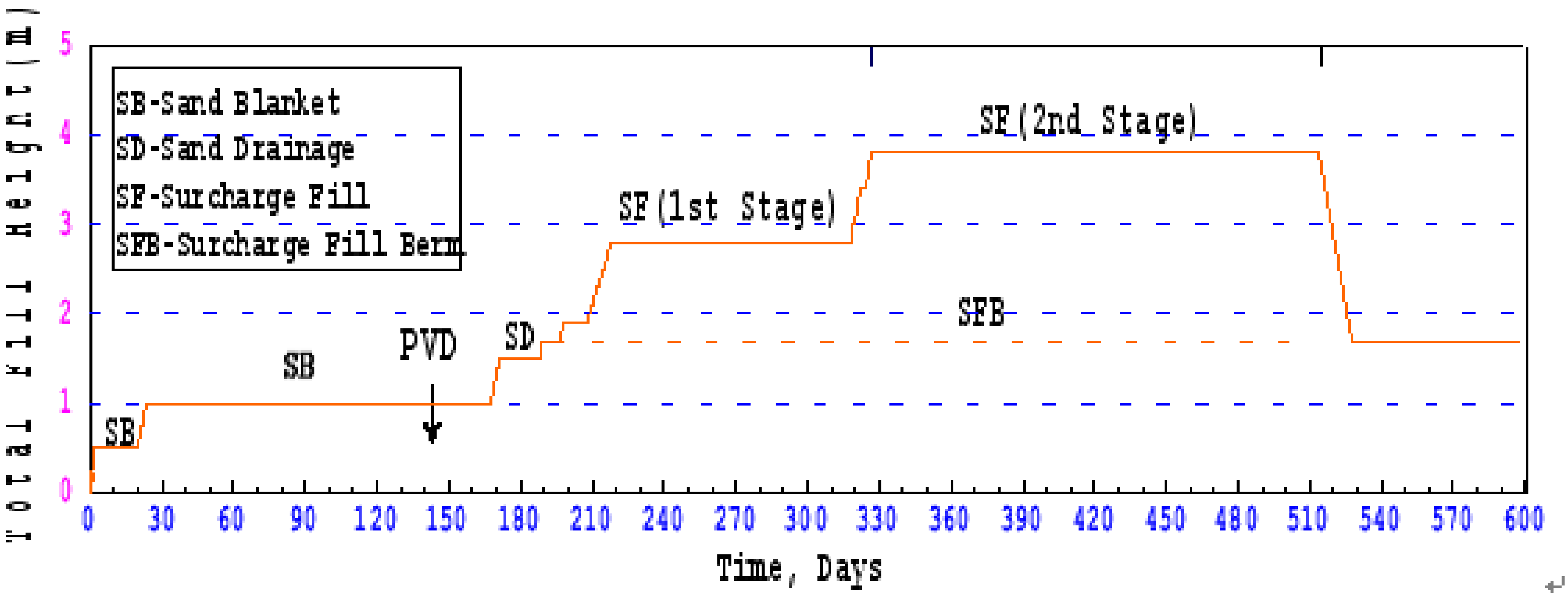
Properties of Subsoil at Reference Section

Soil Types	Depth (m)	γ_m (kN/m^3)	W_C (%)	LL (%)	PL (%)	S_u (kPa)	G_s
weathered crust	0~2	15.7	70	100	30	26.5	2.60
very soft to soft clay	2~10	13.7	110	115	40	19.6	2.60
medium stiff clay	10~15	16.0	59	70	30	34.3	2.61
stiff clay	15~20	17.3	40	70	30	78.5	2.61

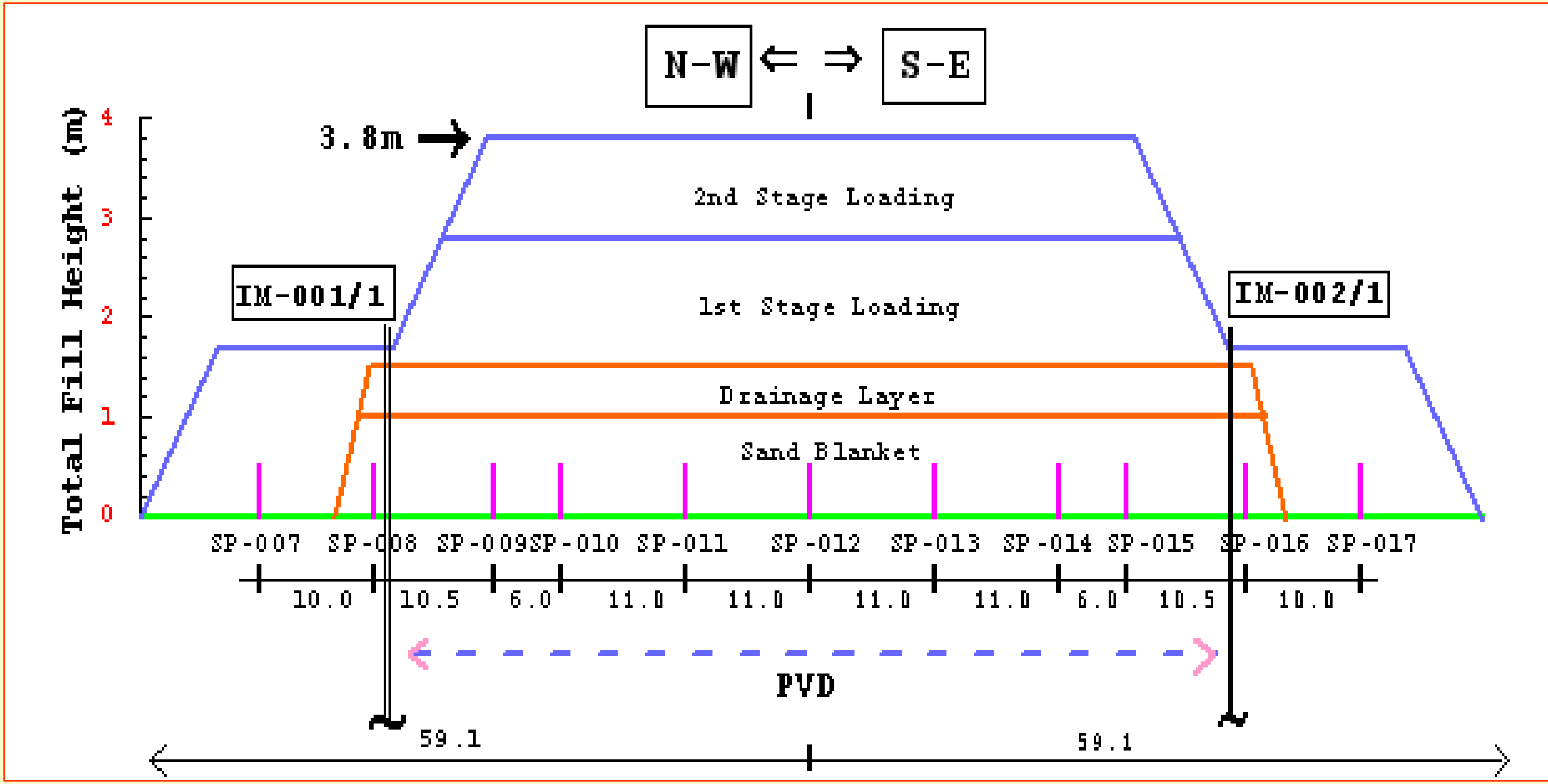
PVD Construction Sequences at Reference Section



Time History of *PVD* Construction at Reference Section



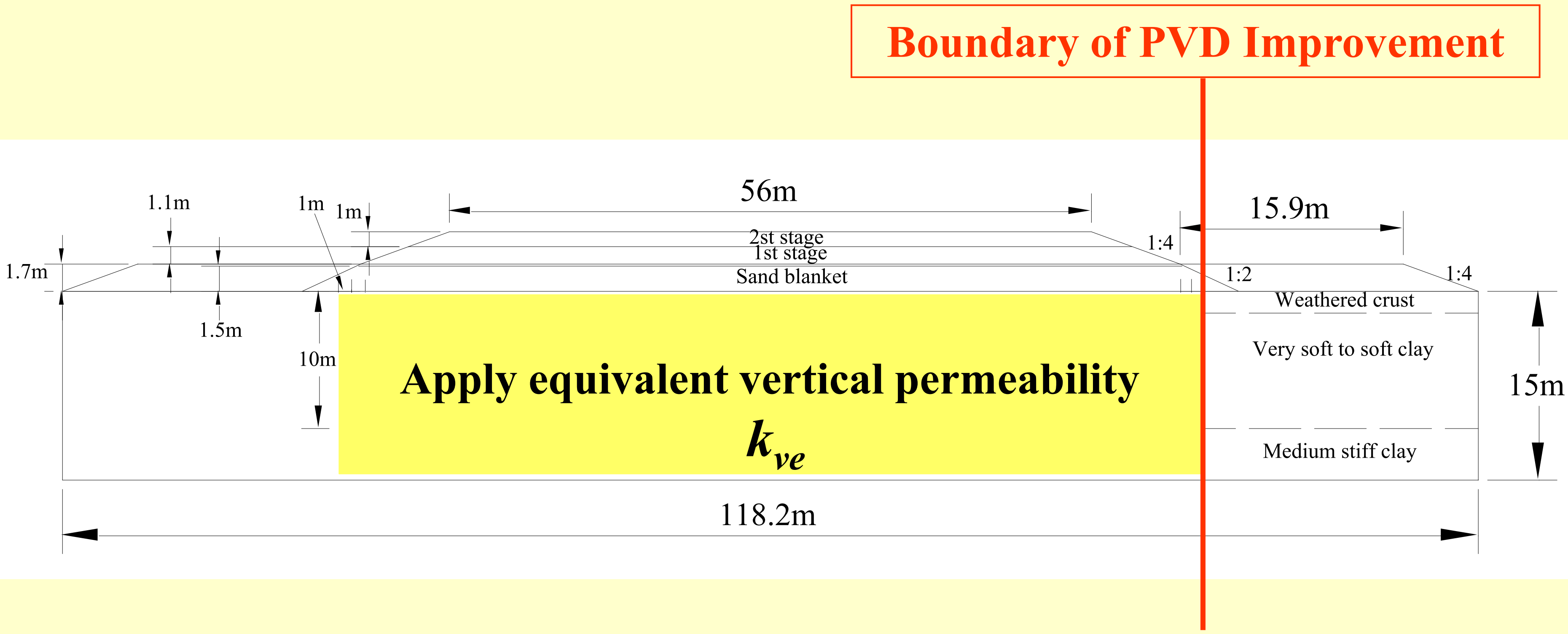
Instrumentation Layout at Reference Section



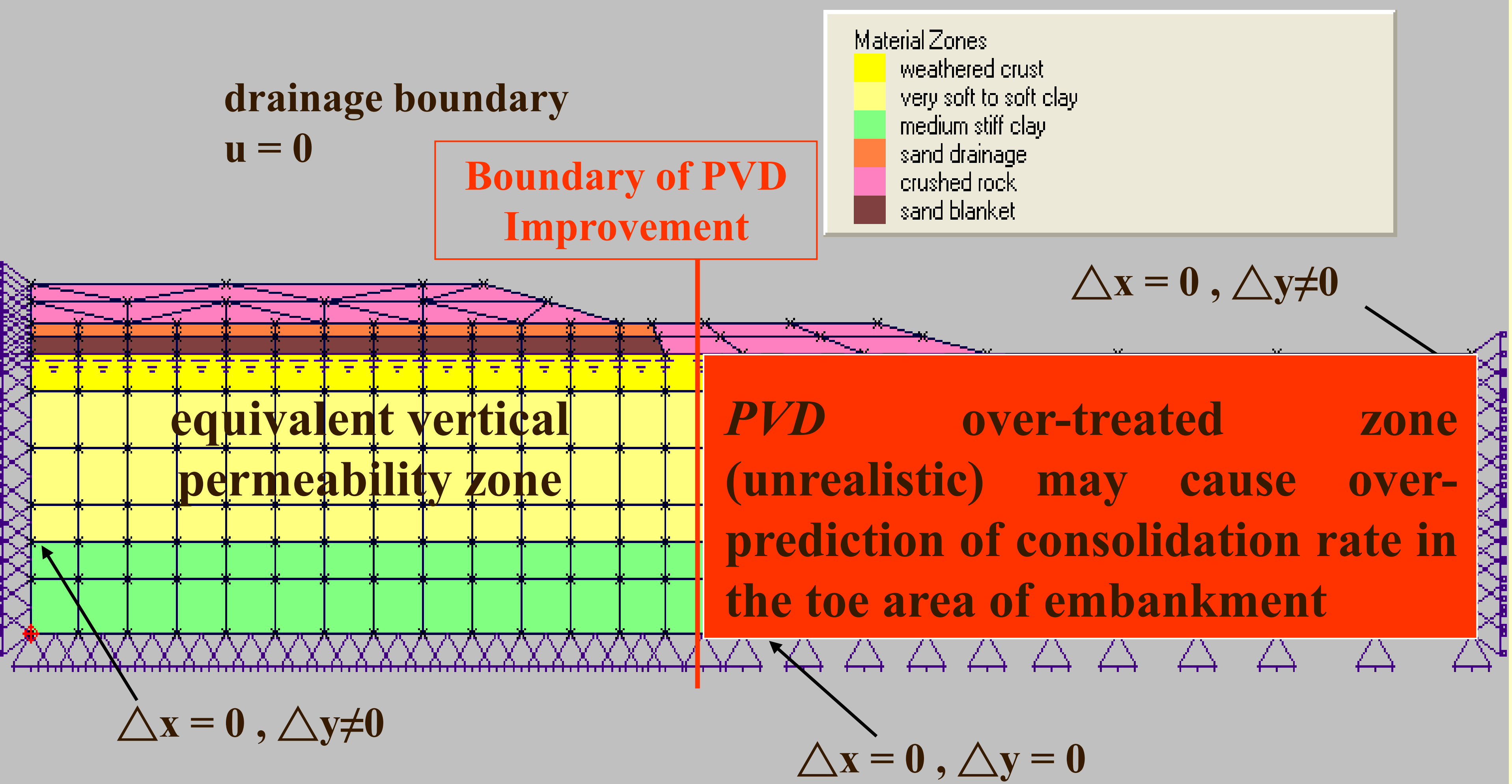
Deep Settlement Gauge at -2m and -12m along centerline

Electronic Piezometer at -2m, -5 and -8m along centerline

Computation Scheme for the Numerical Analysis of *PVD* Improved Ground



Finite Element Discretization of *PVD* Improved Ground



Input Soil Parameters for 2-D Numerical Analysis of Full-Scale PVD Improved Ground

Depth (m)	Soil Type	Model	γ_m (kN/m^3)	κ	λ	e_{cs}	*M*	ν
2~10	Very soft to soft clay	Modified Cam-Clay	13.73	0.13	0.71	5.27	0.9	0.31

(a) Soil Parameter for Modified Cam-Clay Model

Depth (m)	Soil Type	Model	γ_m (kN/m^3)	E_u =500Su (kN/m^2)	ν	*C*	ψ
0~2	Weathered crust	Mohr-Coulomb	15.7	1.32E4	0.30	30	28
10~15	Medium stiff clay	Mohr-Coulomb	16.0	1.71E4	0.30	20	30

(b) Soil Parameter for Mohr-Coulomb Model

Soil Model Parameter for Embankment Surcharge Fill

Fill Soil Type	Model	E (kPa)	ν	γ_m (kN/m^3)
Sand Blanket	Linear Elastic	10000	0.3	18.4
Sand Drainage	Linear Elastic	10000	0.3	18.3
Crushed Rock	Linear Elastic	60000	0.3	21

In-Situ Stress Condition

p'_c

Depth (m)	σ'_h (kN/m^2)	σ'_v (kN/m^2)	u_s PWP (kN/m^2)	P'_c (kN/m^2)
2	10.71	16.68	14.72	41.47
5	19.63	28.45	44.145	42.5
8	27.7	40.21	73.575	60.02
10	33.15	48.045	93.195	71.7
12	55.86	80.045	93.195	118.62
15	89.25	128.045	93.195	189.77

Variation of the Permeability of Soil with Depth

Depth (m)	Soil Type	k_h / k_v	k_h (m/s)	k_v (m/s)	$(k_h / k_s)_l$	C_f	$(k_h / k_s)_f$	k_s (m/s)	k_{ve} (m/s)
0~2	Weather-ed crust	1.63	2.46E-9	1.51E-9	1.75	4	7	3.51E-10	4.72E-8
2~10	Very soft to soft clay	1.63	7.98E-9	4.90E-9	1.75	4	7	1.14E-9	1.53E-7
10~15	Medium stiff clay	1.63	2.50E-9	1.53E-9	1.75	4	7	3.57E-10	1.53E-9

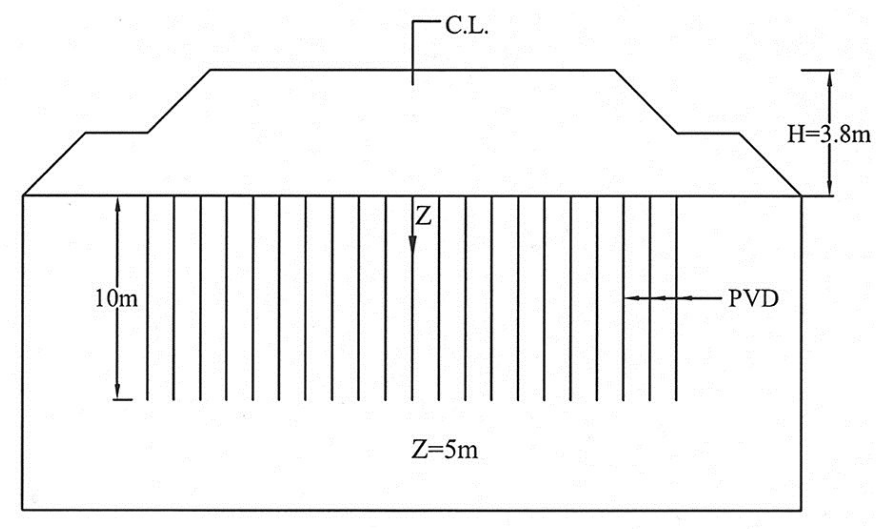
- Subscripts "l" and "f" represent laboratory and field

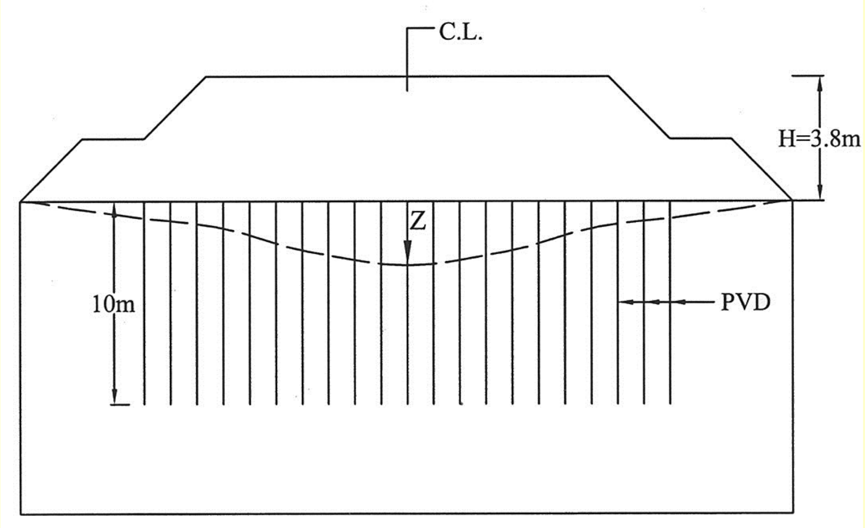
$$\left(\frac{k_h}{k_s}\right)_{field} = C_f \left(\frac{k_h}{k_s}\right)_{laboratory}$$

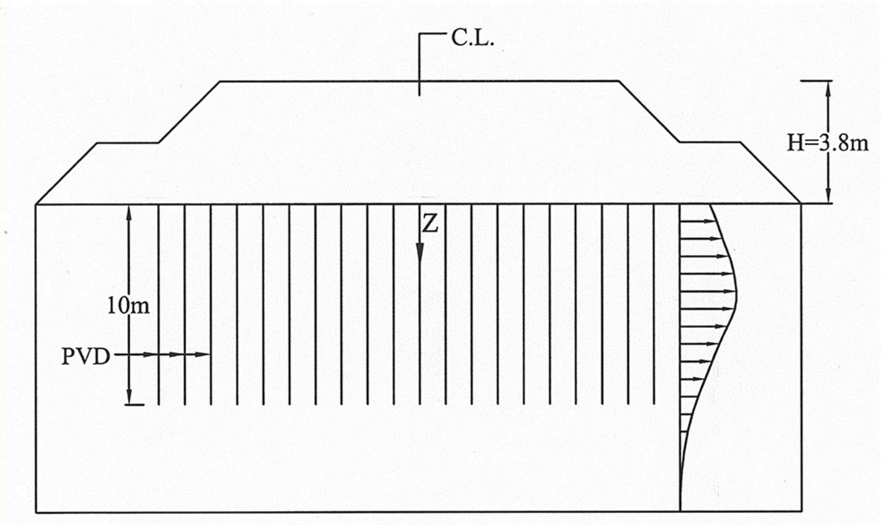
PVD Geometry and Design Parameter

Configuration of *PVD* Installation:	**Square Pattern**
Spacing of *PVD* Installation: $S \times S$	**1 m × 1 m**
Drain Length of *PVD*: l_d	**10 m**
Cross Section of *PVD* : $a \times b$	**4 mm × 98 mm**
Mandrel Dimension: $l \times w$	**125 mm × 45 mm**
Equivalent Diameter of the Mandrel: d_m (= 2 r_m)	**84.6 mm**
Diameter of Smeared Zone: d_s (= 2 r_s and r_s =2 r_m= d_m)	**169.2 mm**
Diameter of Influence Zone of *PVD* : d_e=2 r_e =1.13S	**1130 mm**
Equivalent Diameter of *PVD*: d_w=(a+b)/2= 2 r_w	**51 mm**
Spacing Ratio of *PVD*: $n = d_e / d_w = 1.13S / d_w$	**22.2**
Disturbance Ratio of Subsoil: d_s / d_w	**3.3**
Discharge Capacity of *PVD* (Laboratory): q_w=k_w iA	**940.83 m^3/yr**

RESULTS AND DISCUSSIONS

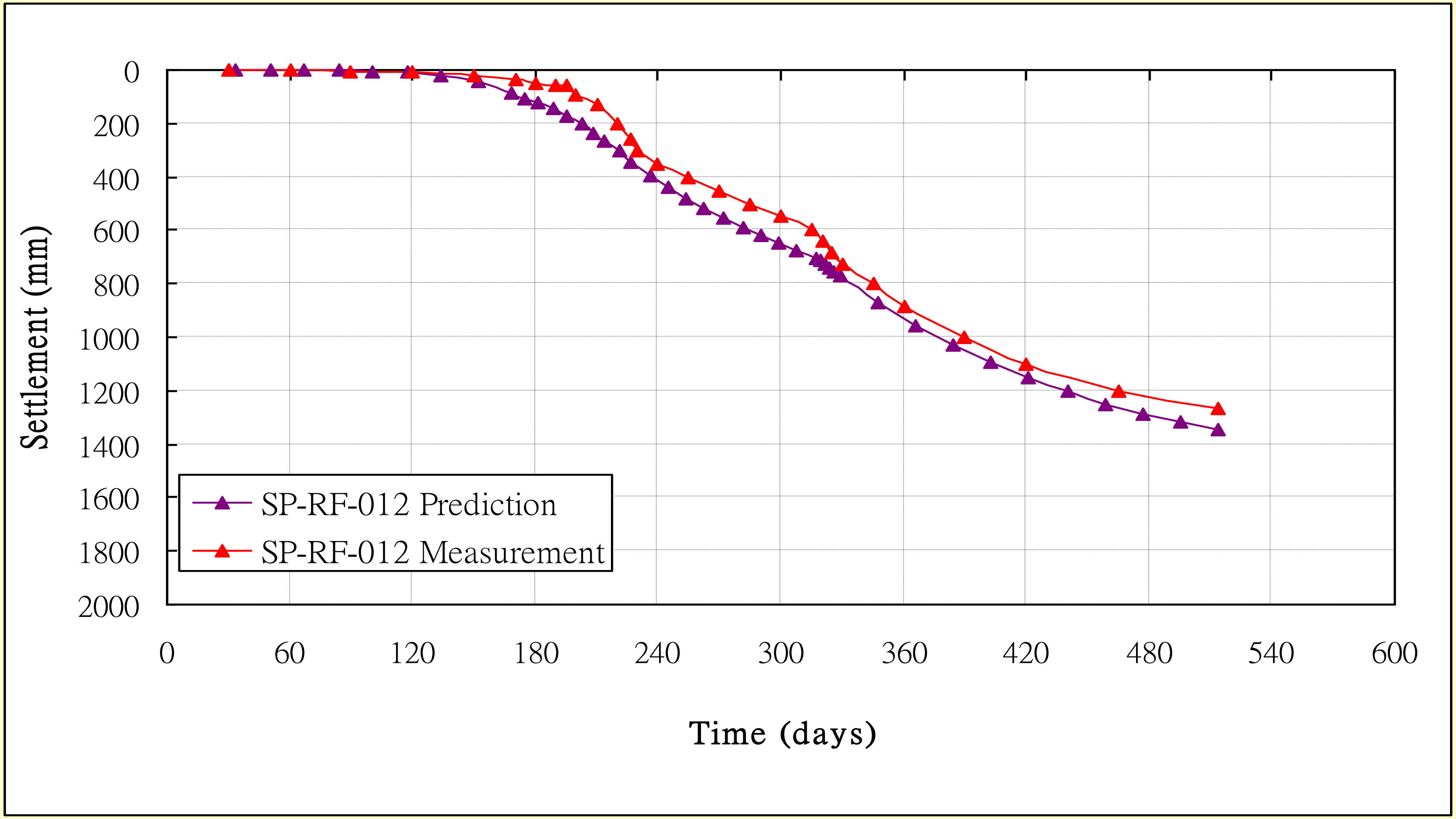


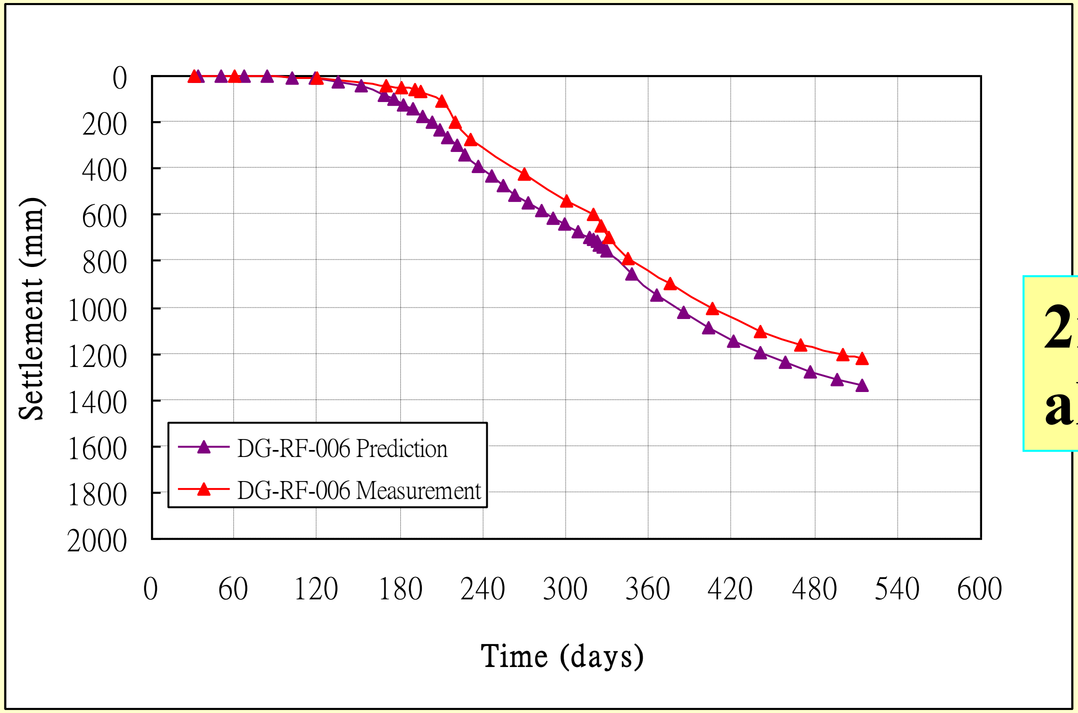




Comparison of Settlement at Various Depths along Centerline between Prediction and Measurement

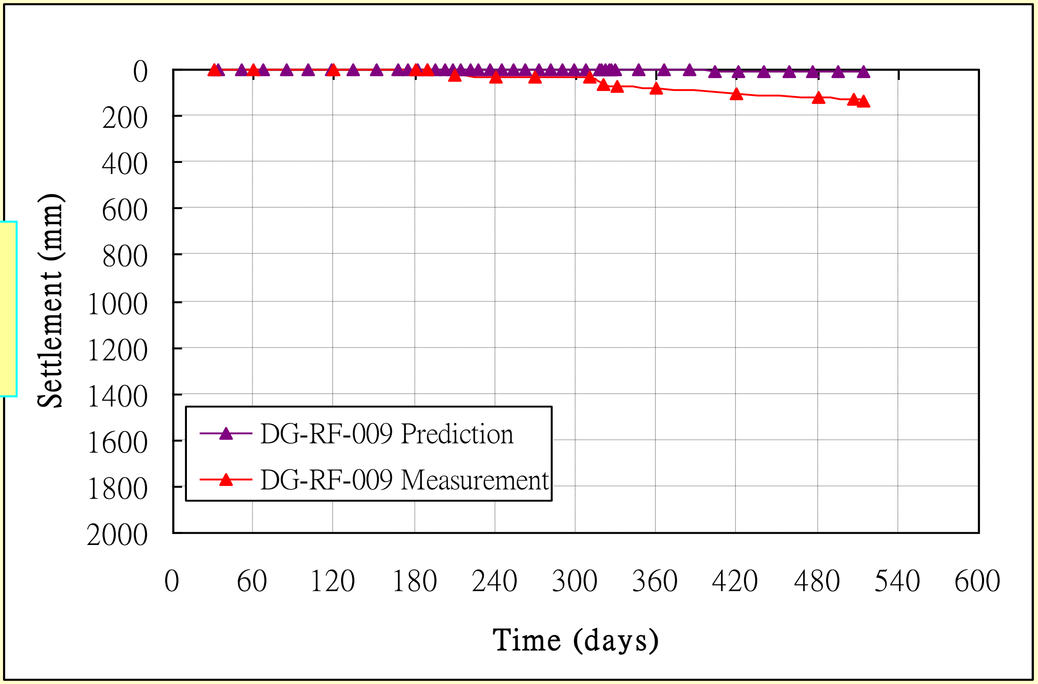
Surface Settlement along Centerline (Z=0m)





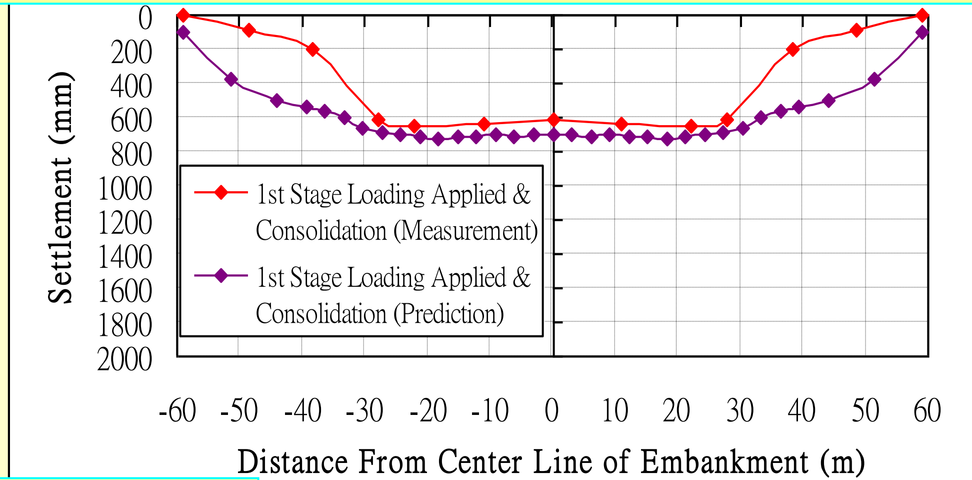
2m below Ground Surface along Centerline (Z=-2m)

12m below Ground Surface along Centerline (Z=-12m)

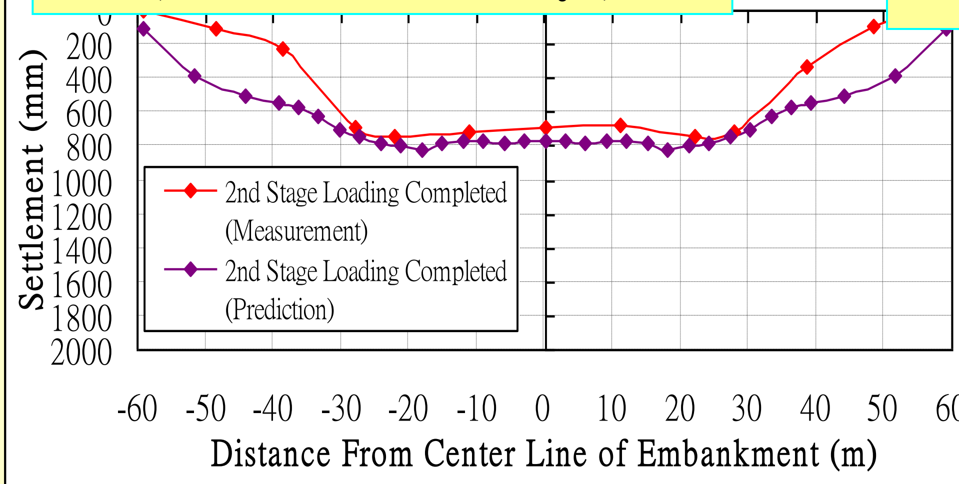


Comparison of Ground Settlement Profile between Prediction and Measurement

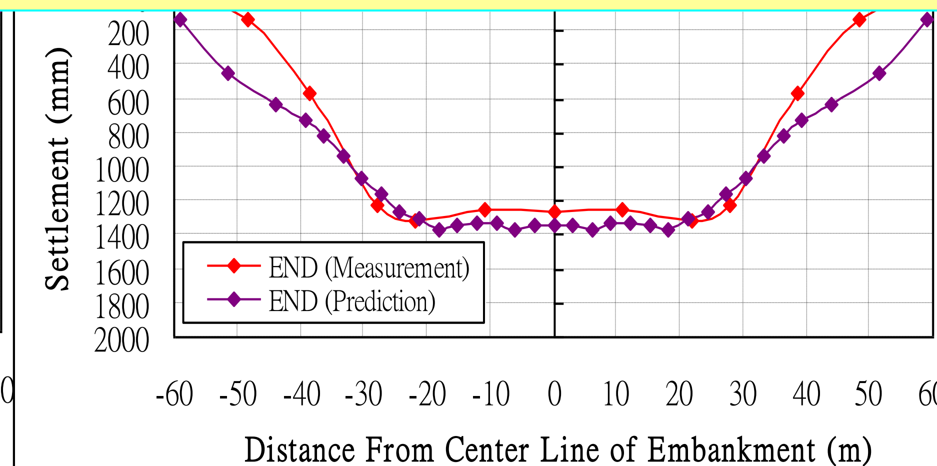
3 Months after 1st Stage Loading Applied (H=2.8m, t=215~305days)



2nd Stage Loading Complete (H=3.8m, t=325days)

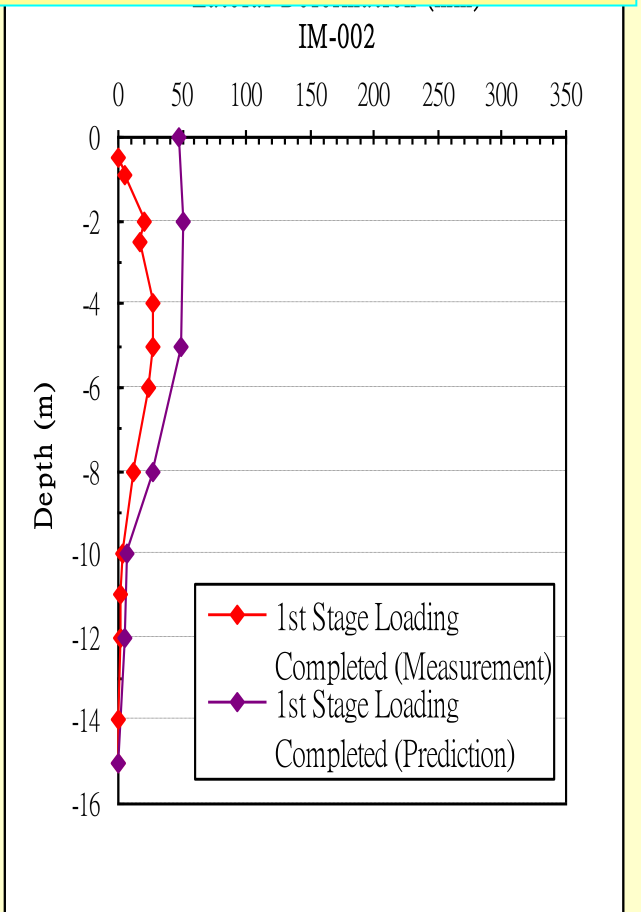


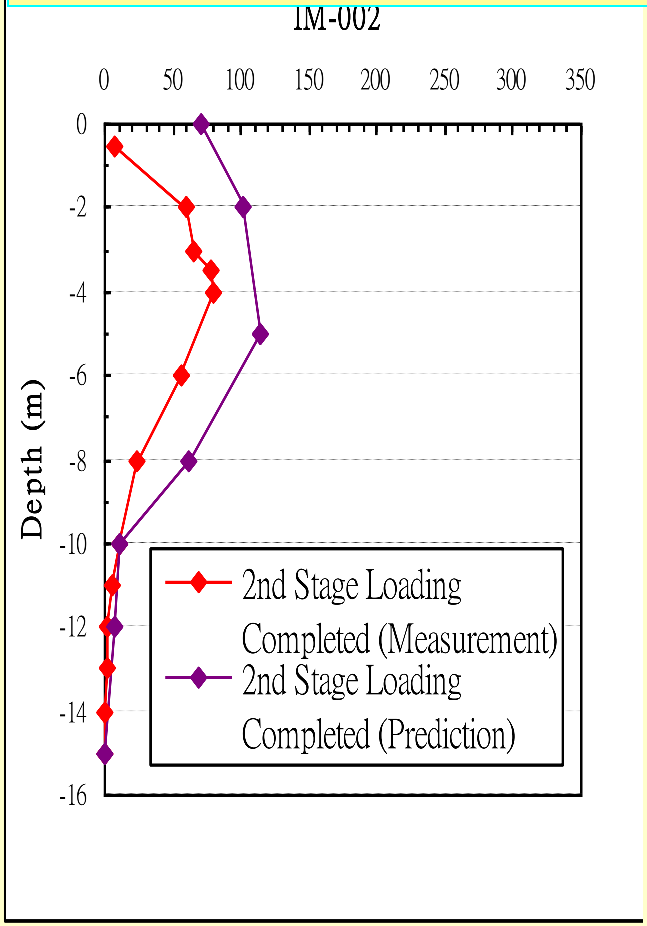
6 Months after 2nd Stage Loading Applied (H=3.8m, t=505days)

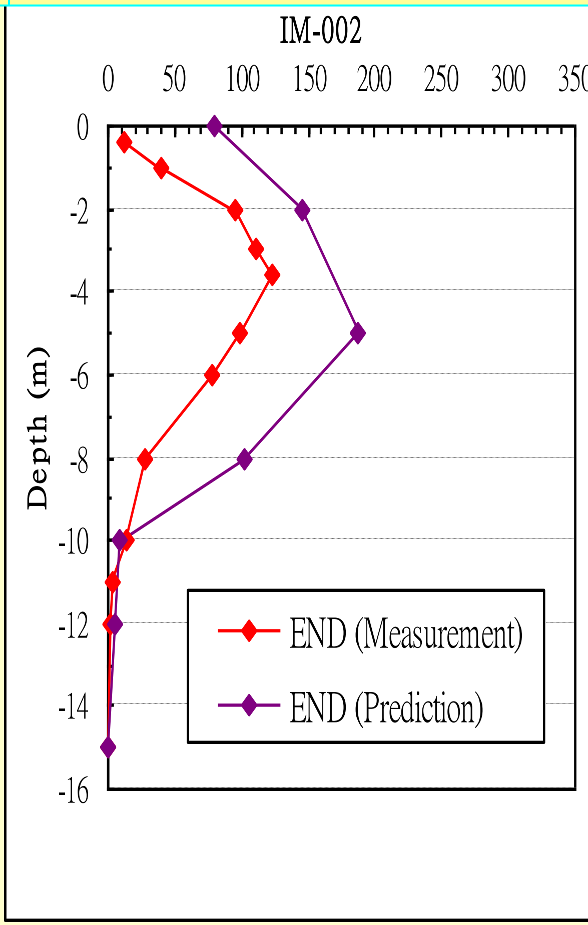


Comparison of **Lateral Movement Profiles** between Prediction and Measurement of Inclinometer *IM-002*

1st Stage Loading Completed (H=2.8m, t=215days)	2nd Stage Loading Completed (H=3.8m, t=325days)	At the End of Measurement (H=3.8m, t=514days)

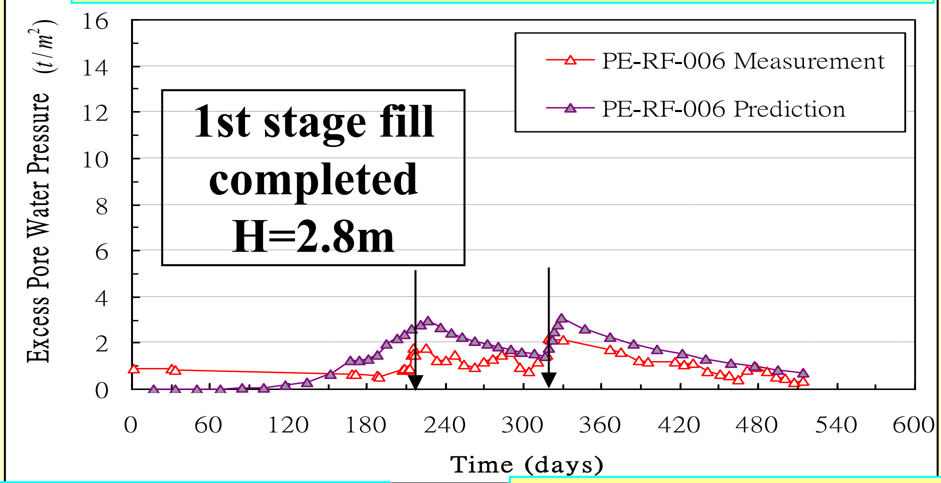




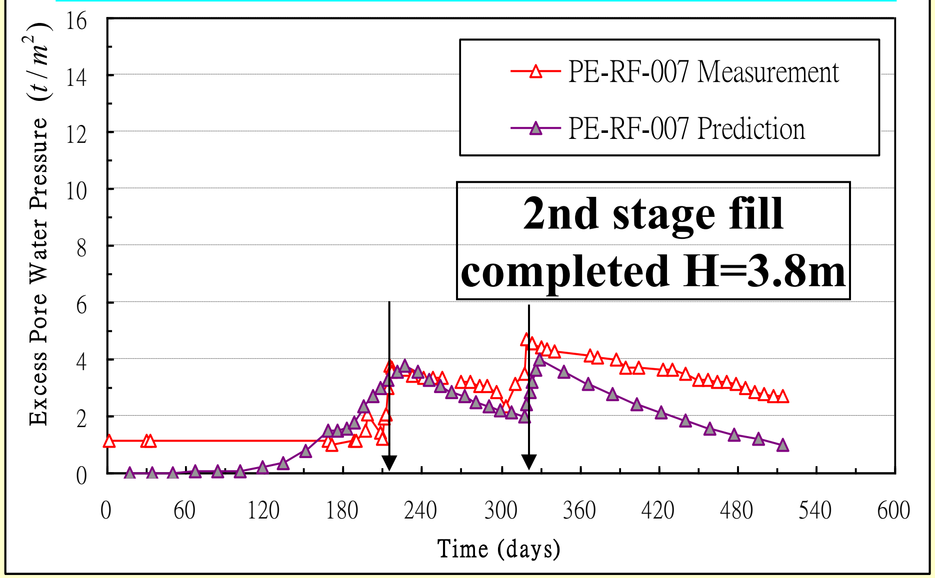


Comparison of Excess Pore Pressure at Various Depths along Center Line between Prediction and Measurement

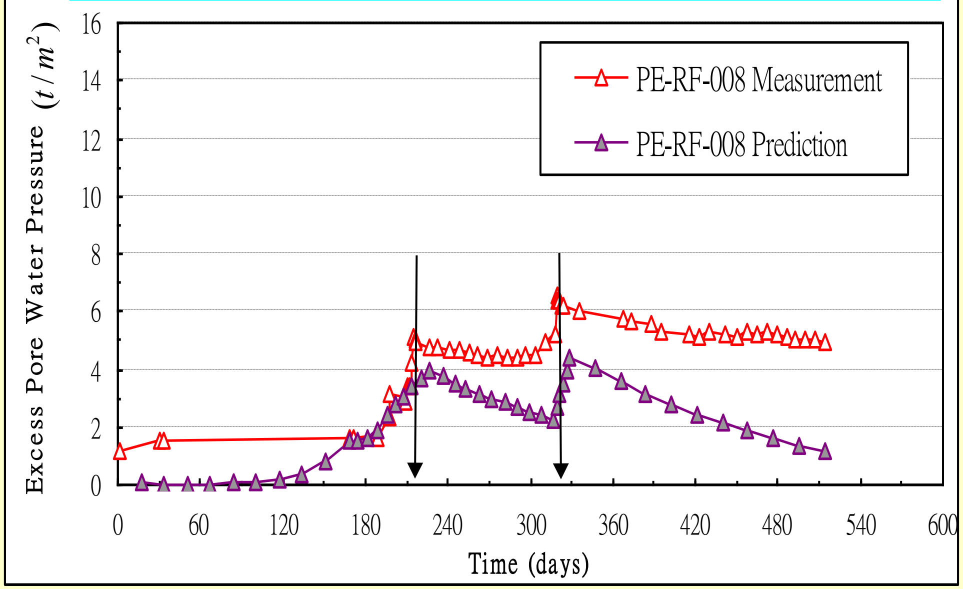
2m below Ground Surface (Z=-2m)



5m below Ground Surface (Z=-5m)



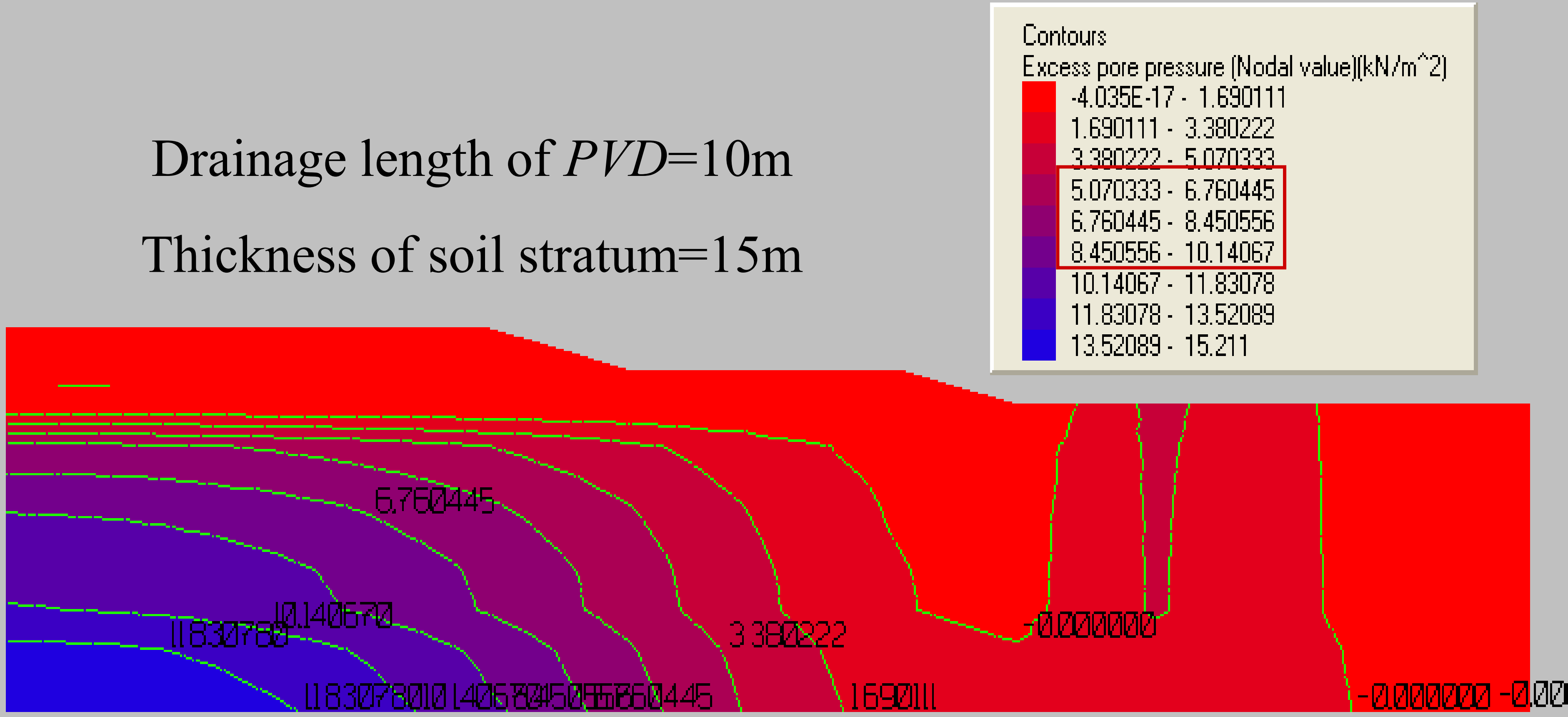
8m below Ground Surface (Z=-8m)



Excess Pore Pressure Contours of PVD Improved Ground at the End of Measurement (t = 514days)

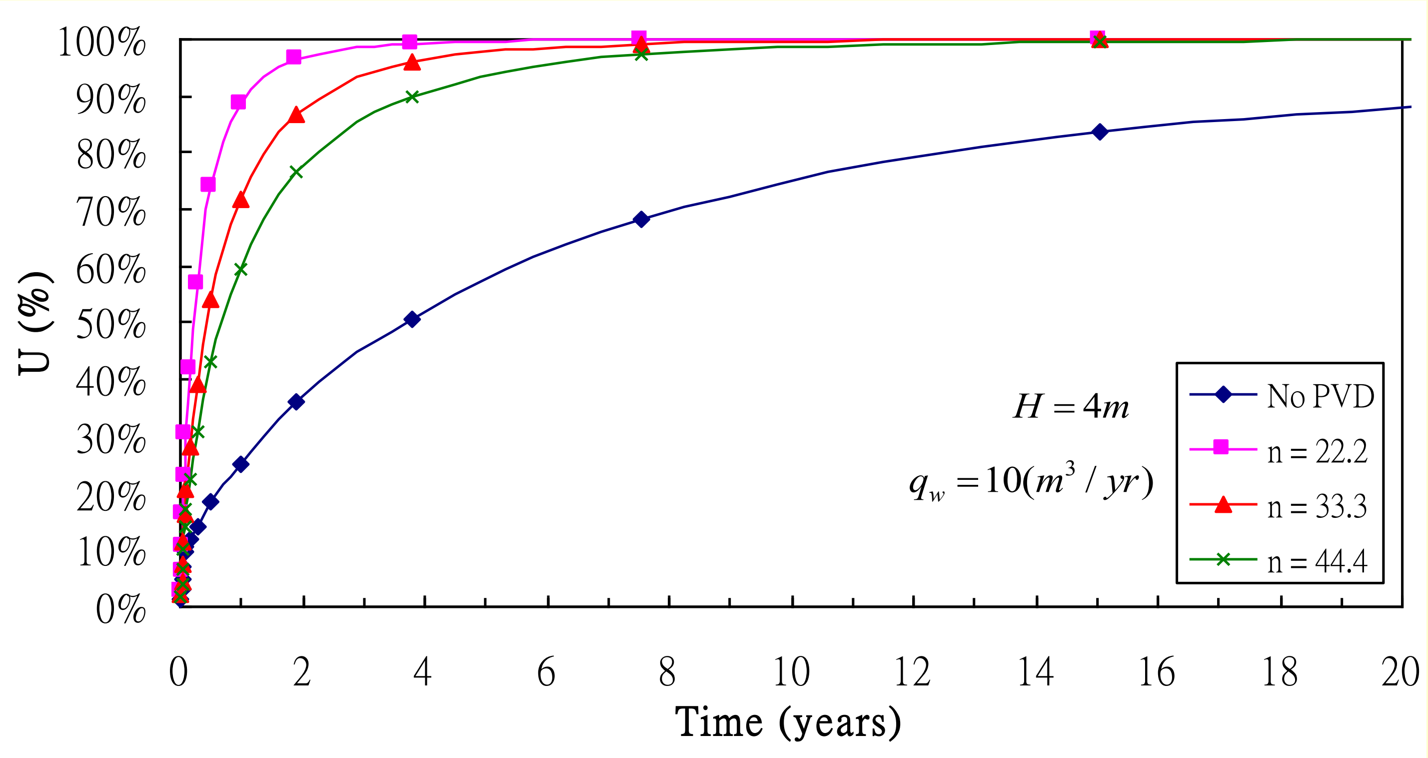
Drainage length of *PVD*=10m

Thickness of soil stratum=15m



PARAMETERIC STUDIES

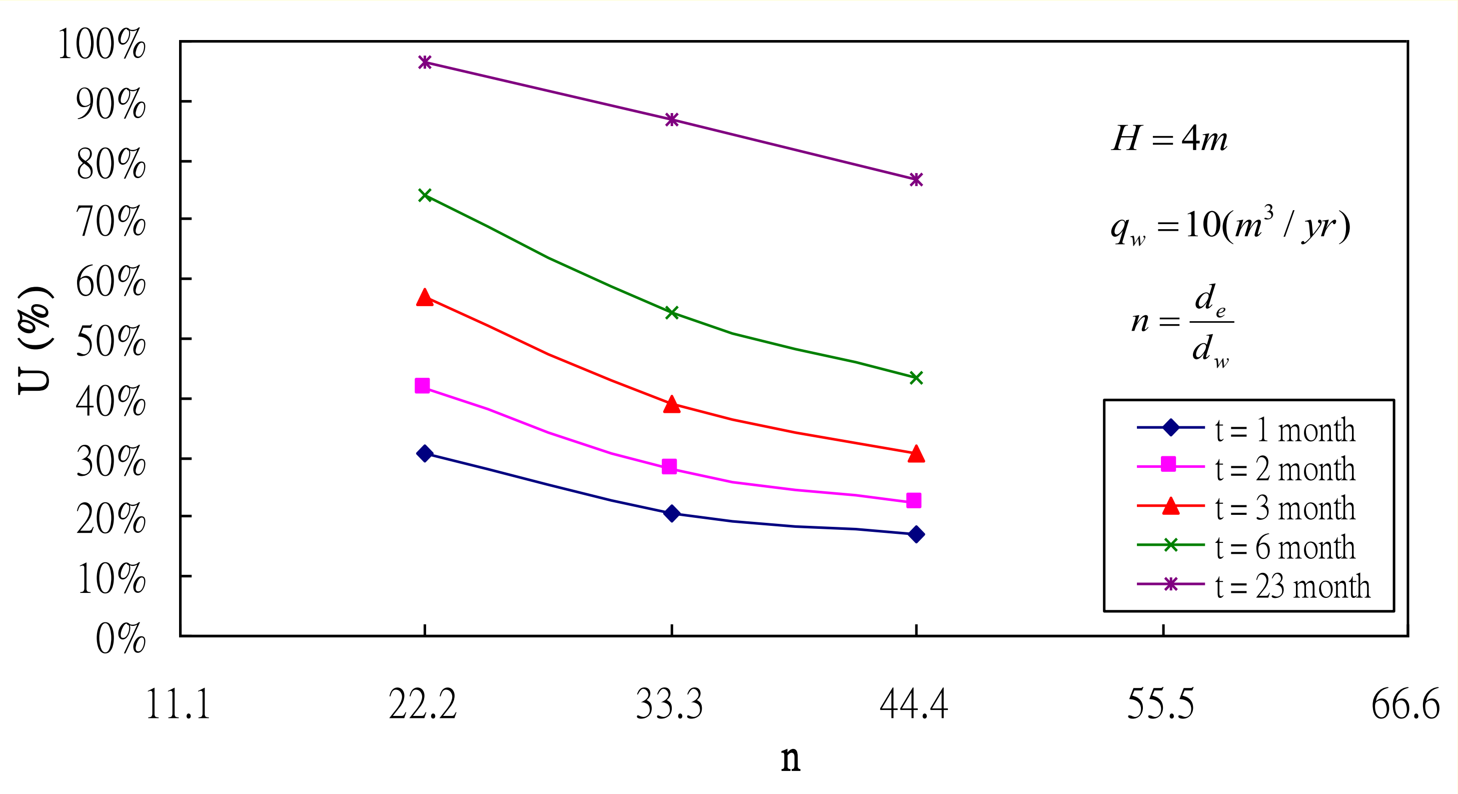
Consolidation Rate of *PVD* Improved Ground for Various Installations Spacing S=1m, 1.5m , 2m, No *PVD*



H=4m , q_w=10(m^3/yr)

※ $n=d_e/d_w=1.13S/d_w$

Consolidation Rate of *PVD* Improved Ground for Various Installation Spacing at t=1mon, 2mon, 3mon, 6mon and 23mon



***H*=4*m* , q_w=10(m^3/yr)**

H=1 m ; $S_{tr}(\infty)$=380~389 mm ; $[S_{tr}(\infty)]_{average}$=384 mm										
q_w (m^3/year)		10			100			1000		
n (= d_e / d_w)		22.2	33.3	44.4	22.2	33.3	44.4	22.2	33.3	44.4
U (%)	t=6 month	74.4	50.8	36.8	77.4	55.1	40.5	78.0	55.5	41.0
	t=23 month	97.0	86.9	74.8	97.7	89.5	78.6	97.9	89.7	79.0
H=2 m ; $S_{tr}(\infty)$=876~850 mm ; $[S_{tr}(\infty)]_{average}$=864 mm										
q_w (m^3/year)		10			100			1000		
n (= d_e / d_w)		22.2	33.3	44.4	22.2	33.3	44.4	22.2	33.3	44.4
U (%)	t=6 month	68.5	48.4	36.4	72.6	51.5	38.0	73.3	52.1	38.6
	t=23 month	94.9	83.2	71.3	96.5	86.0	73.9	96.7	86.4	74.5
H=3 m ; $S_{tr}(\infty)$=1254~1298 mm ; $[S_{tr}(\infty)]_{average}$=1279 mm										
q_w (m^3/year)		10			100			1000		
n (= d_e / d_w)		22.2	33.3	44.4	22.2	33.3	44.4	22.2	33.3	44.4
U (%)	t=6 month	71.3	51.4	38.8	76.0	53.8	42.0	76.4	55.0	42.5
	t=23 month	95.8	85.1	73.7	97.2	87.7	77.3	97.3	88.5	77.8
H=4 m ; $S_{tr}(\infty)$=1441~1489 mm ; $[S_{tr}(\infty)]_{average}$=1473 mm										
q_w (m^3/year)		10			100			1000		
n (= d_e / d_w)		22.2	33.3	44.4	22.2	33.3	44.4	22.2	33.3	44.4
U (%)	t=6 month	74.2	54.4	43.2	78.6	57.8	45.8	79.2	59.1	46.2
	t=23 month	96.5	87.0	76.6	97.7	89.5	79.8	97.8	90.2	80.2
U (%)=[$S_{tr}(t)/S_{tr}(\infty)$]×100% and $S_{tr}(t)$=[U (%)×$S_{tr}(\infty)$]/100%										

Conclusions

- The spacing influence factor, n (= de / dw), plays a very crucial role in *PVD* design while the effect of discharge capacity, q_w, on consolidation rate is not as apparent as expected in numerical analysis.

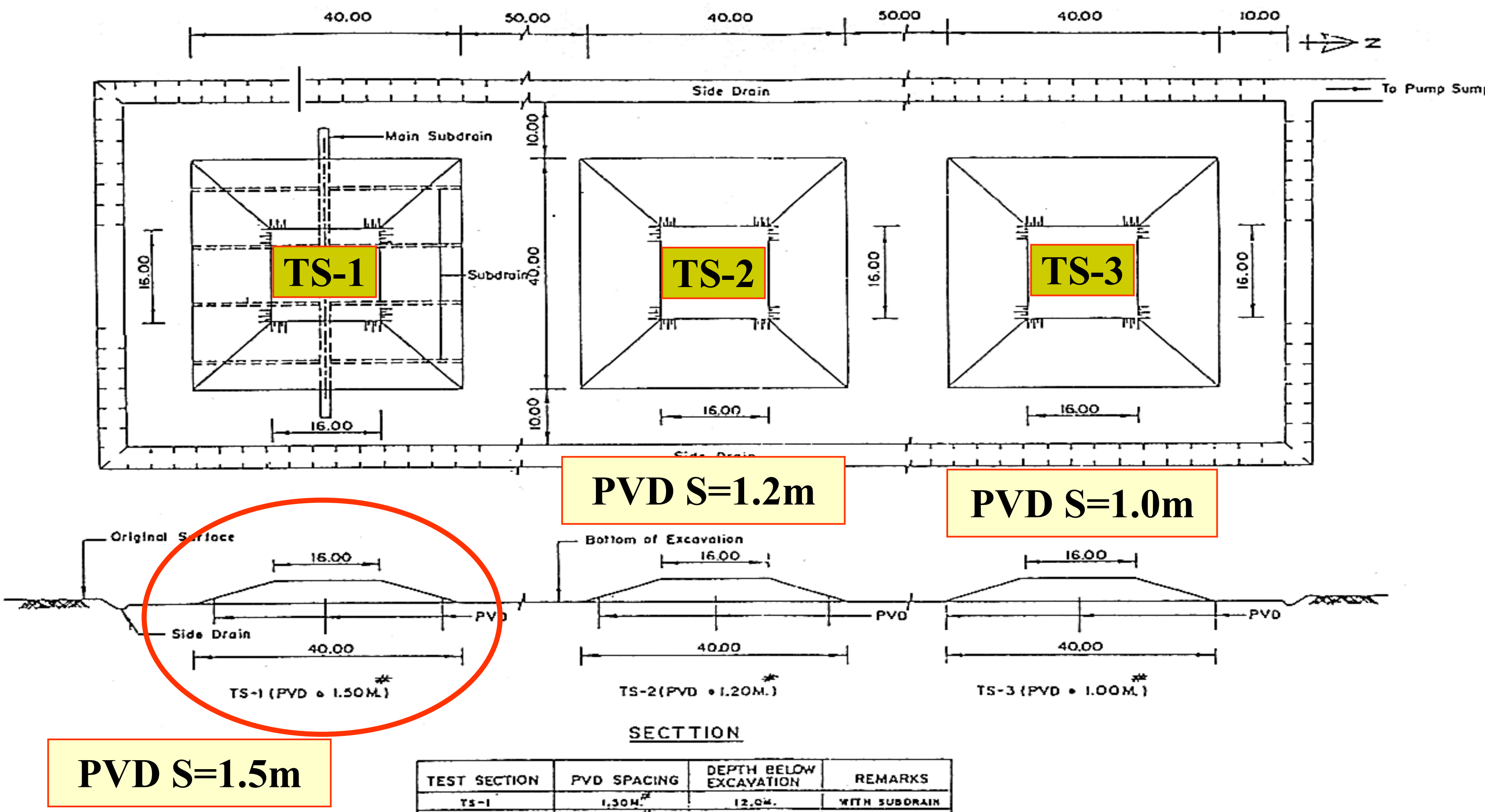
- For typical Bangkok subsoil, a *PVD* improved ground with 1 m × 1 m square configuration (or $n \approx 22.2$) and 10 m drainage length, the elapsed time required to achieve high degree of consolidation (for U>90%) is suggested not less than 1 year under embankment surcharge fill of 4 m height.

THREE DIMENSIONAL NUMERICAL MODELING OF *PVD* IMPROVED GROUND

(Flac^{3D} Analysis)

SUBSOIL CONDITIONS OF TESTING EMBANKMENT AT *Nong Ngu Hao* (*NNH*) FIELD SITE

Testing Embankments with Different *PVD* Configuration

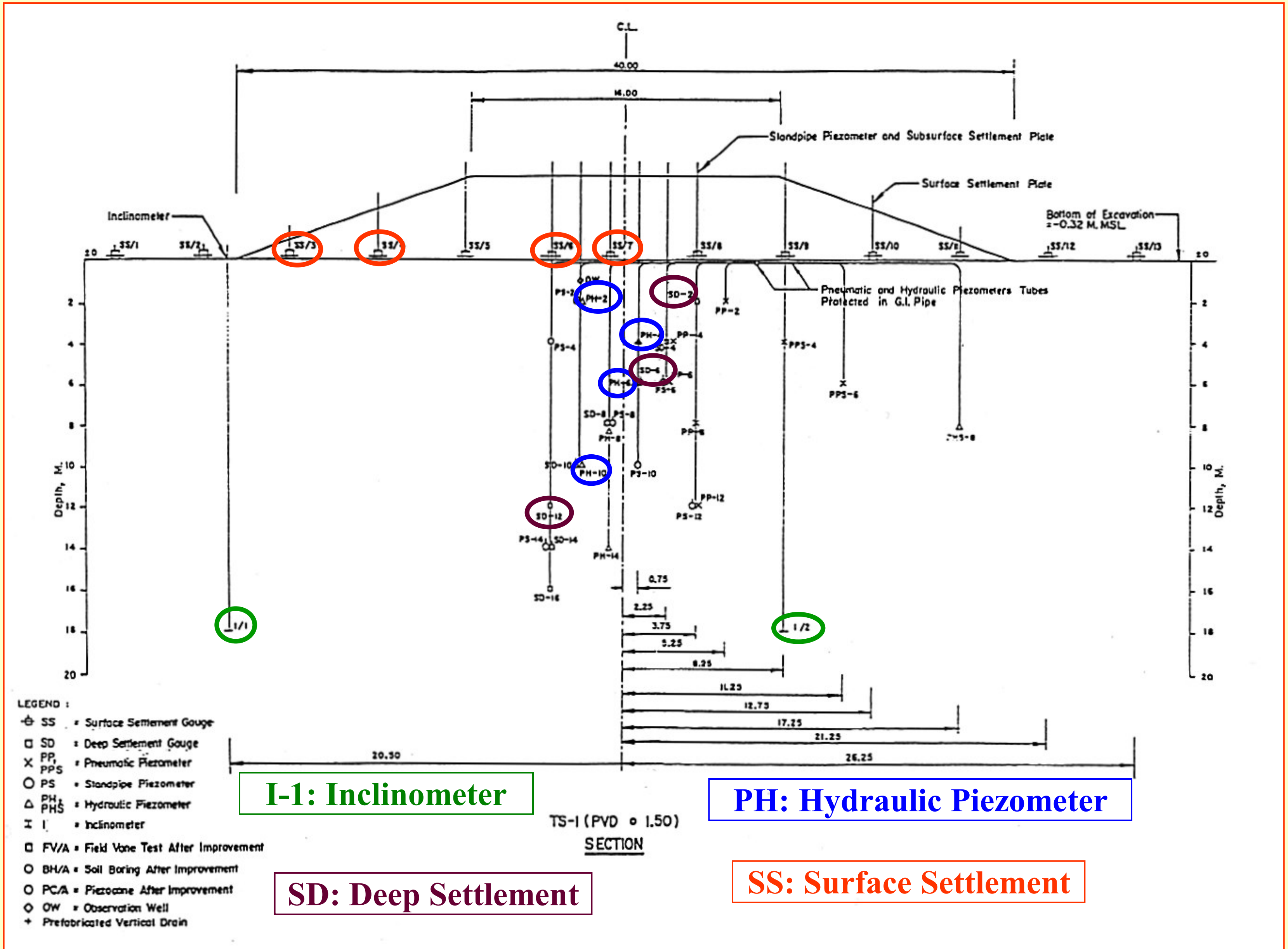


TEST SECTION	PVD SPACING	DEPTH BELOW EXCAVATION	REMARKS
TS-1	1.30M.#	12.0M.	WITH SUBDRAIN
TS-2	1.20M.#	12.0M.	
TS-3	1.00M.#	12.0M.	

Generalized Soil Profile for Testing Embankment

Depth (*m*)	**Soil type**
0~2	Weathered Clay
2~8.5	Very Soft Clay
8.5~12	Soft Clay
12~16	Medium Stiff Clay
16~below	Stiff Clay

Instrumentation at Testing Embankment *TS-1* and Measurements Used for Comparisons



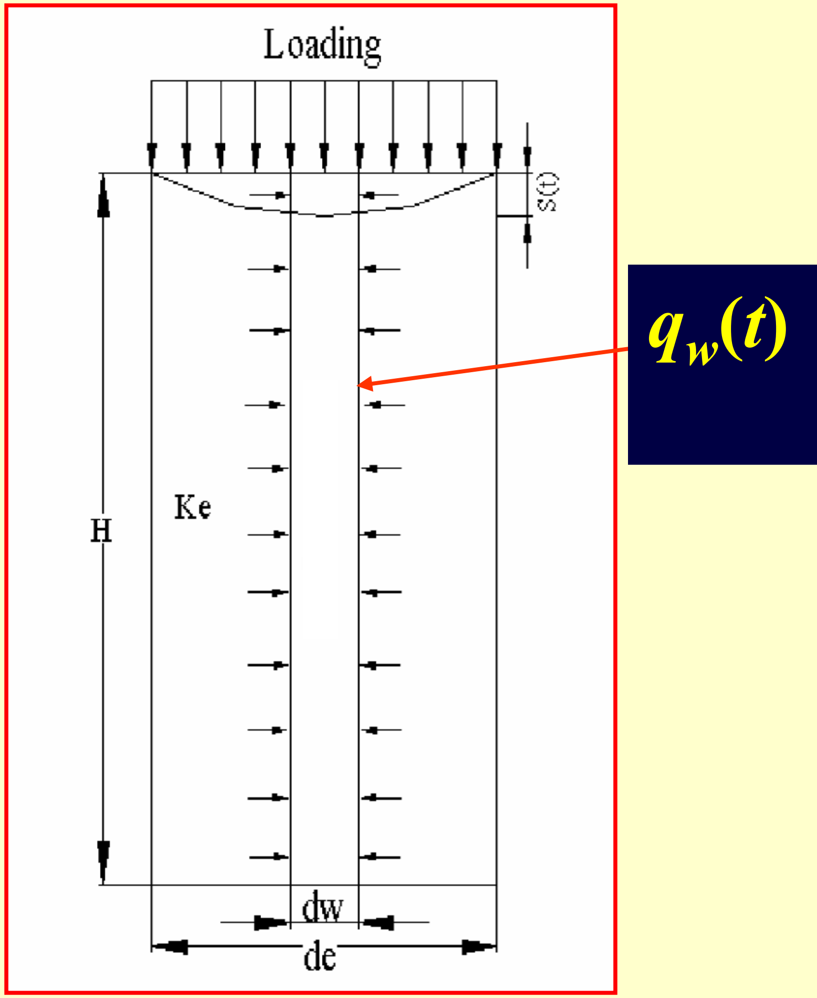
MODELING OF WELL RESISTANCE AND SMEAR EFFECT

Well Resistance

Change the Discharge Capacity of *PVD* with Elapsed Consolidation Time $q_w = q_w(t)$.

discharge capacities reduced with elapsed time

- **lateral pressure**
- **Creep behavior of filter**
- **Clogging caused by fine particles**
- **Folding the drain**

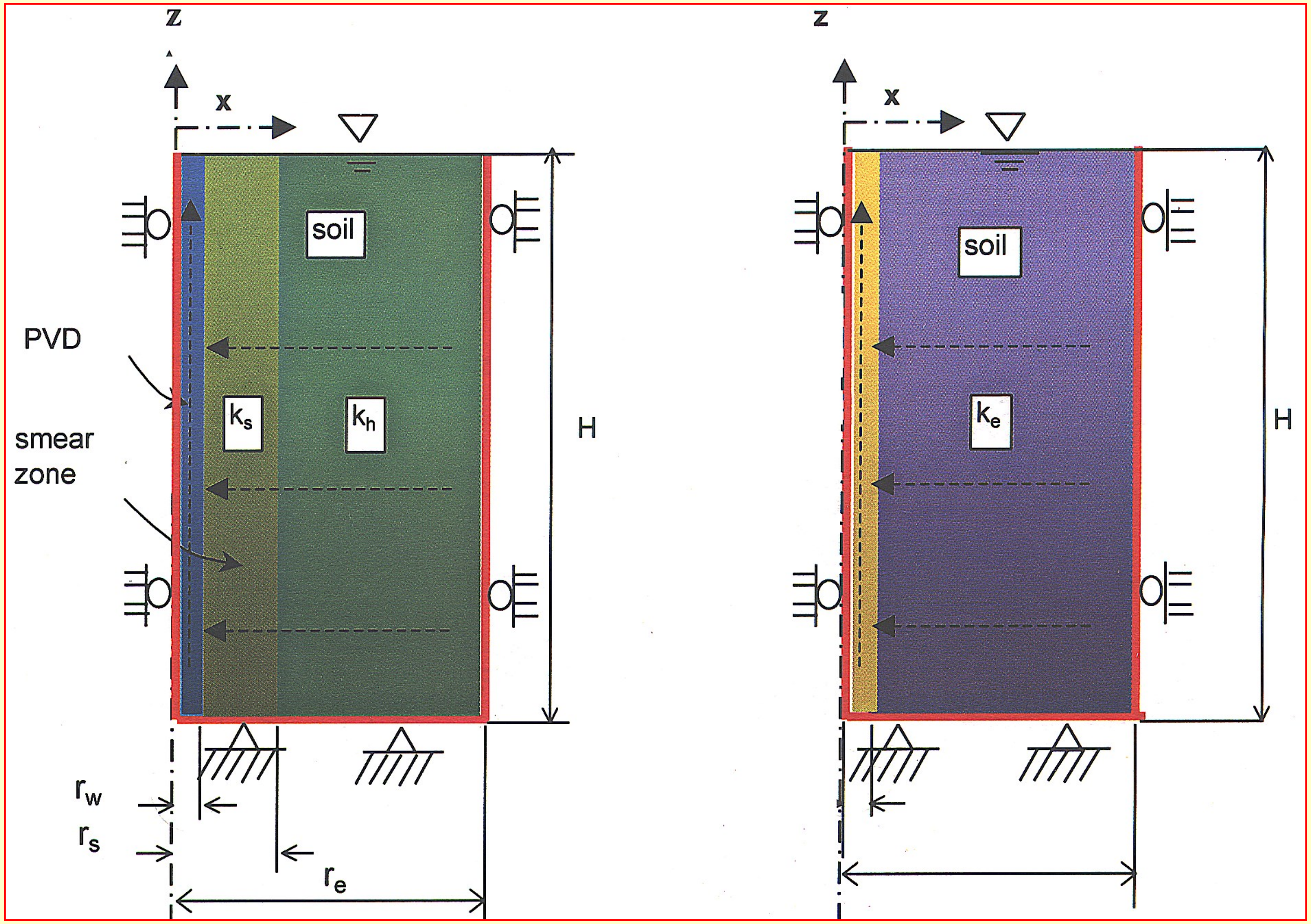


Discharge Capacity of *PVD* Presented by Previous Researchers

Sources	Discharge Capacity m^3/year	Lateral Pressure *kPa*
Jamiolkowski et al. (1983)	10 -15	300-500
Den Hoedt (1981)	95	50-300
Kremer et al. (1982)	256	100
Kremer (1983)	790	15
Hansbo (1979)	50-100	Not given
Ricner et al. (1986)	100	Not given
Van Zanten (1986)	790-1580	150-300
Holtz et al. (1989)	100-150	300-500
Lawrence and Koerner (1988)	150	Not given
Koda et al. (1984)	100	50
De Jager et al. (1990)	315-1580	150-300
Bergado et al (1996)	30-100	Field Tests

Smear effect

Applying an equivalent horizontal permeability k_e



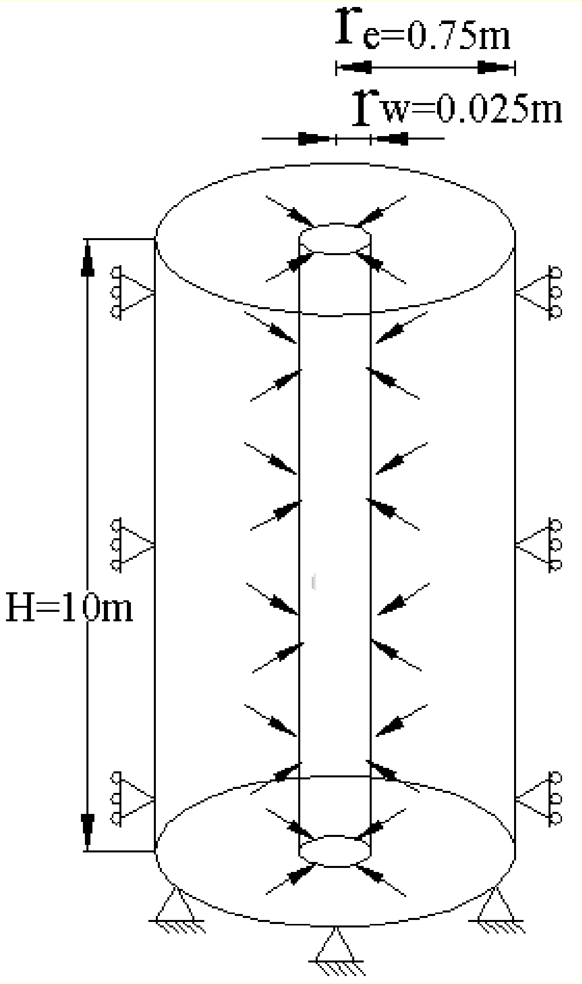
(a) Smear effect **in field condition**

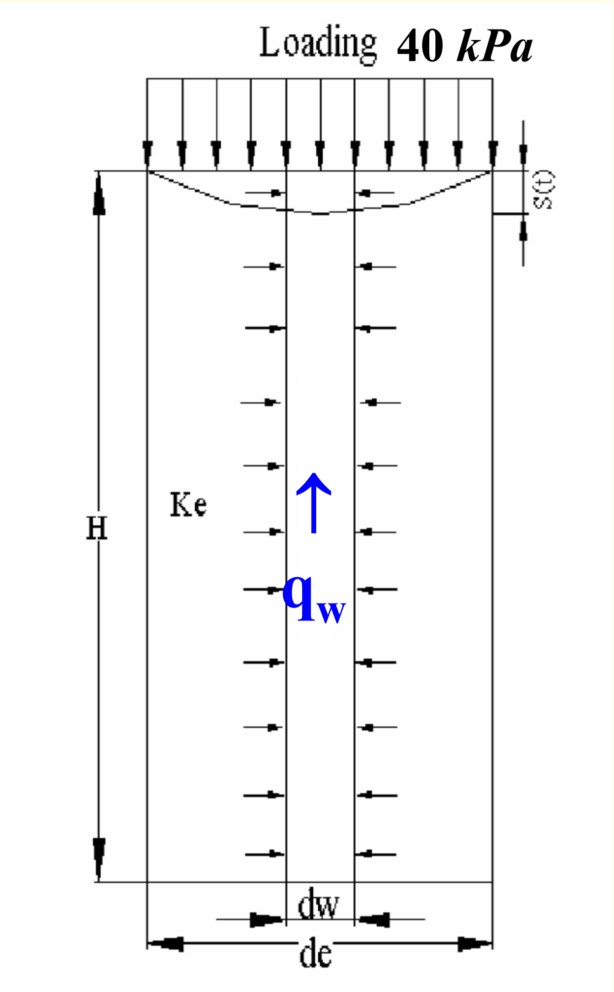
(b) Smear effect in **equivalent horizontal permeability**

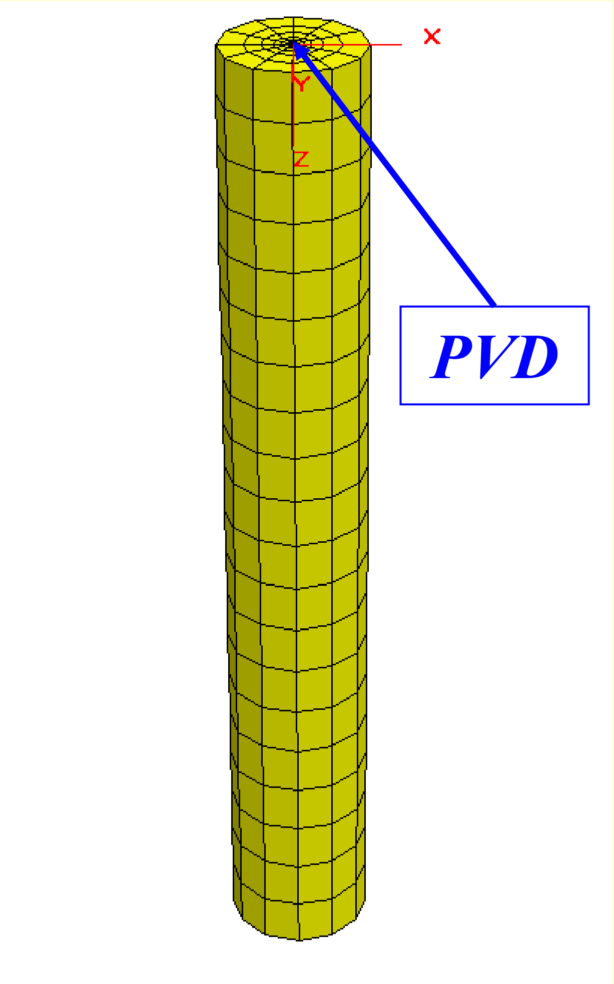
NUMERICAL MODELING OF *PVD* IMPROVED UNIT CELL

(Flac^{3D} Analysis)

Geometry Model and Numerical Discretization Of *PVD* Improved Unit Cell (Zeng, 1989)







Soil Model Parameters for Unit Cell Analysis

Soil model	**Loading (*kPa*)**	γ_t (*kN/m³*)	γ_d (*kN/m³*)	ρ_d (*kg/m3*)	***n***	***K* (*kPa*)**	***G* (*kPa*)**
Linear elastic	40	14.5	7.29	7.43	0.7	1800	460

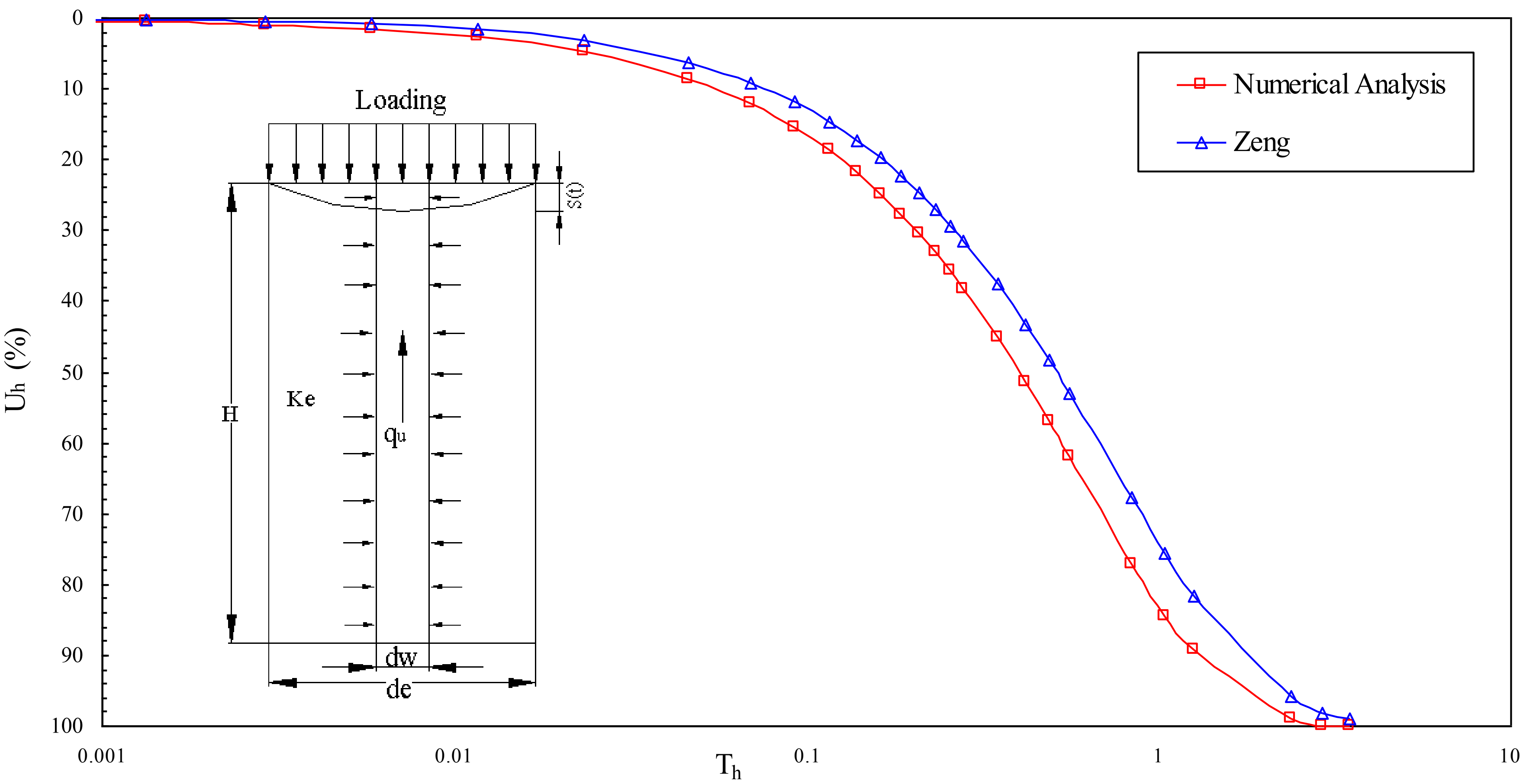
C_h (m^2/day)	k_h (*m*/sec)	k_s (*m/sec*)	k_e (*m/sec*)
3.13E-01	1.00E-04	2.50E-05	5.64E-05

PVD Drainage Parameters for Unit Cell

Drain length	10 m
Cross sectional area	$100 \times 3\ mm^2$
Mandrel dimension	$150 \times 45\ mm^2$
Spacing Ratio: $n = d_e / d_w$	30
Smear ratio: d_s/d_w	2.4

H (m)	r_w (m)	r_m (m)	r_s (m)	r_e (m)	q_w (m^3/yr)	k_w (m/day)
10	**0.025**	**0.03**	**0.06**	**0.75**	**100**	**139.5**

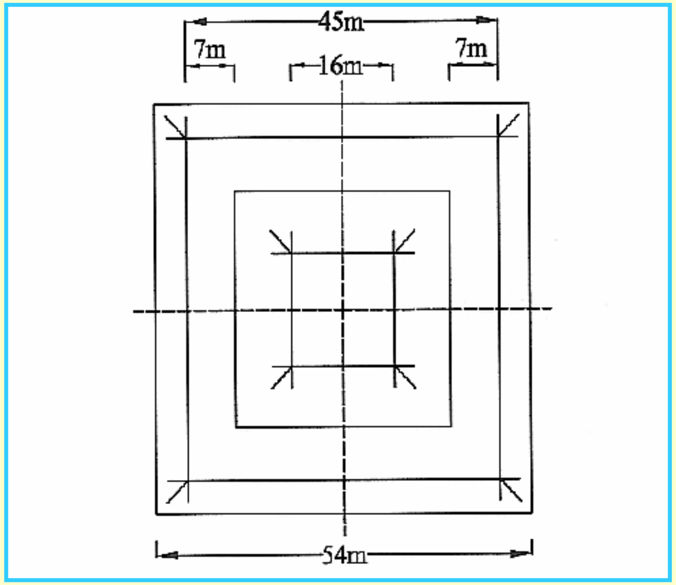
Comparison of average Consolidation rate of unit cell between Numerical results and Zeng's solutions

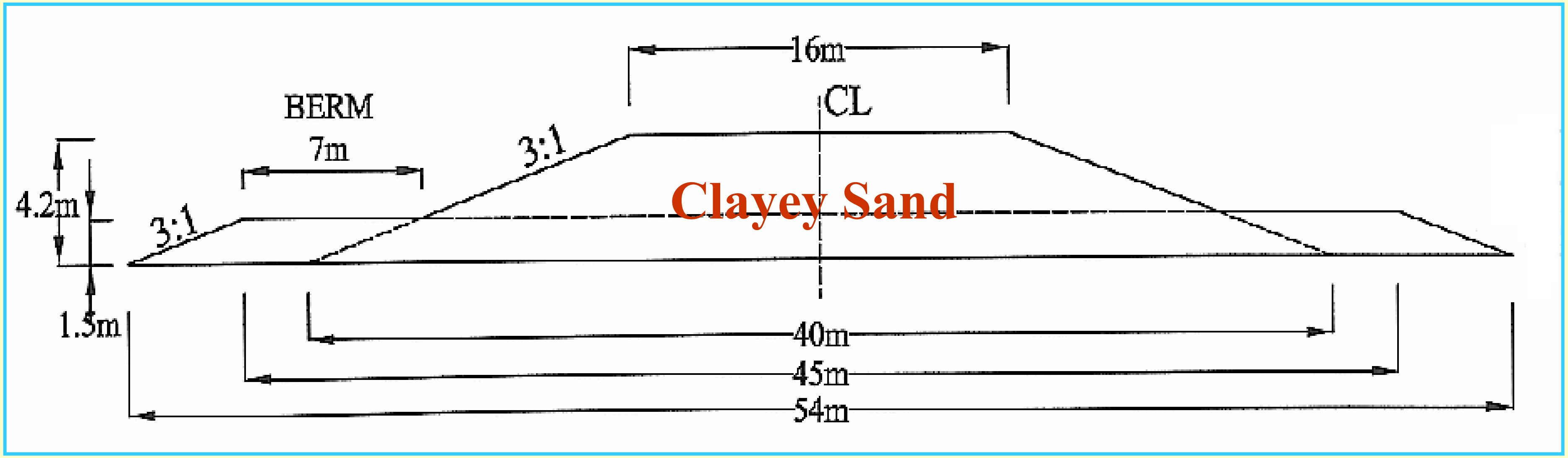


3-D NUMERICAL MODELING OF *PVD* IMPROVED GROUND

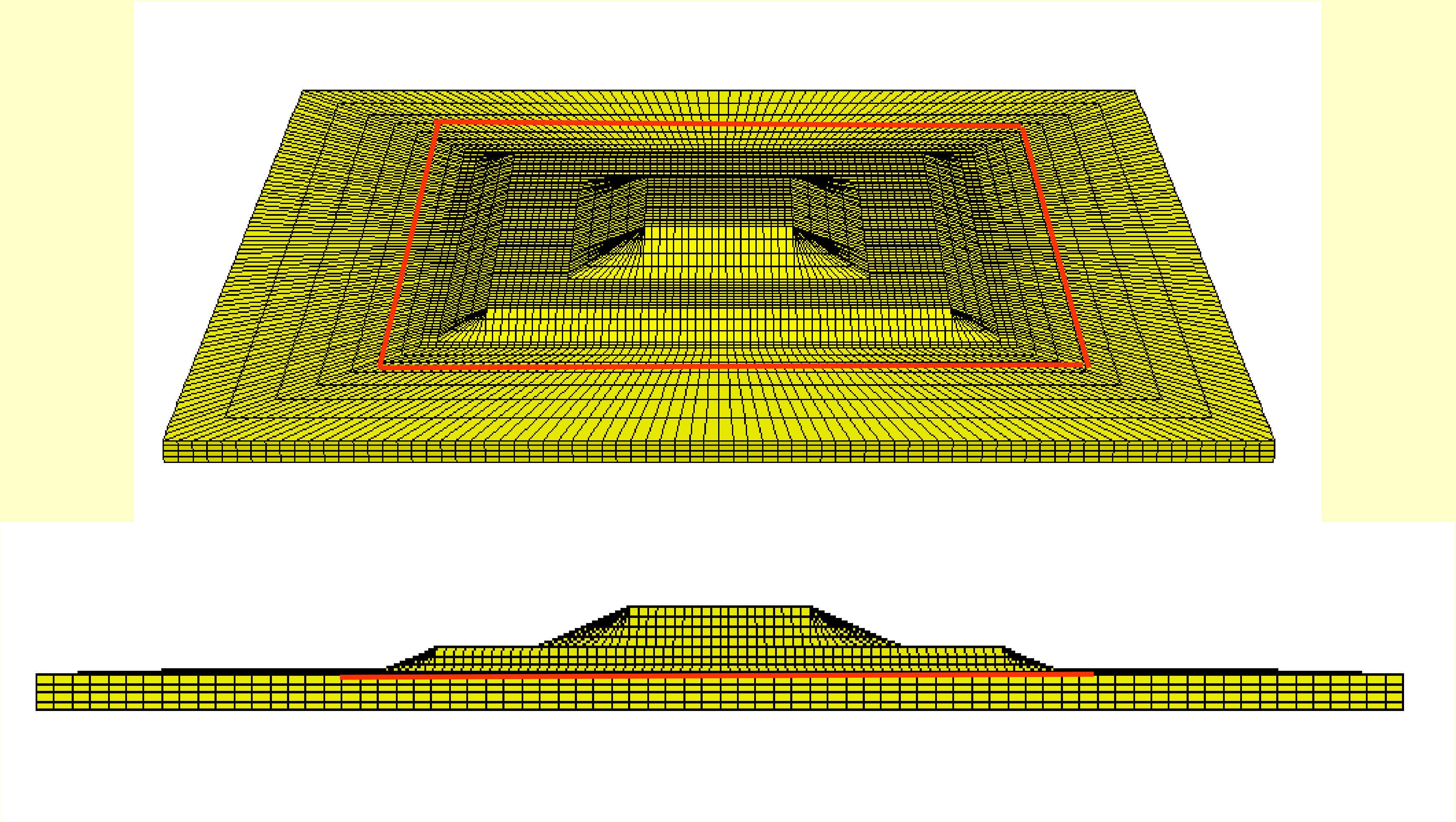
(Flac^{3D} Analysis)

Details of Test Embankment *TS-1* at *Nong Ngu Hao* (*NNH*) Field Site





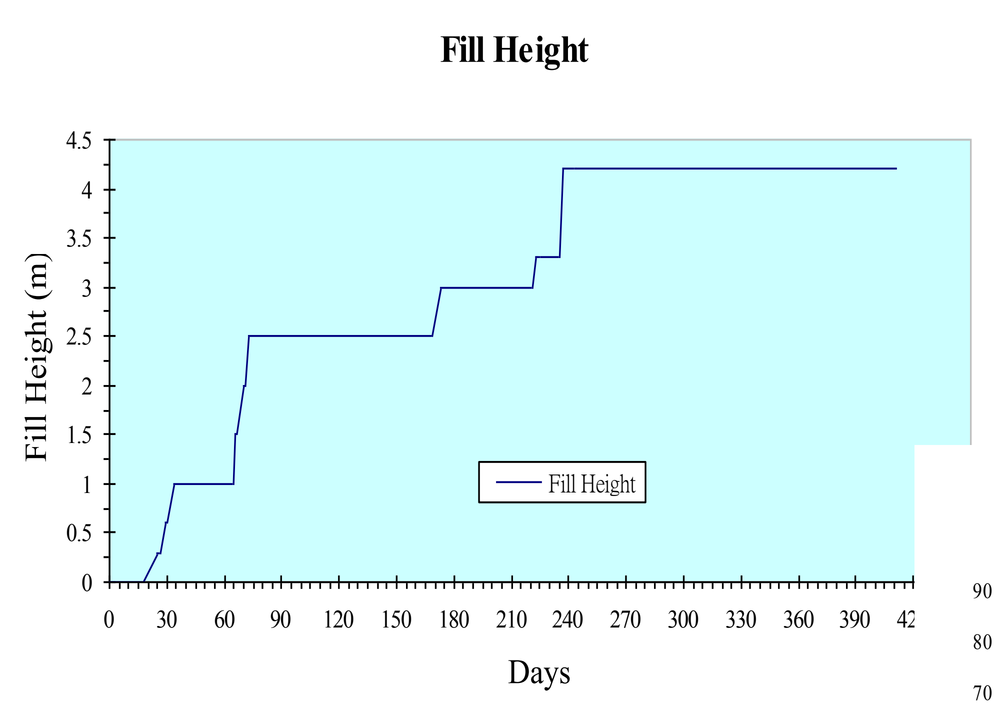
Evaluation of Surcharge Pressure on *PVD* Improved Ground due to Embankment Fill

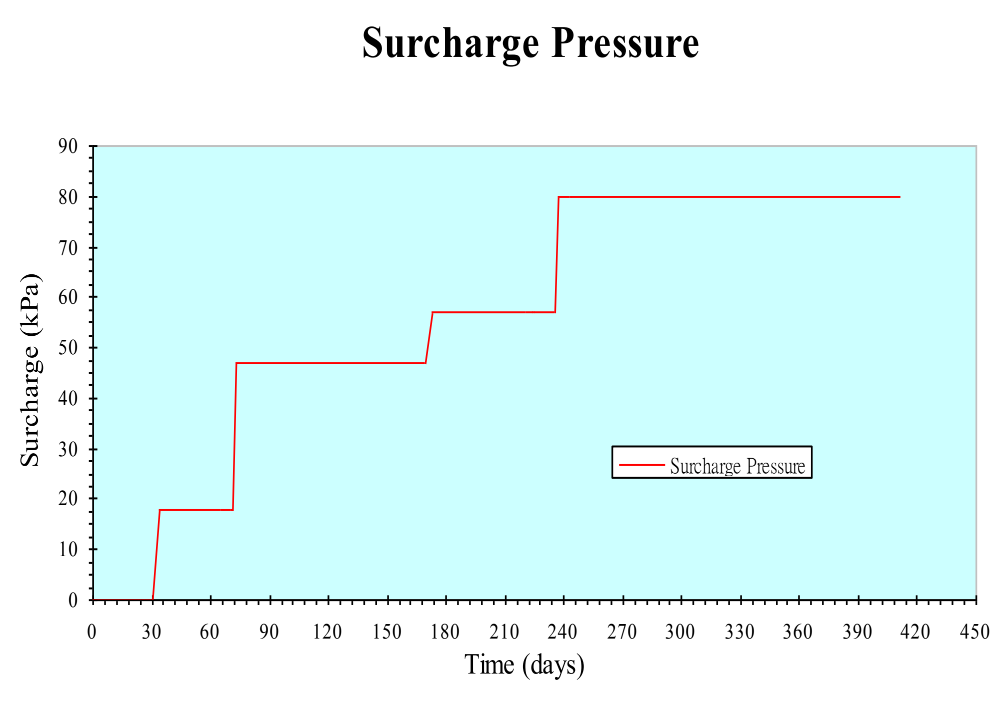


Equivalent Surcharge Pressures due to Stage Construction of Testing Embankment

Construction Stage	**Fill Height (*m*)**	**Equivalent Incremental Surcharge $\Delta\sigma_z$ (*kPa*)**	**Equivalent Accumulative Surcharge σ_z (*kPa*)**
1	1.0	17.9	17.9
2	2.5	29.1	47.0
3	3.0	8.0	55.0
4	4.2	25.0	80.0

Conversion of Embankment Fill Surcharge Time History to Pressure Surcharge Time History





Input Soil Parameters for 3-D Numerical Analysis of *PVD* Improved Ground in *NNH* Field Site

Depth (*m*)	γ_t (kN/m^3)	*n*	*K* (*kPa*)	*G* (*kPa*)	λ	κ	*M*	P_{c0} (*kPa*)
2~4	14.4	0.74	33.6E+03	1.12E+02	0.634	0.127	0.9	4.48E+01
4~6	14.5	0.71	5.60E+02	1.59E+02	0.569	0.114	0.9	3.41E+01
6~8	14.3	0.75	4.97E+02	1.53E+02	0.990	0.198	1.0	3.55E+01
8~10	14.3	0.74	1.02E+03	2.19E+02	0.573	0.15	1.2	6.37E+01
10~12	15.4	0.67	1.39E+03	3.62E+02	0.421	0.084	1.12	7.48E+01

Depth: 2~10m (very soft clay), 10~12m (soft clay)

Soil Parameter for Modified Cam Model

Input Soil Parameters for 3-D Numerical Analysis of *PVD* Improved Ground in *NNH* Field Site

Depth (m)	γ_t (kN/m^3)	n	K (kPa)	G (kPa)	c (kPa)	ϕ ($deg.$)	σ^t (kPa)	ψ ($deg.$)
0~2 (weathered clay)	16.1	0.72	1.44E+05	4.79E+04	30	28	56.42	0
12~16 (stiff clay)	16.3	0.67	1.88E+06	4.91E+05	20	30	34.64	0
Backfill	18		3.33E+03	2.00E+03	30	28	56.4	0

$\sigma^t = c'/\tan\phi'$ =tension limits

Soil Parameter for Mohr-Coulomb Model

Determination of the Permeability in Smear Zone

Depth (*m*)	k_h (*cm/sec*)	k_v (*cm/sec*)	$(k_h/k_s)_l$	C_f	$(k_h/k_s)_f$	k_s (*cm/sec*)
0~2	1.36E-07	6.78E-08	2	4	8	1.69E-08
2~4	2.01E-07	1.00E-07	2	4	8	2.51E-08
4~6	2.73E-07	1.36E-07	2	4	8	3.41E-08
6~8	2.73E-07	1.36E-07	2	4	8	3.41E-08
8~10	4.12E-07	2.06E-07	2	4	8	5.16E-08
10~12	4.12E-07	2.06E-07	2	4	8	5.16E-08
12~16	2.33E-07	1.17E-07	2	4	8	2.92E-08

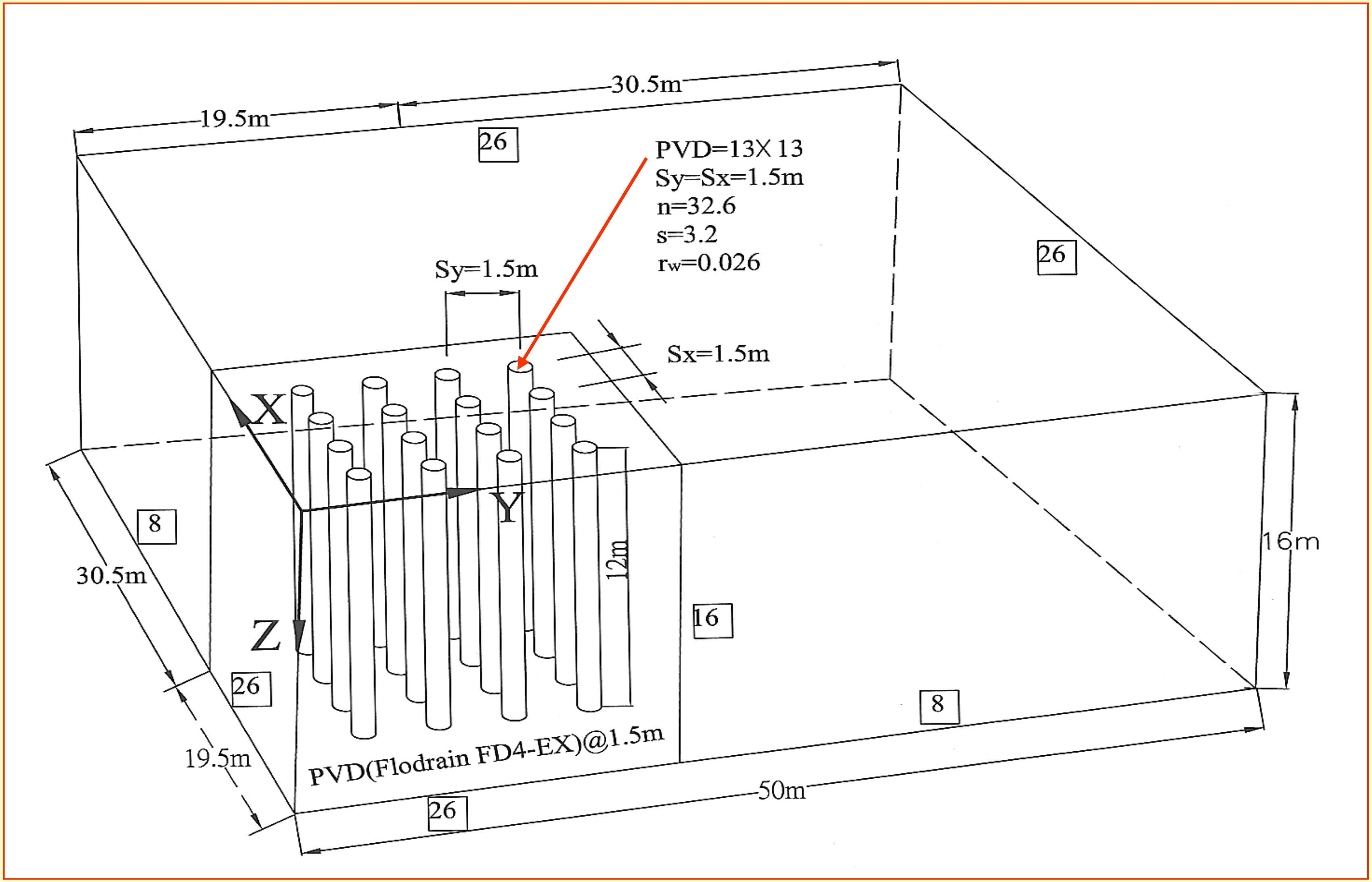
Drainage Parameters of *PVD* (Flodrain, FD4-X)

Drain Configuration	Square Pattern
Drain Spacing : S	1.5 m
Drain length : l_d	12 m
Cross sectional area: width a × thickness b	$100 \times 4\ mm^2$
Mandrel dimension : $l \times w$	$125 \times 45\ mm^2$
Equivalent diameter of *PVD*: $d_w=(a+b)/2$	0.052 m
Equivalent radius of *PVD*: r_w $(=d_w/2=(a+b)/4)$	0.026 m
Radius of the influence zone of the drain: r_e $(=d_e/2)$	0.847 m
Spacing Ratio: $n = (d_e / d_w) = (1.13S / d_w)$	32.6
Radius of smeared zone: r_s $(=d_s/2= 2d_m/2=4r_m/2 =2r_m)$	0.084 m
Equivalent radius of the mandrel: r_m $(=d_m/2)$	0.042 m
Smear Ratio of Subsoil: $(r_s / r_w)= (d_s / d_w)=(2d_m / d_w)$	3.2

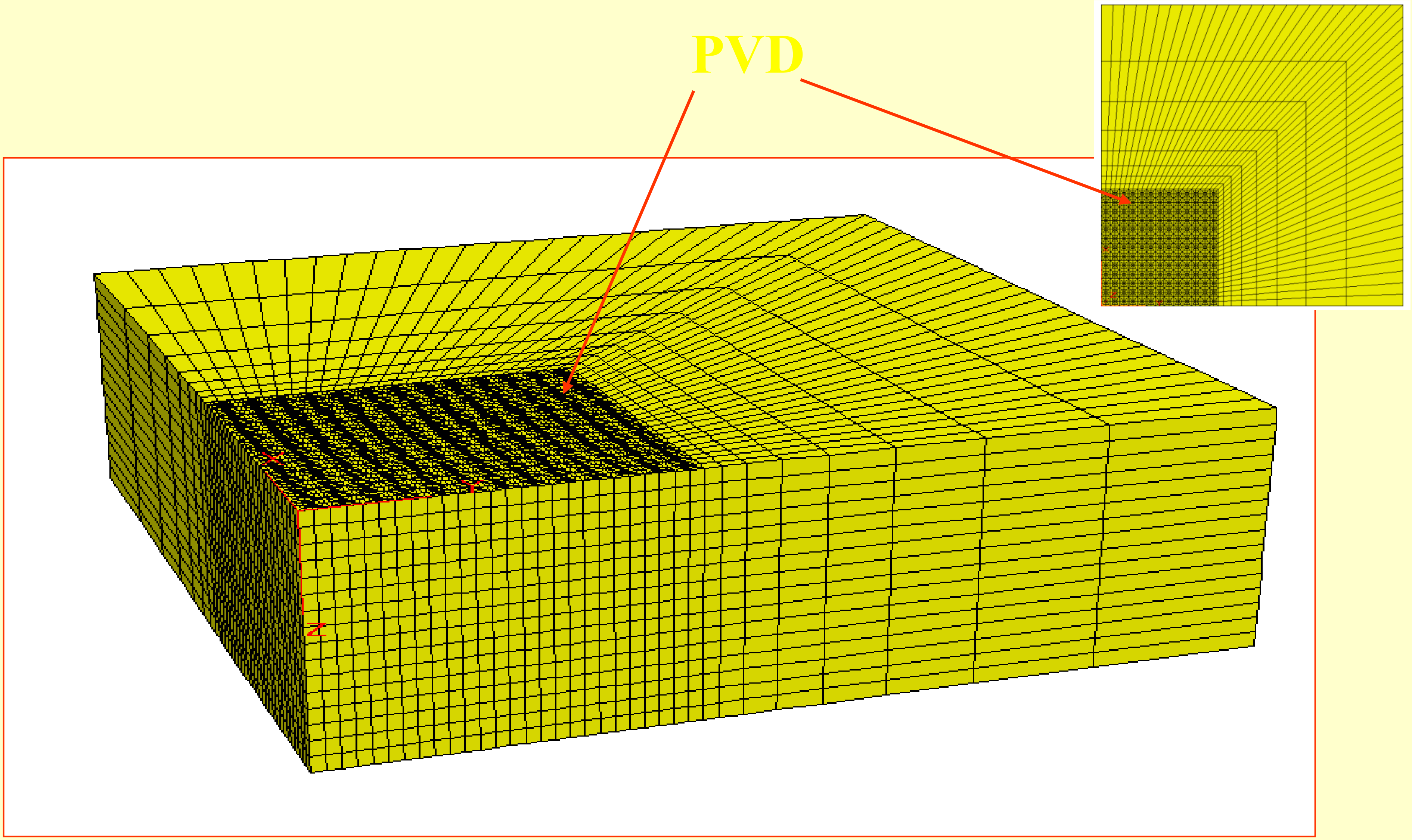
Discharge Capacity Varied with the Elapsed Time during Consolidation

Time	q_w ($m^3/year$)	q_w (m^3/sec)	k_w (cm/sec)
1 day	100	3.17E-06	1.49E-01
7 days	90	2.85E-06	1.34E-01
30 days	70	2.22E-06	1.05E-01
60 days	50	1.59E-06	7.47E-02
100 days	40	1.27E-06	5.98E-02
200 days	30	9.51E-07	4.48E-02

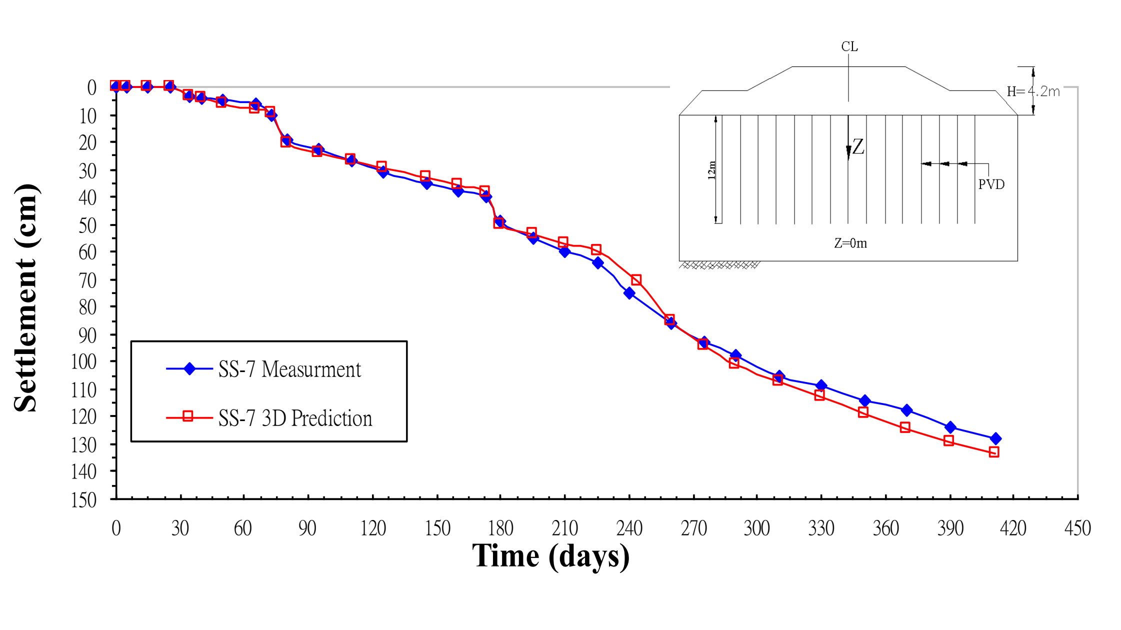
Geometry Model for 3-D Numerical Analysis of *PVD* Improved Ground of Nong Ngu Hao (*NNH*) Field Site



Finite Difference Mesh for 3-D Numerical Analysis of Full Scale *PVD* Improved Ground



3-D Prediction and Measurement of Settlement Rate along the Centerline of Embankment

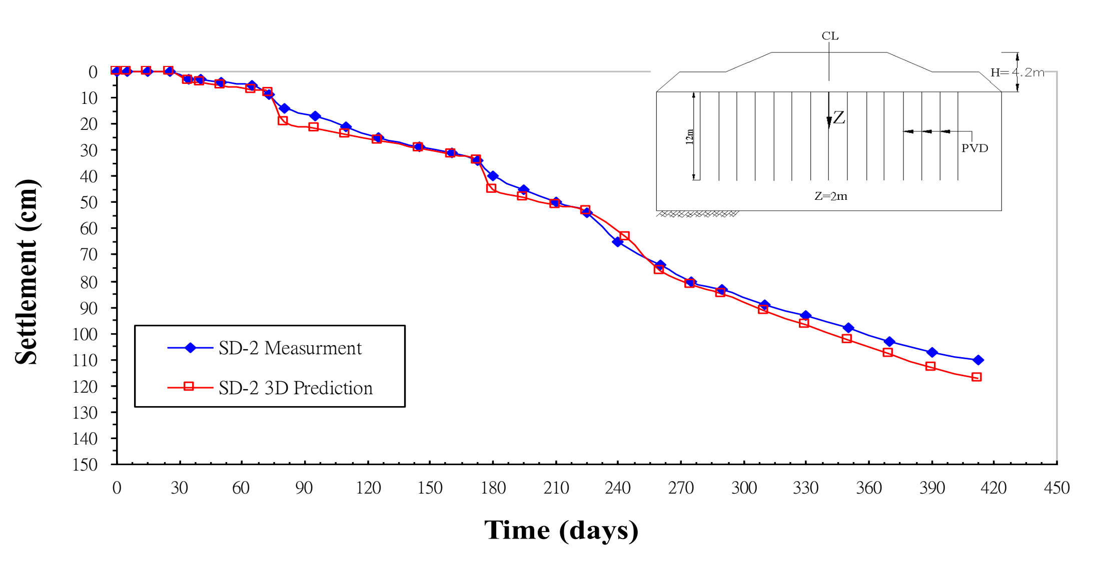


Surface Settlement

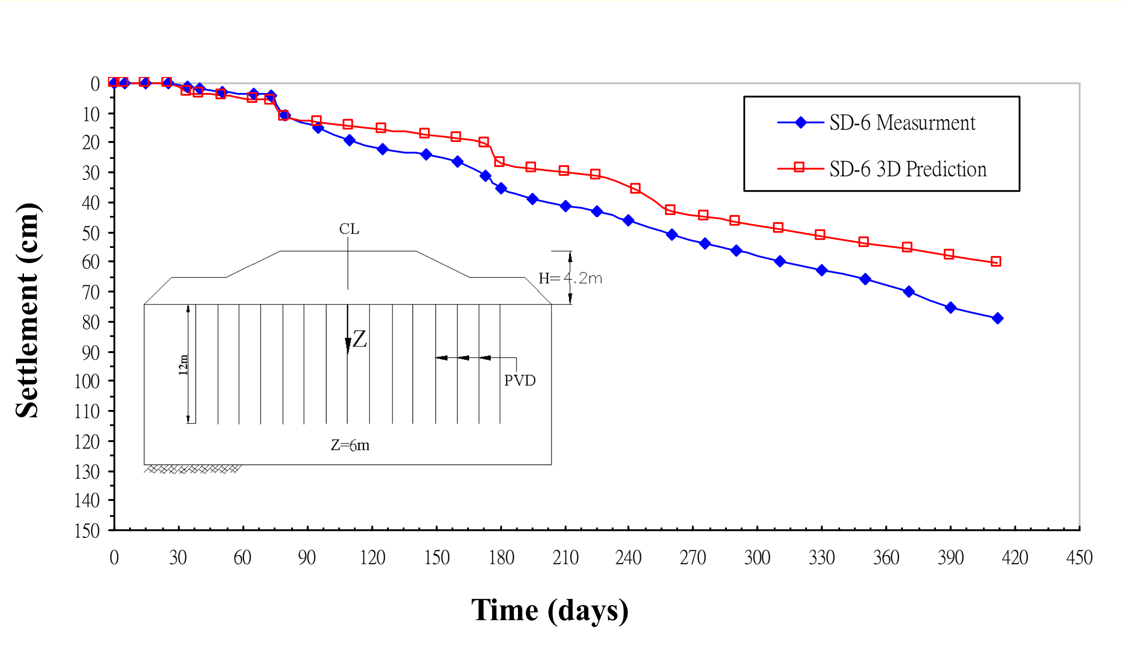
Z=0m

2m below Ground Surface

Z=2m



3-D Prediction and Measurement of Settlement Rate along the Centerline of Embankment

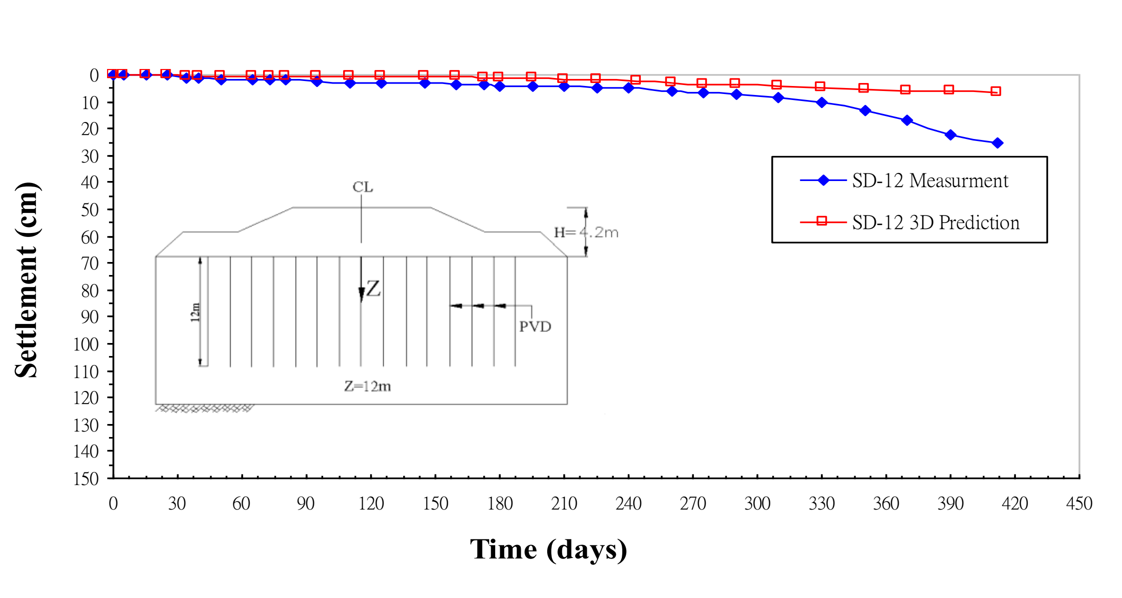


6m below Ground Surface

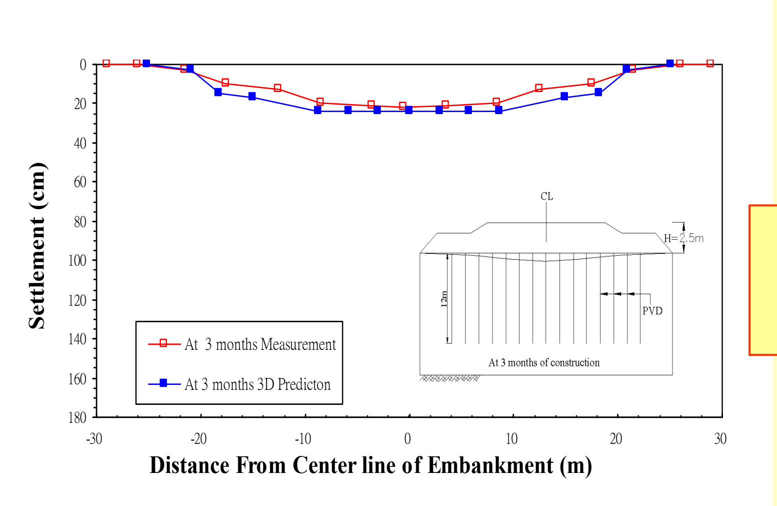
Z=6m

12m below Ground Surface

Z=12m

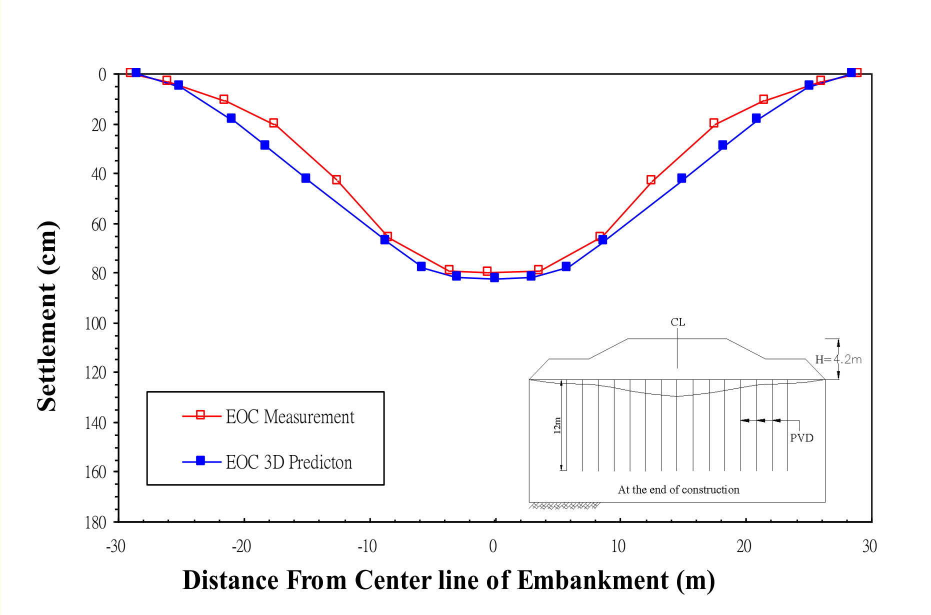


Comparison of Ground Settlement Profiles between 3-D Prediction and Measurement

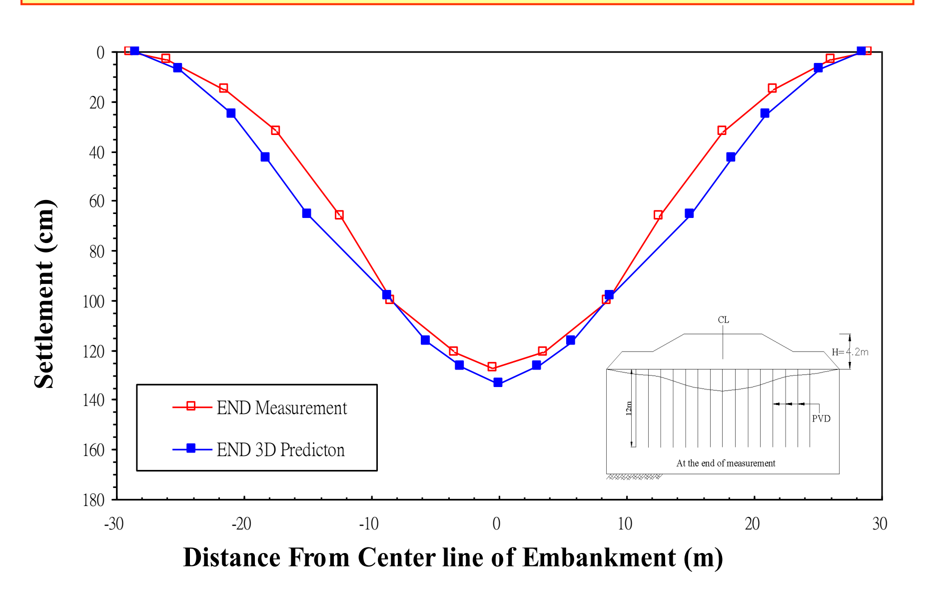


3 months after the construction *t*=90 days

End of Construction *t*=240days

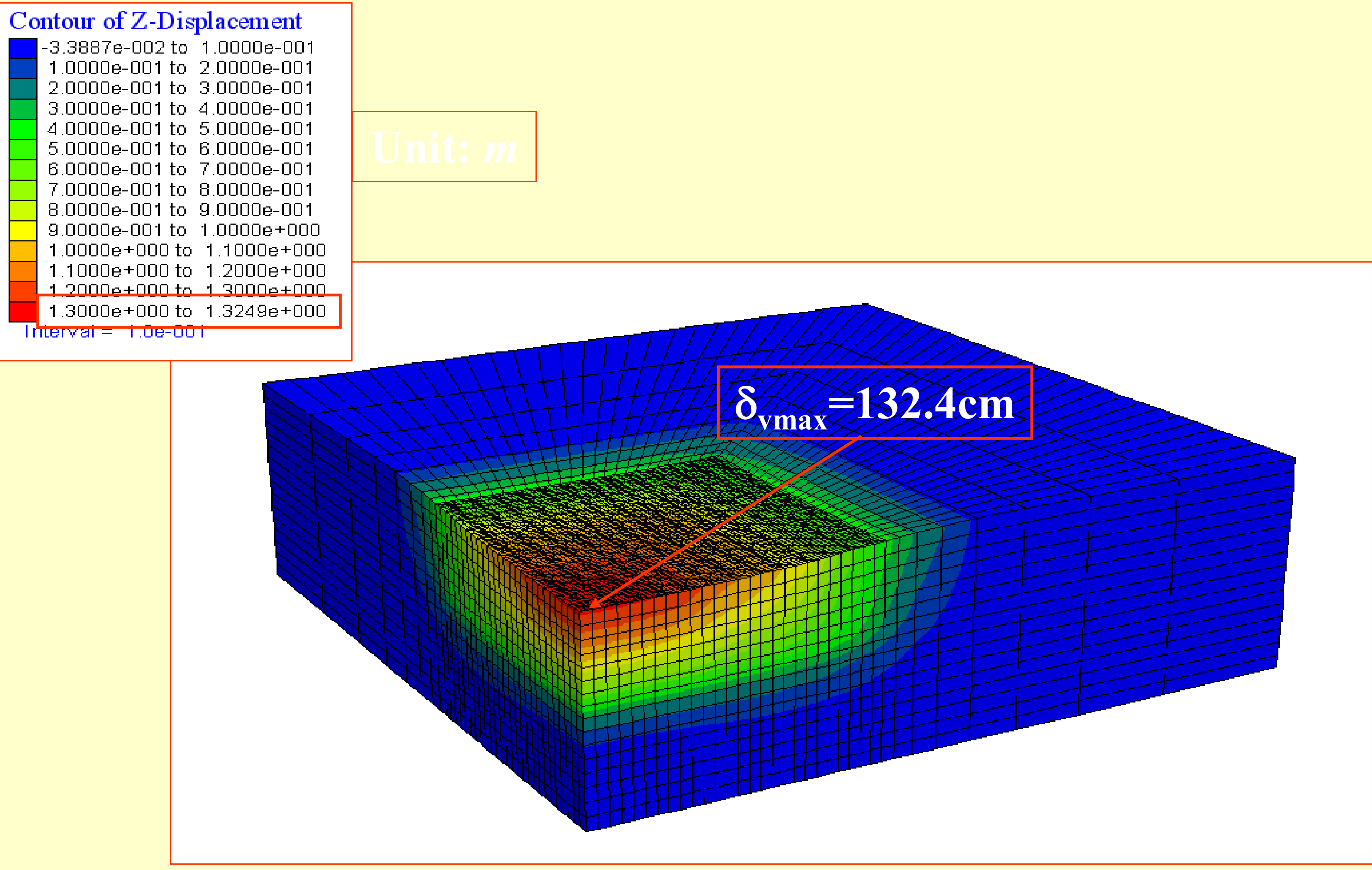


End of Instrumentation *t*=420days

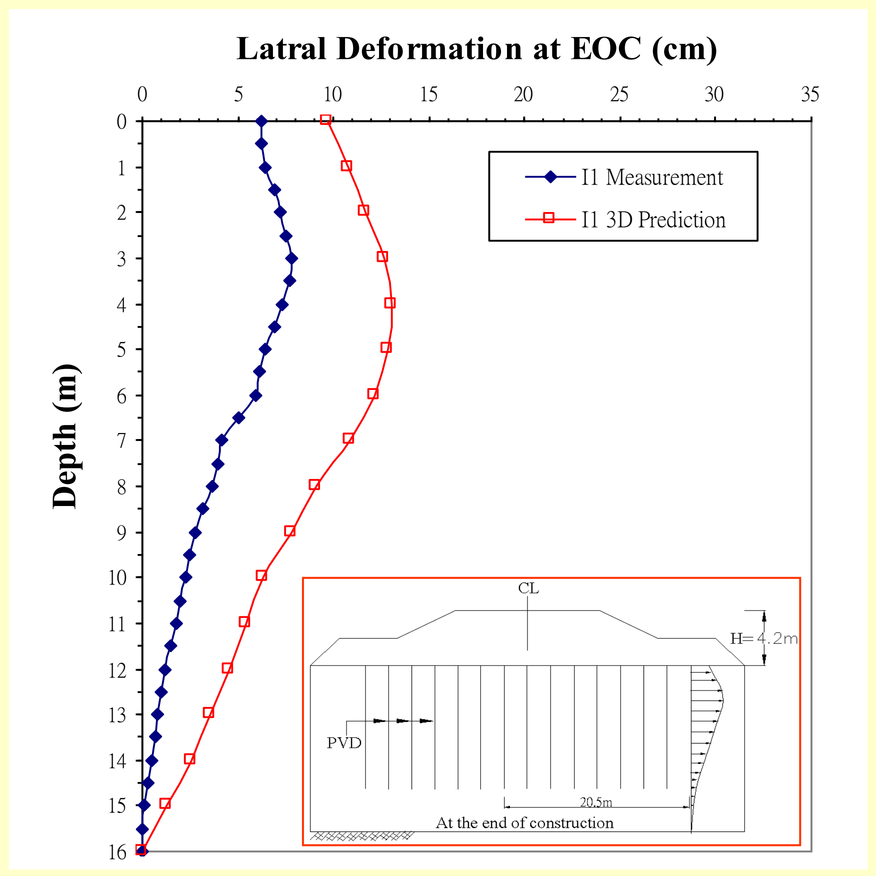


Settlement Contours of *PVD* Improved Ground at the end of Instrumentation (*t*=420 days)

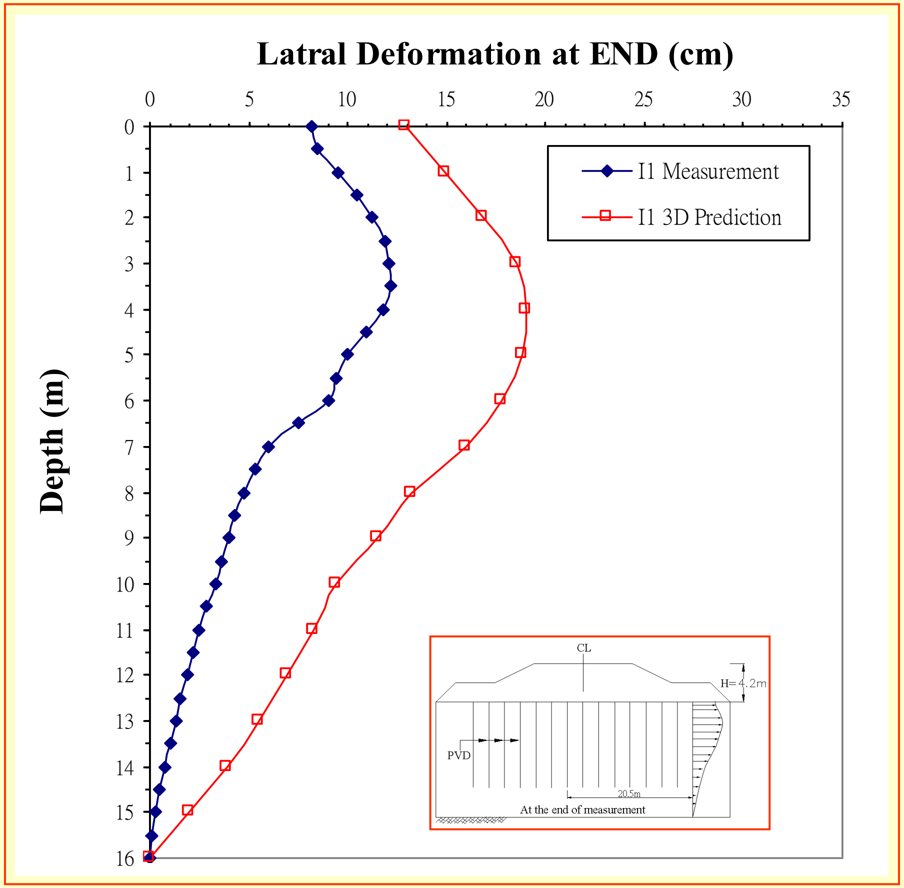
Unit: *m*



Comparison of Lateral Movement Profiles between 3-D Prediction and Measurement of Inclinometer I-1

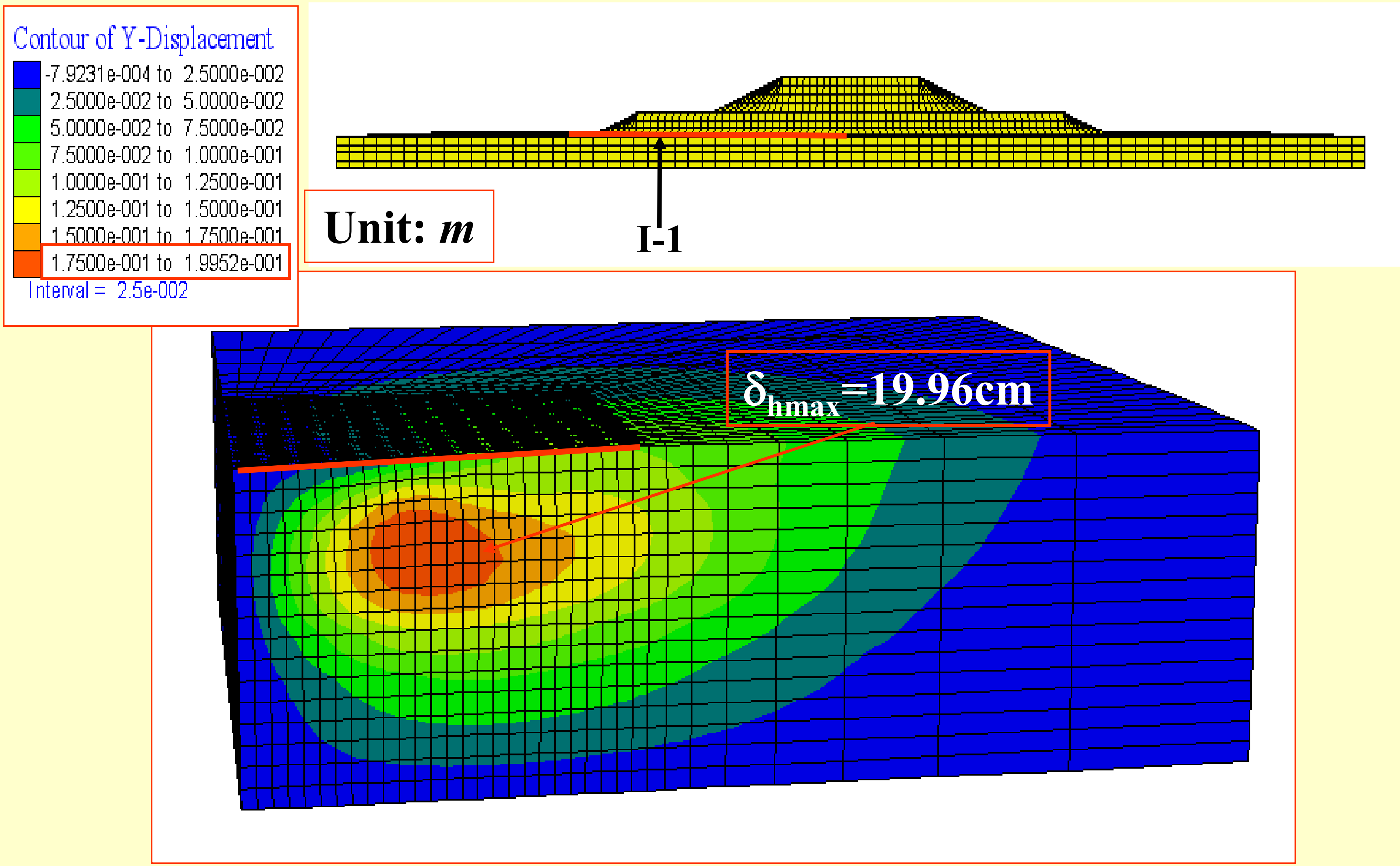


At the End of Construction t=420days

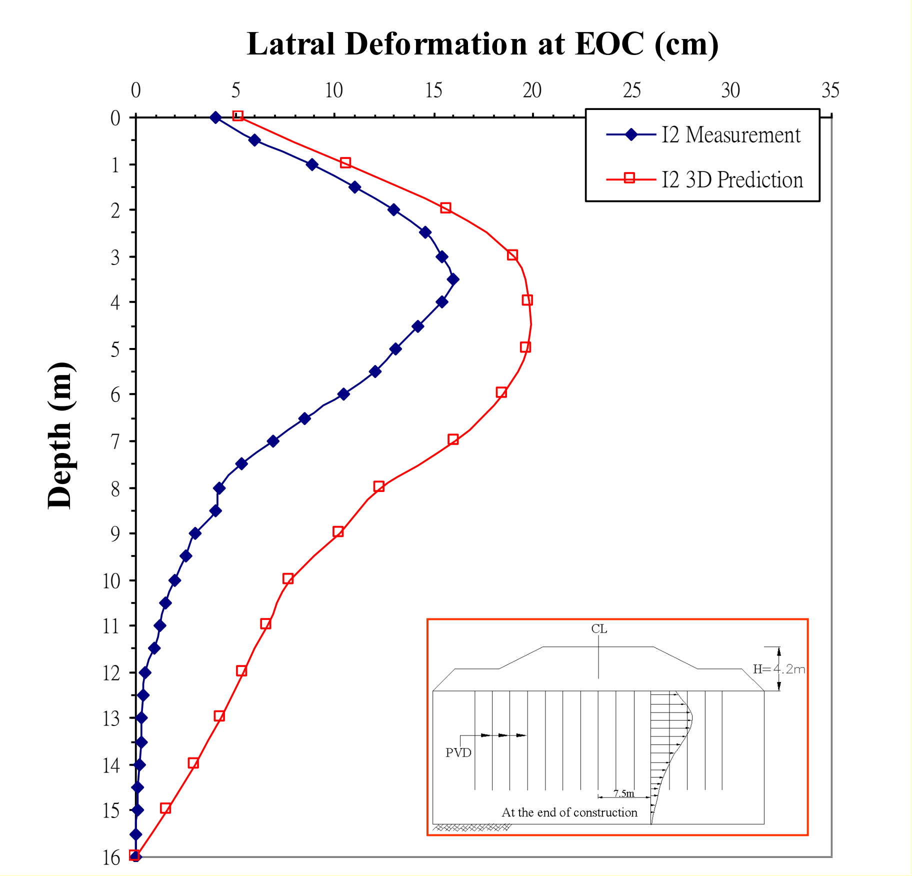


At the End of Instrumentation t=420days

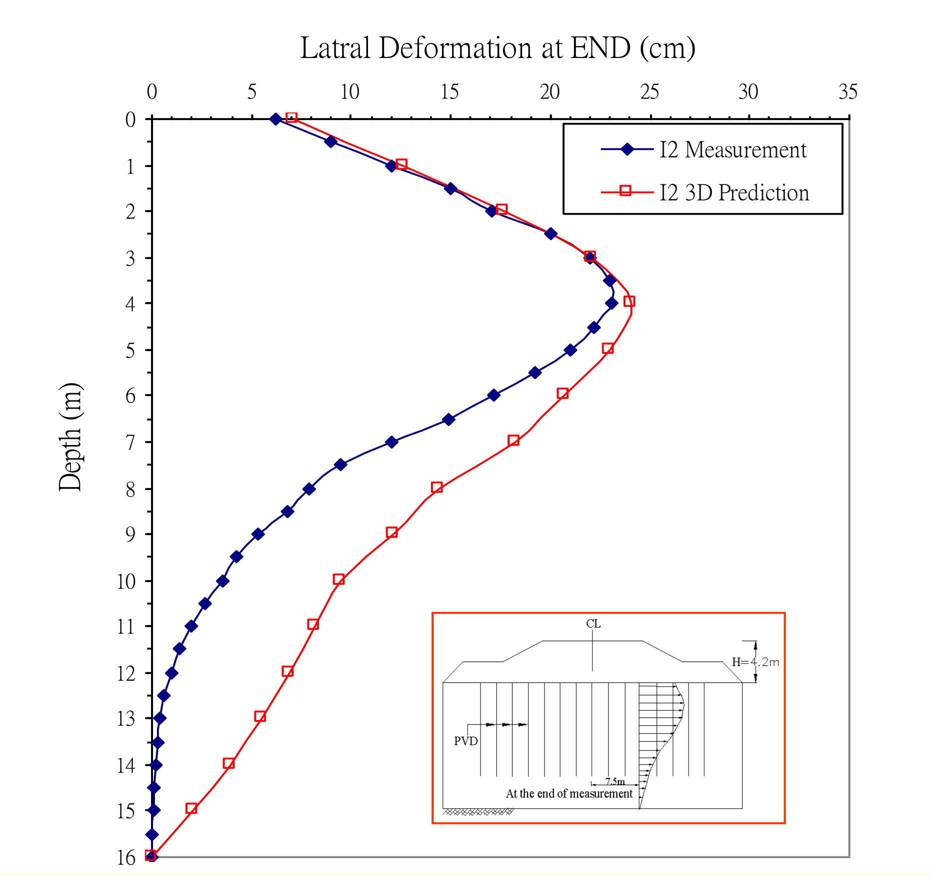
Lateral Movement Contours of PVD Improved Ground at the End of Instrumentation (I-1)



Comparison of Lateral Movement Profiles between 3-D Prediction and Measurement of Inclinometer I-2

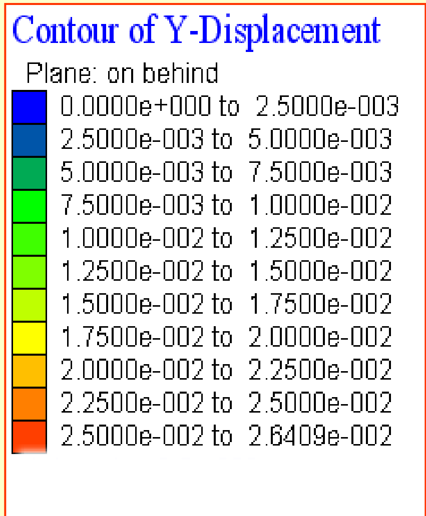


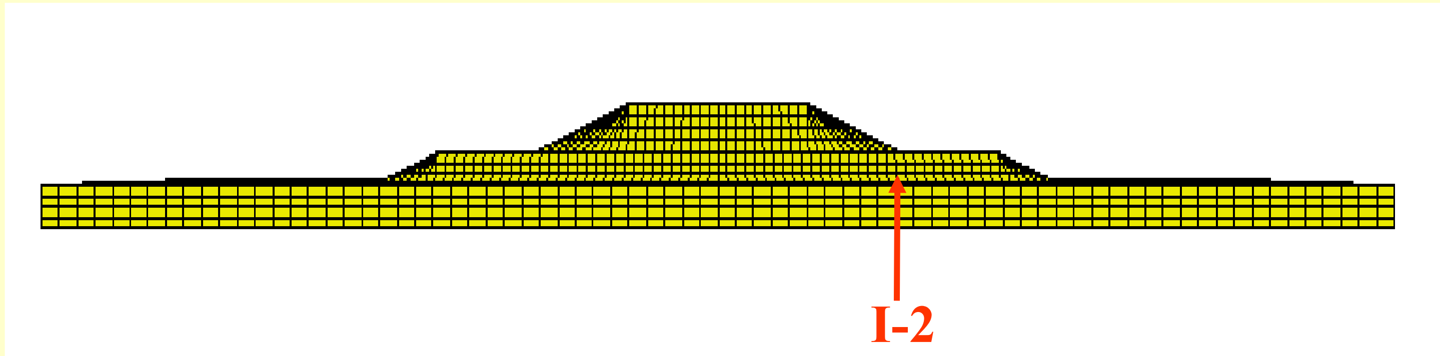
At the End of Construction
t=420 days

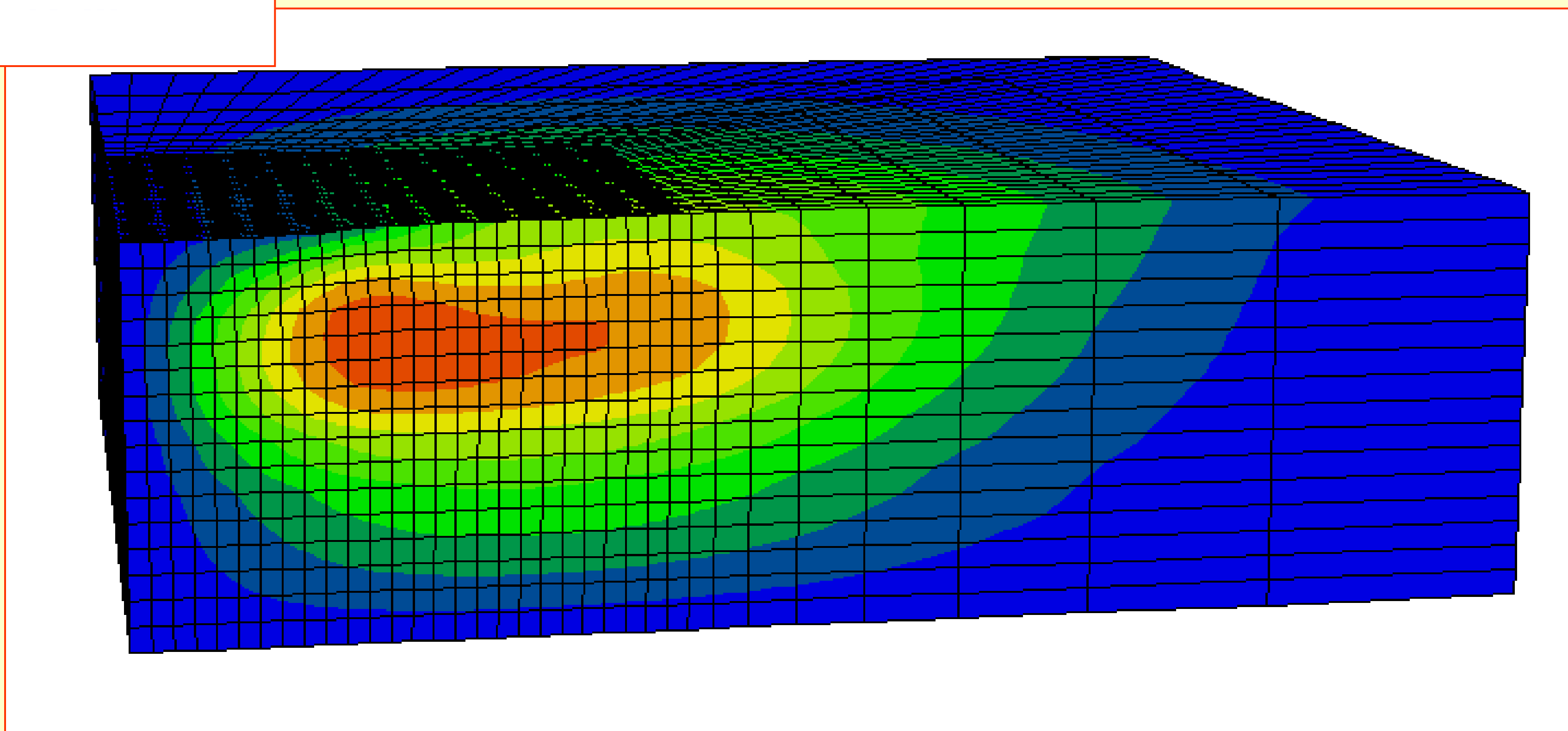


At the End of Instrumentation
t=420 days

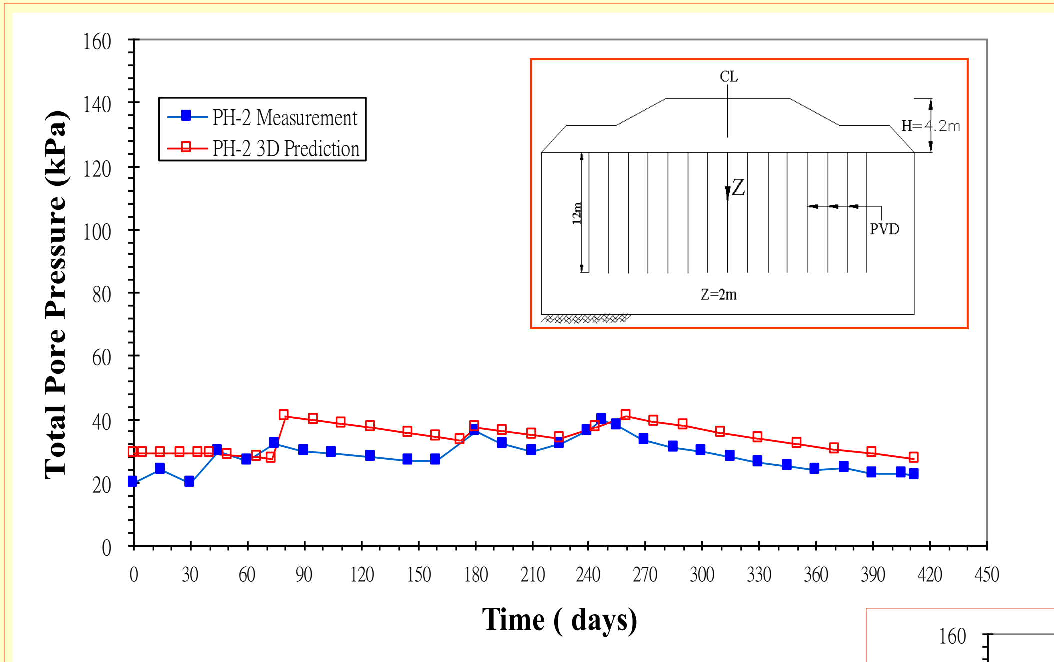
Lateral Movement Contours of PVD Improved Ground at the End of Instrumentation (I-2)







Comparison of **Total Pore Pressure** between 3-D Prediction and Measurement

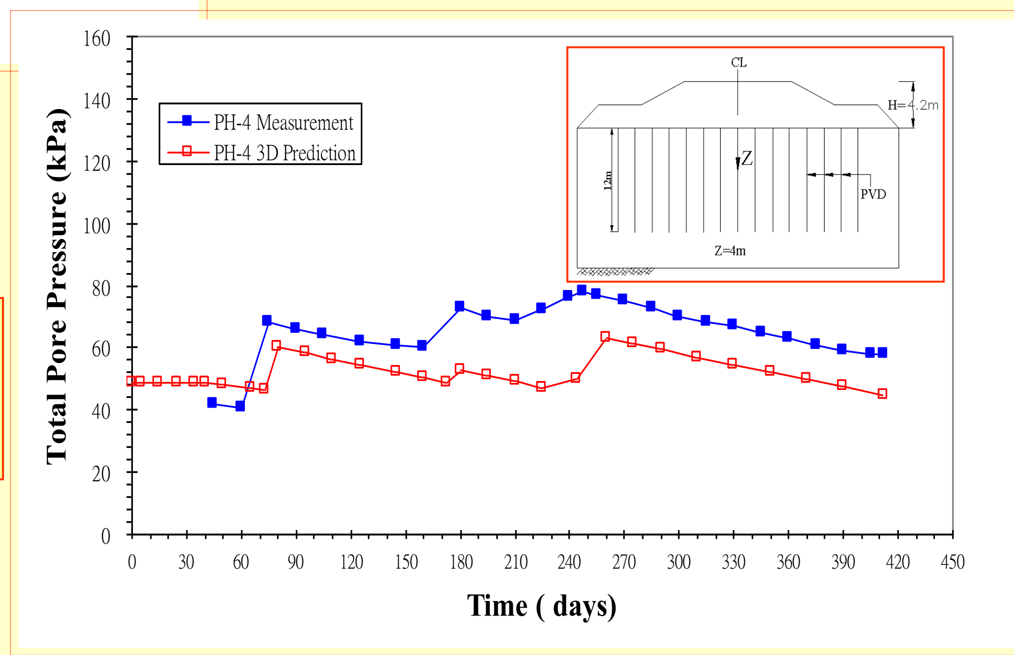


2m below Ground Surface

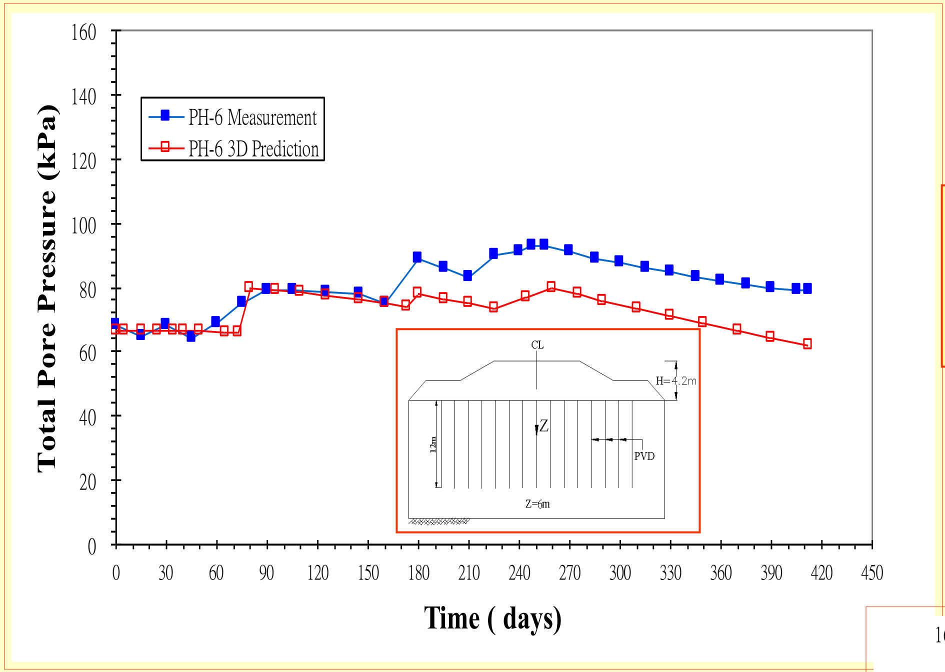
Z=2m

4m below Ground Surface

Z=4m



Comparison of Total Pore Pressure between 3-D Prediction and Measurement

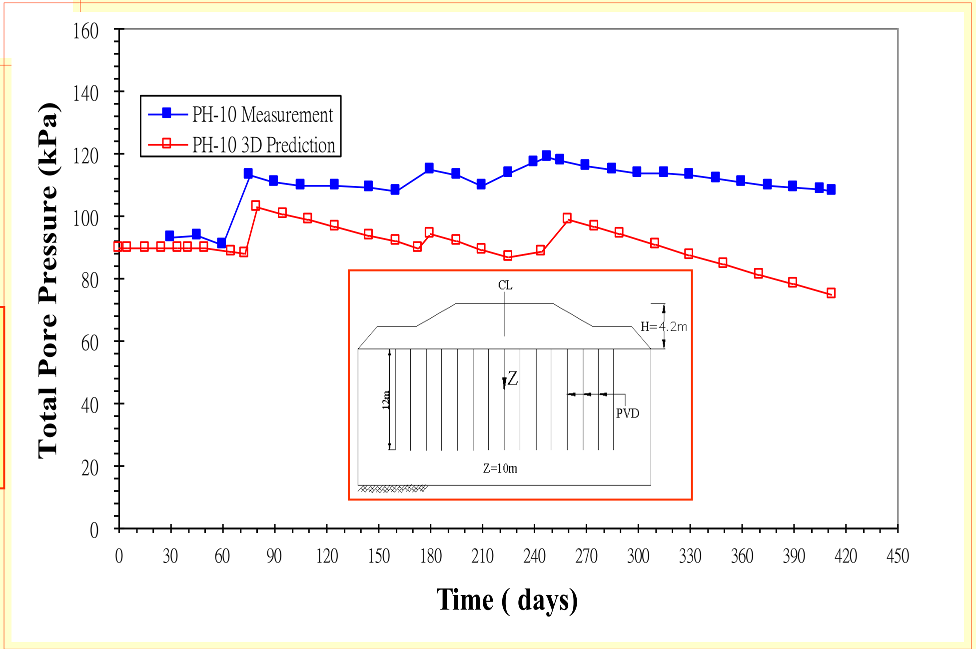


6m below Ground Surface

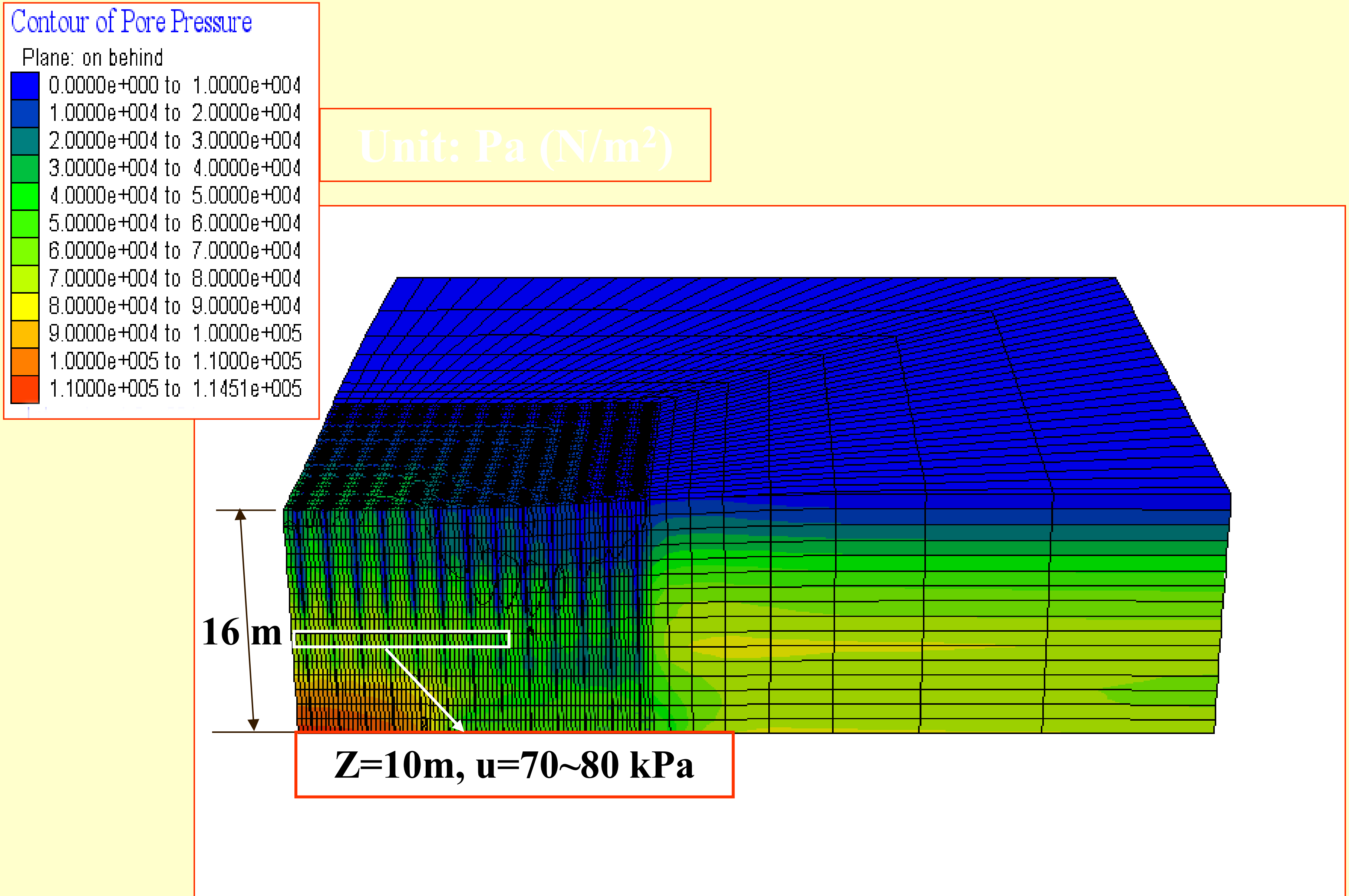
Z=6m

10m below Ground Surface

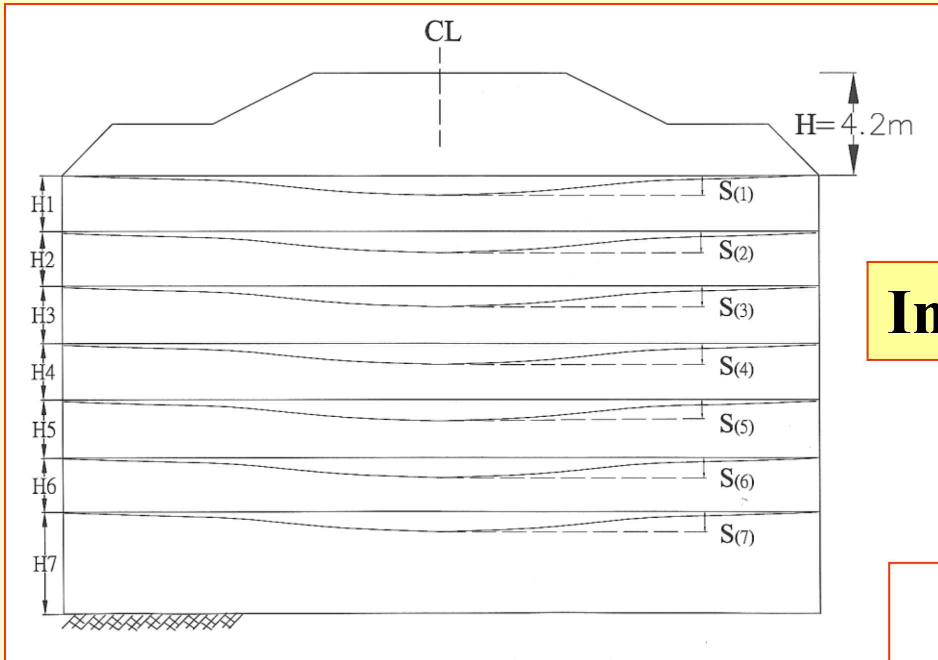
Z=10m



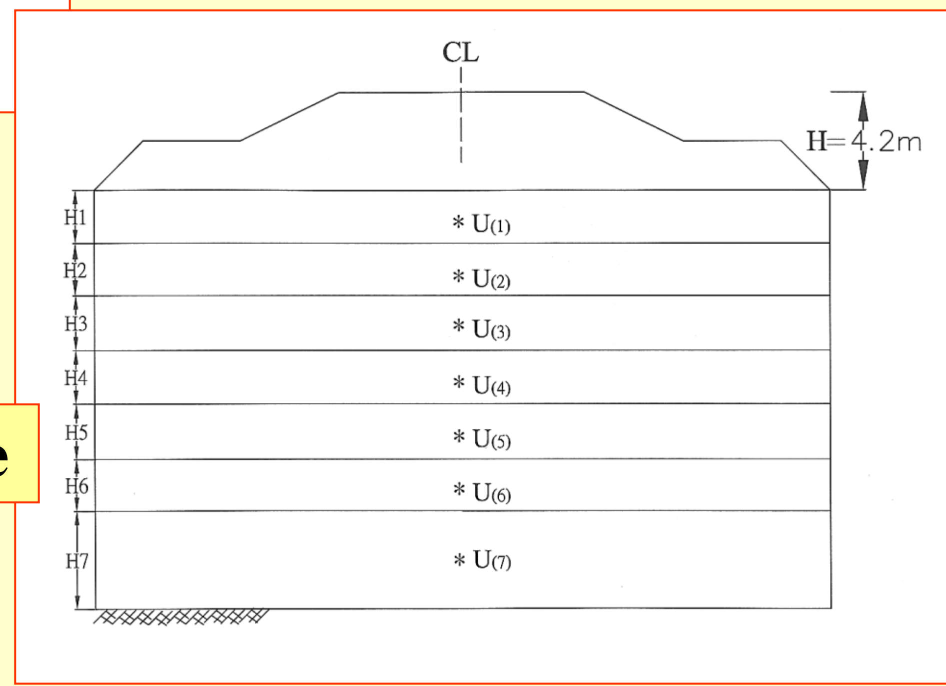
Total Pore Pressure Contours of PVD Improved Ground at the End of Instrumentation (t=420day)



The Degree of Consolidation in Calculation

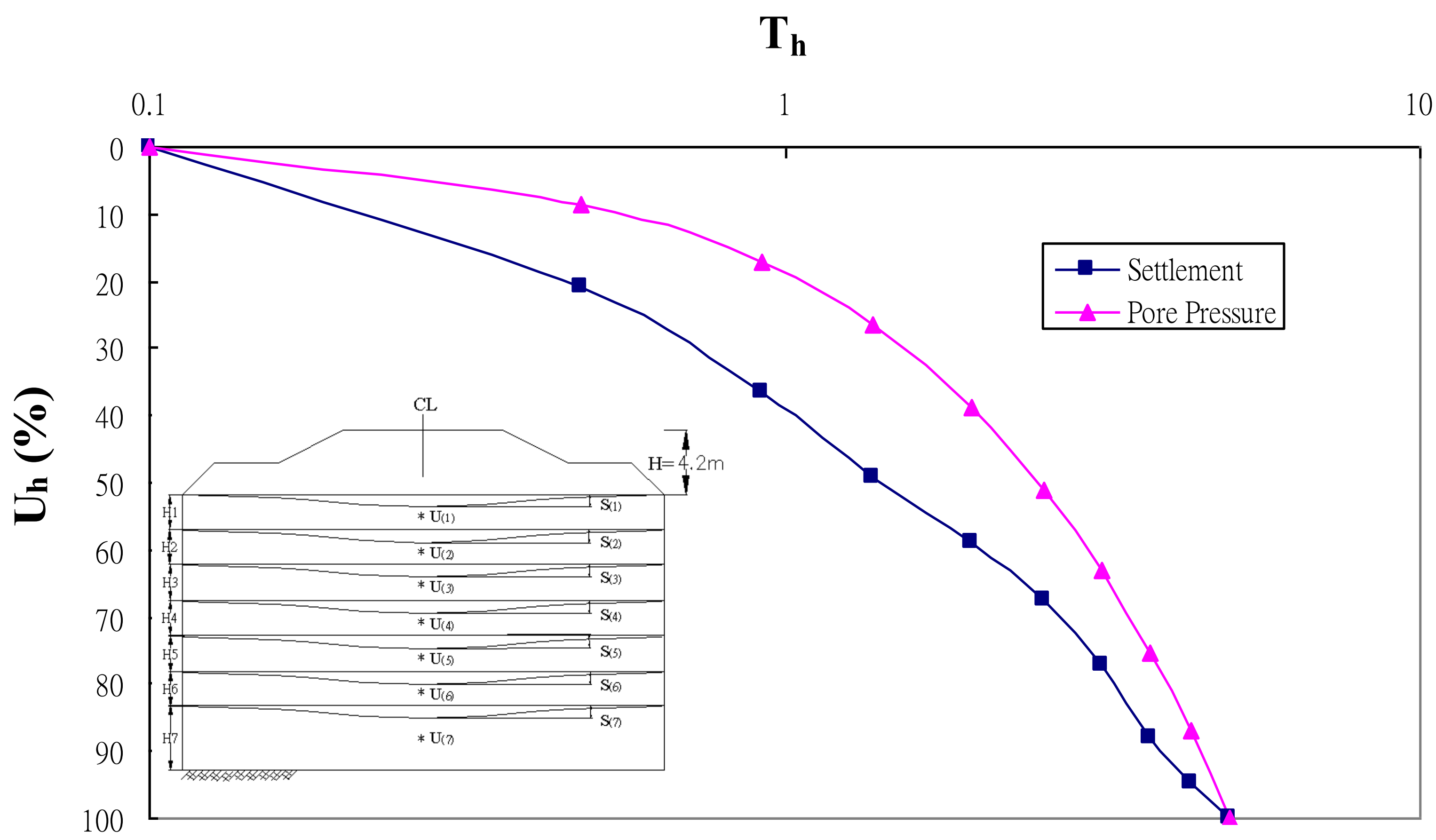


In terms of Settlement



In terms of Excess Pore Pressure

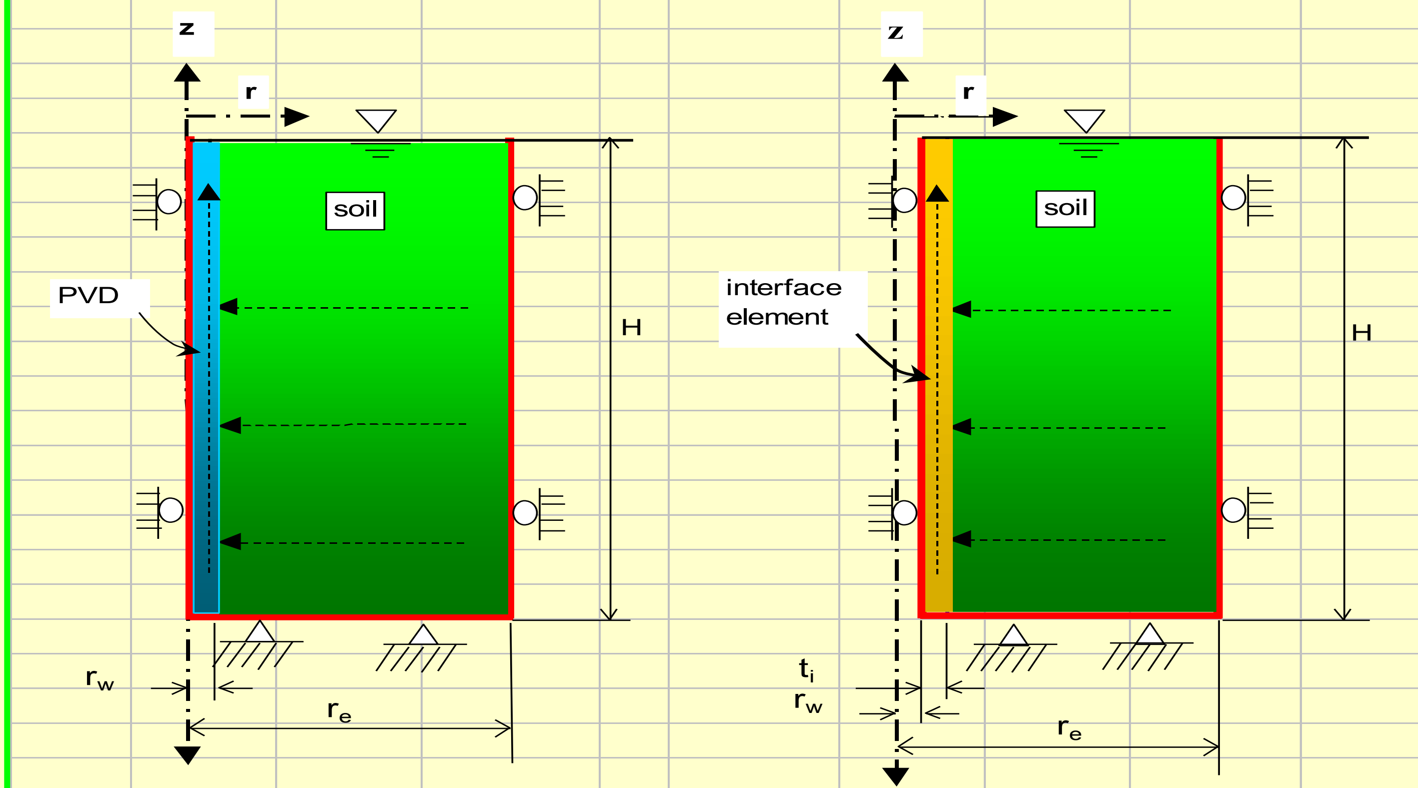
Degree of Consolidation in Term of Settlement Rate and Excess Pore Pressure Dissipation Rate



2-D NUMERICAL MODELING oF *PVD* IMPROVED GROUND

(Plaxis Analysis)

Numerical Modeling of *PVD* Using Interface Element



(a) unit cell with Prefabicated Vertical Drain

(b) unit cell with interface element

: closed consolidation boundary

: pore water flow

t_i : thickness of interface element

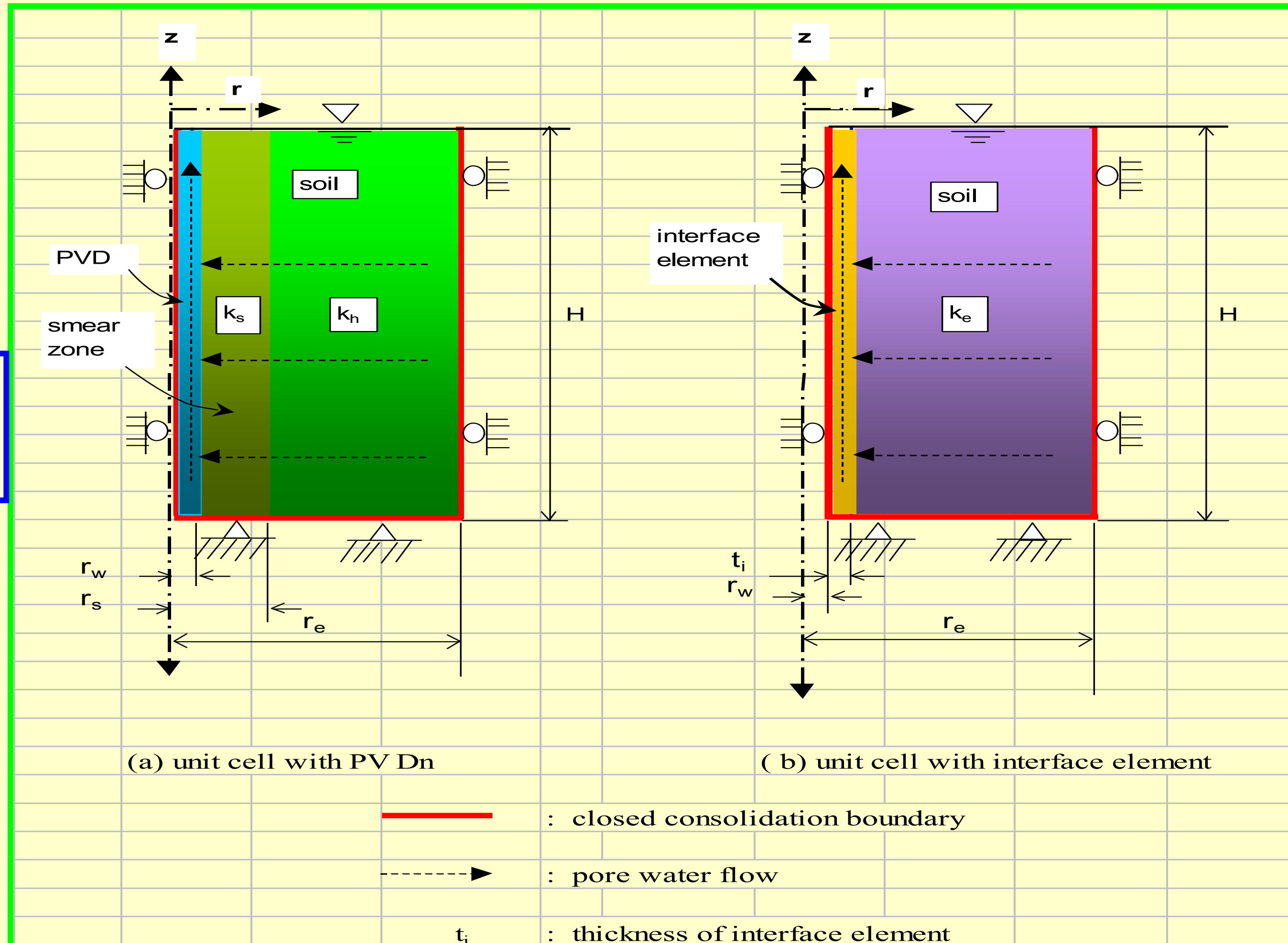
Well Resistance And Smear Effect

Discharge capacity:

$q_w = 1000\sim10\ m^3/day$

Well resistance :

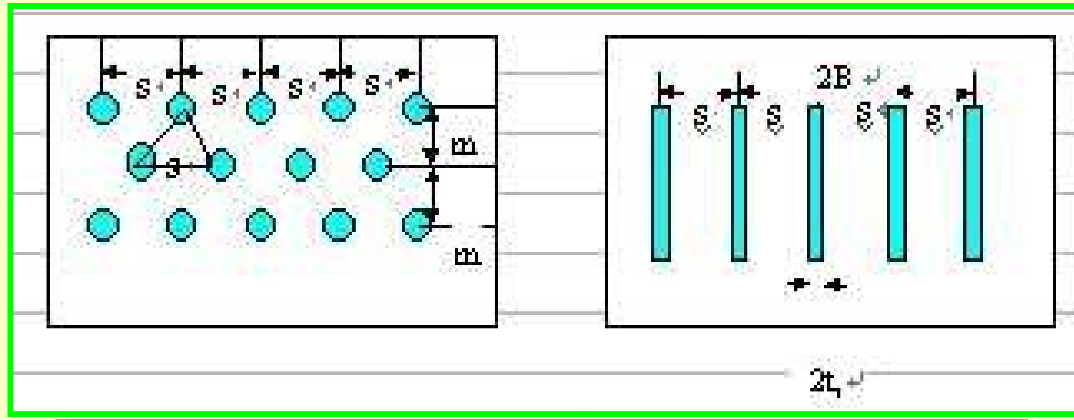
$k_w = (q_w/\pi r_w^{\,2})\ m/day$



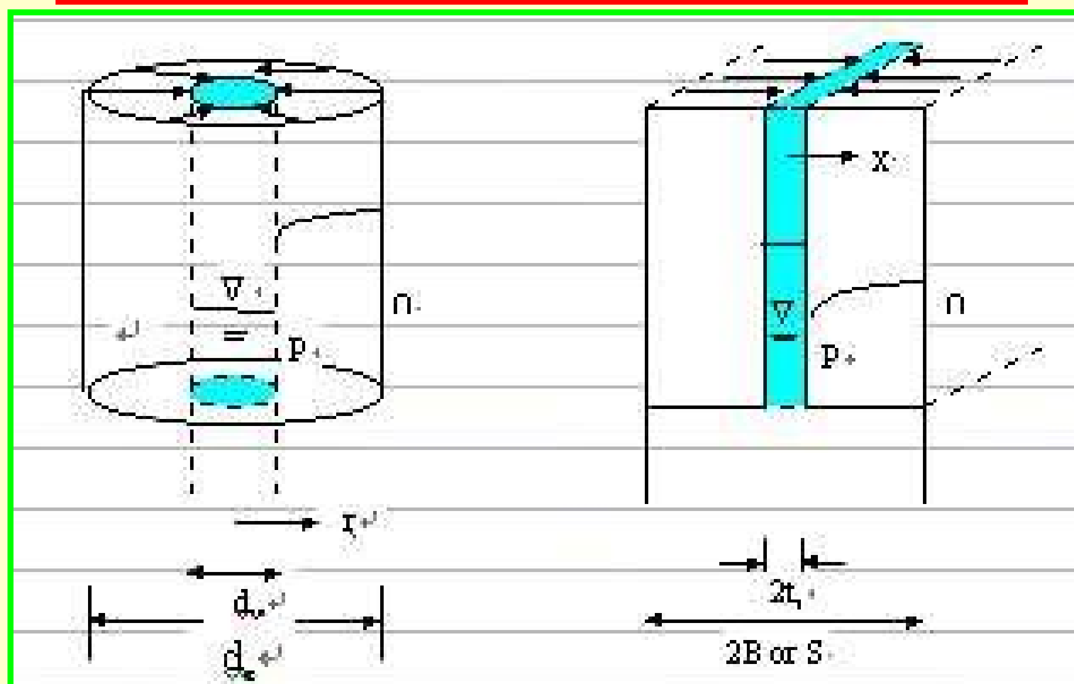
Smear effect :

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

Conversion of Axis-symmetric Radial Flow to 2-D Plain Flow



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

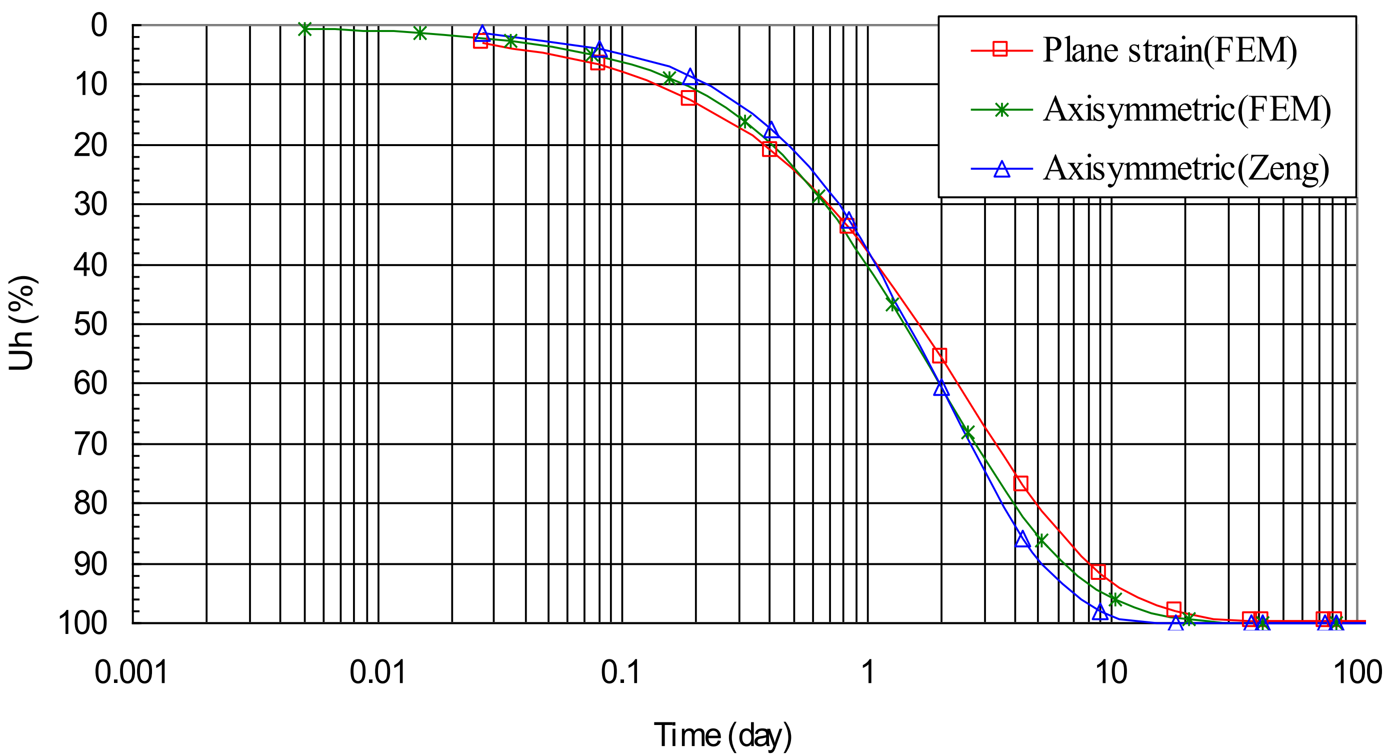


- **Equaling the average consolidation rate for both cases**

- **S= smear ratio=(r_s/r_w)**
- **n=influence ratio=(r_e/r_w)**
- **$r_w=(b+t)/4$**

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

Conversion of Axis-symmetric 2-D Radial Flow To 2-D Plane Flow With Well Resistance And Smear Effect



- q_w=20 m^3/yr ; k_h=8.64x10^{-4} m/day ; (k_h/k_s)=4
- s= smear ratio=(r_s/r_w)=2.4 ; H=10 m ; n=influence ratio=(r_e/r_w)=27

Conversion Of Permeability From Axis-symmetric Radial Flow To 2-D Plane Flow With Smear Effect in SBIA

General	k_h/k_s	10	15	5
	Spacing (m)	1		
	H (m)	12		
	Configuration	square		
Axis-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 (m³/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 (m³/yr)	20		
	k_w (m/day)	0.76		
	B (m)	0.5		
	m(m)	1		
	t_{ipl} (m)	0.06		

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

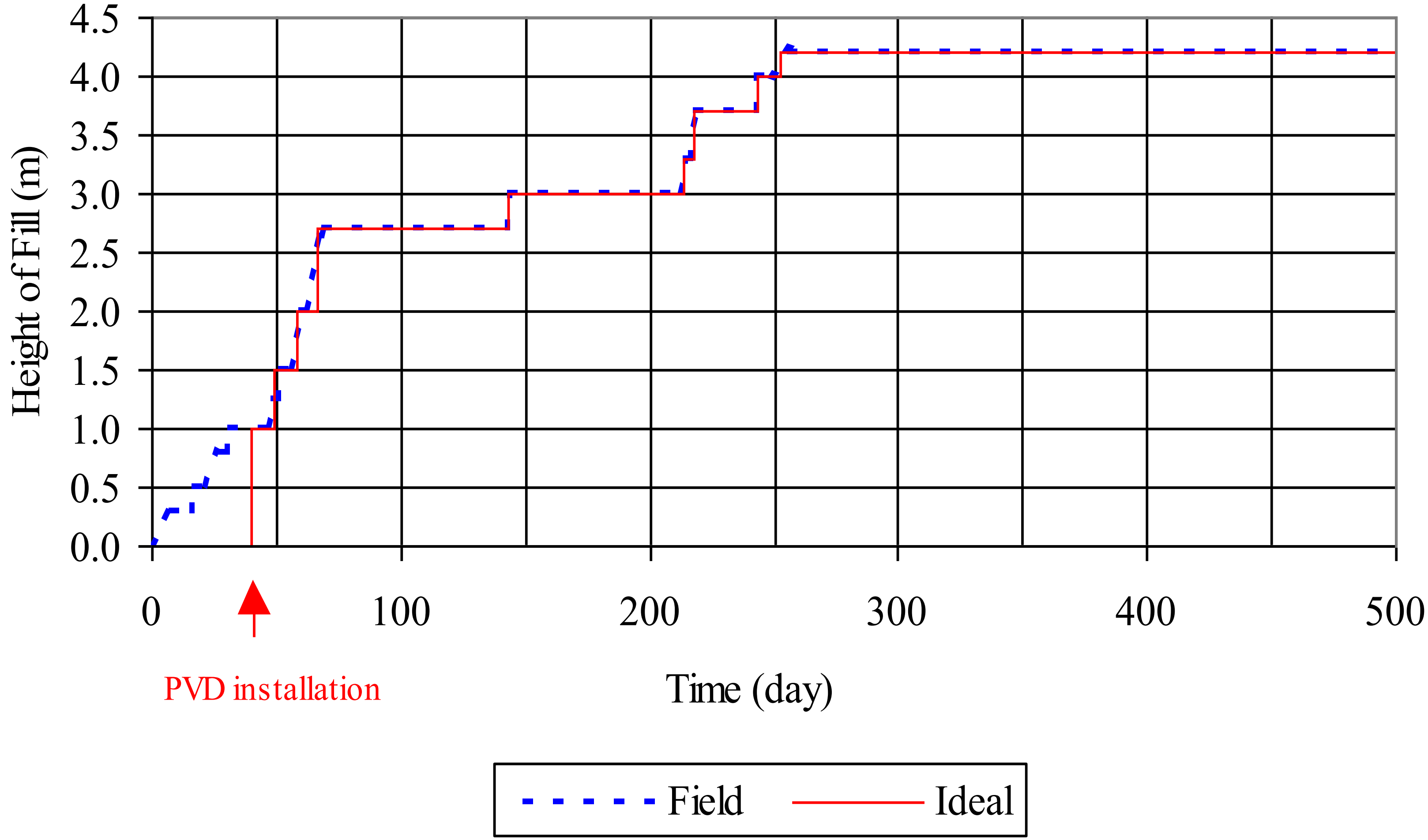
$$t_{ipl} = \pi r_w^2 / m = \left(q_w / 2mk_{wpl}\right)$$

Soil Model Parameters For FEM Analysis In SBIA Project

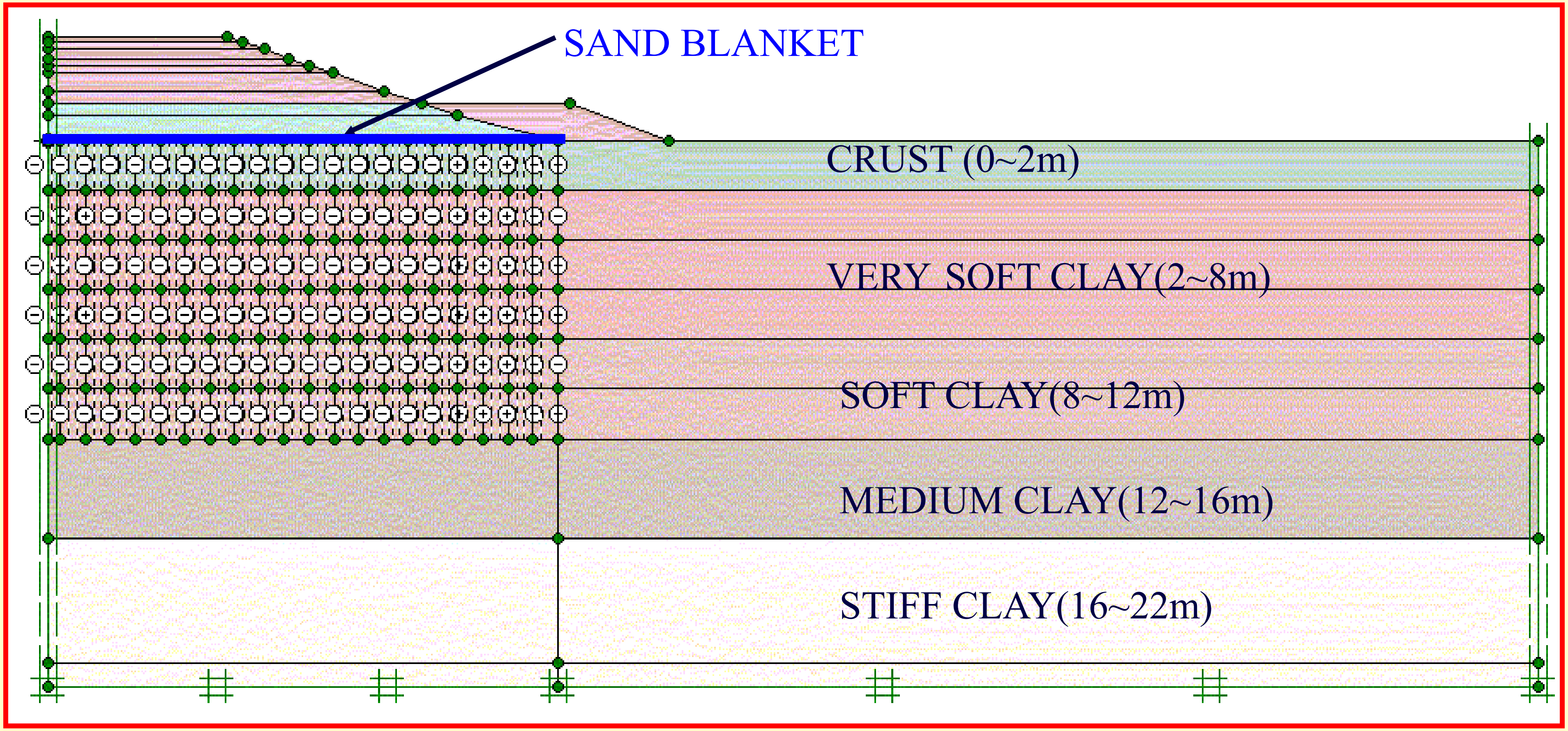
Depth (m)	c' (kpa)	ϕ' (degree)	λ^*	κ^*	K_o	k_h (m/day)	k_v (m/day)	γ_t (kN/m^3)	γ_d (kN/m^3)	OCR
0 ~ 2 crust	30	28	0.130	0.013	0.70	2.59E-03	2.59E-03	16.0	9.41	7.00
2 ~ 4 very soft clay	10	23	0.239	0.024	0.65	1.01E-03	5.90E-04	14.2	7.10	3.00
4 ~ 6 very soft clay	10	23	0.239	0.024	0.65	1.01E-03	5.90E-04	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

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
back fill	10	30	0.50	7000	8.64E+00	8.64E+00	19.0	17.00

Construction Sequences Of Testing Embankment (TS-1)and *PVD* in SBIA



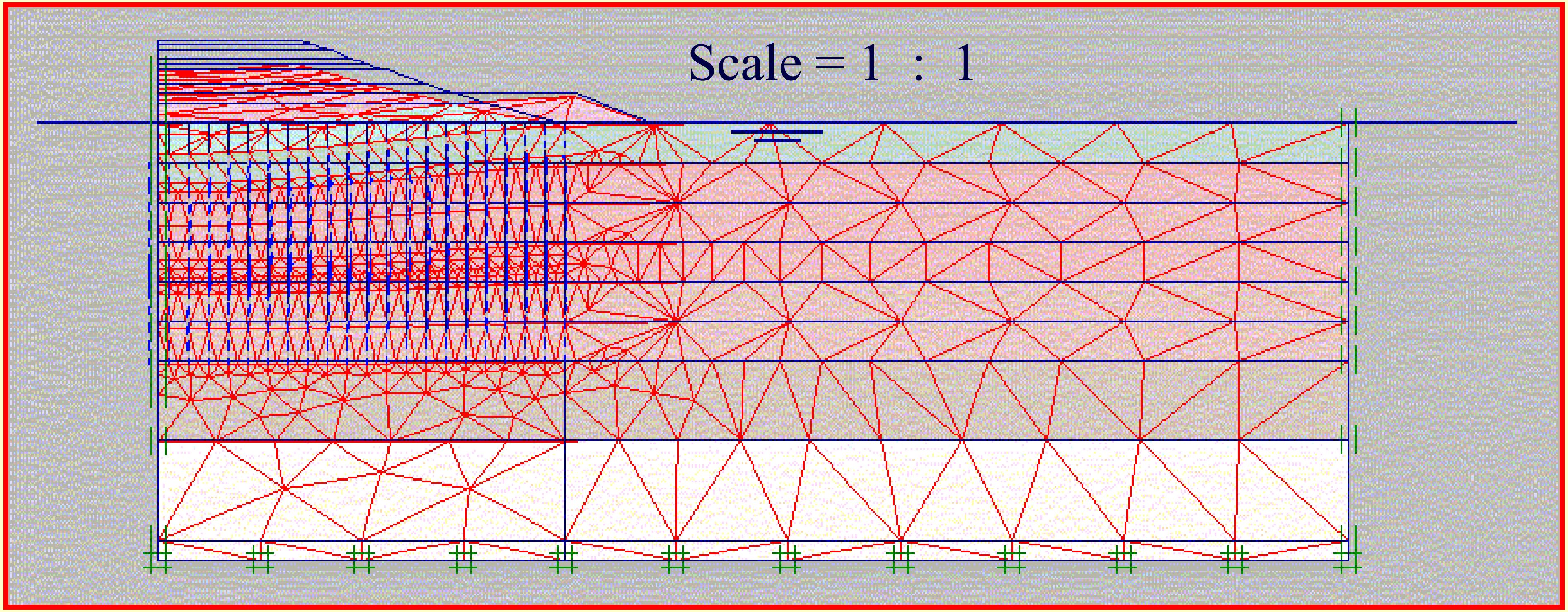
Finite Element Mesh of *PVD* Improved Ground in SBIA



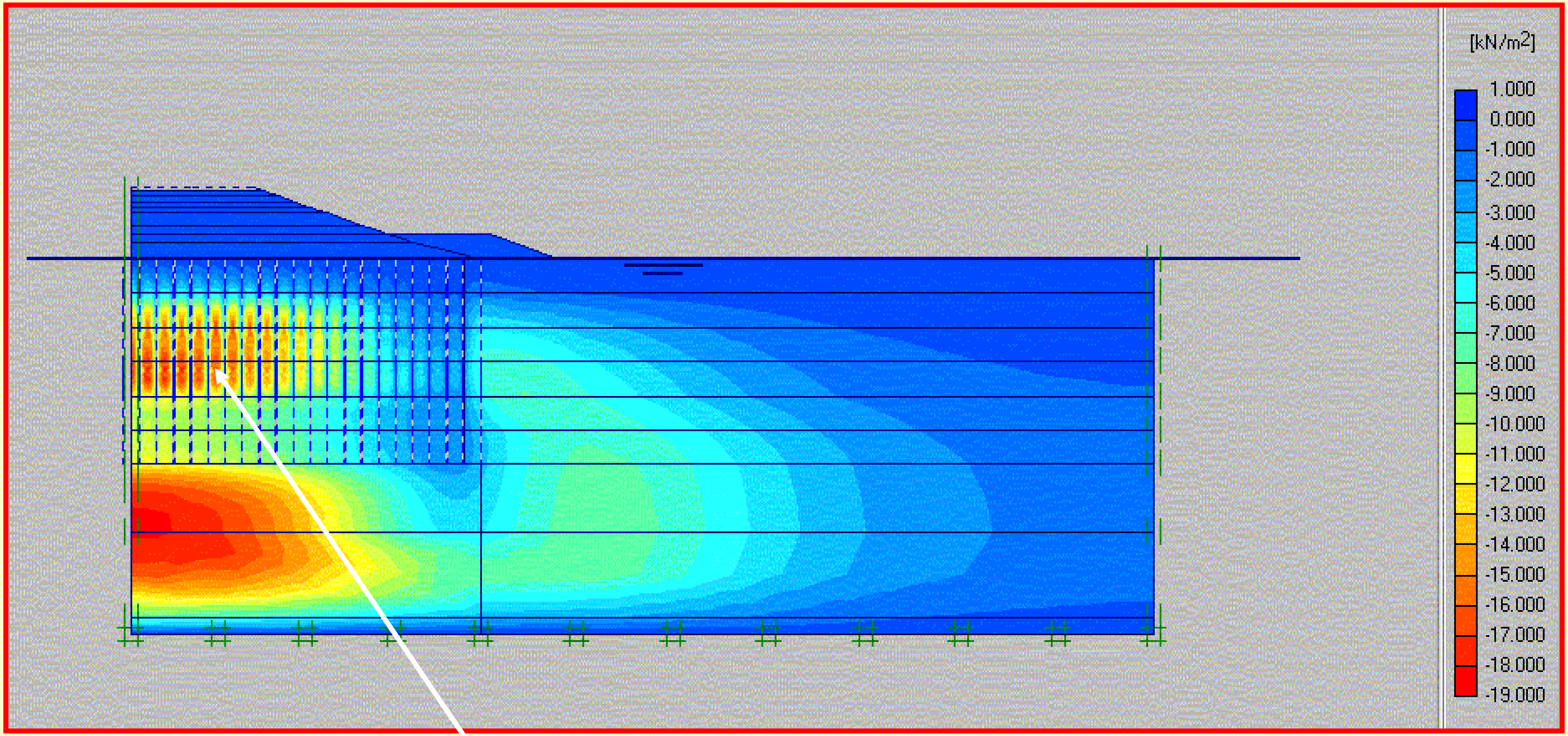
PVD: l_d=12m, b=100mm, a=3mm, $r_w=(d_w/2)=(a+b)/4$

S=1m (Square), $d_e=2(r_e)=1.13(S)$, r_e=0.565m

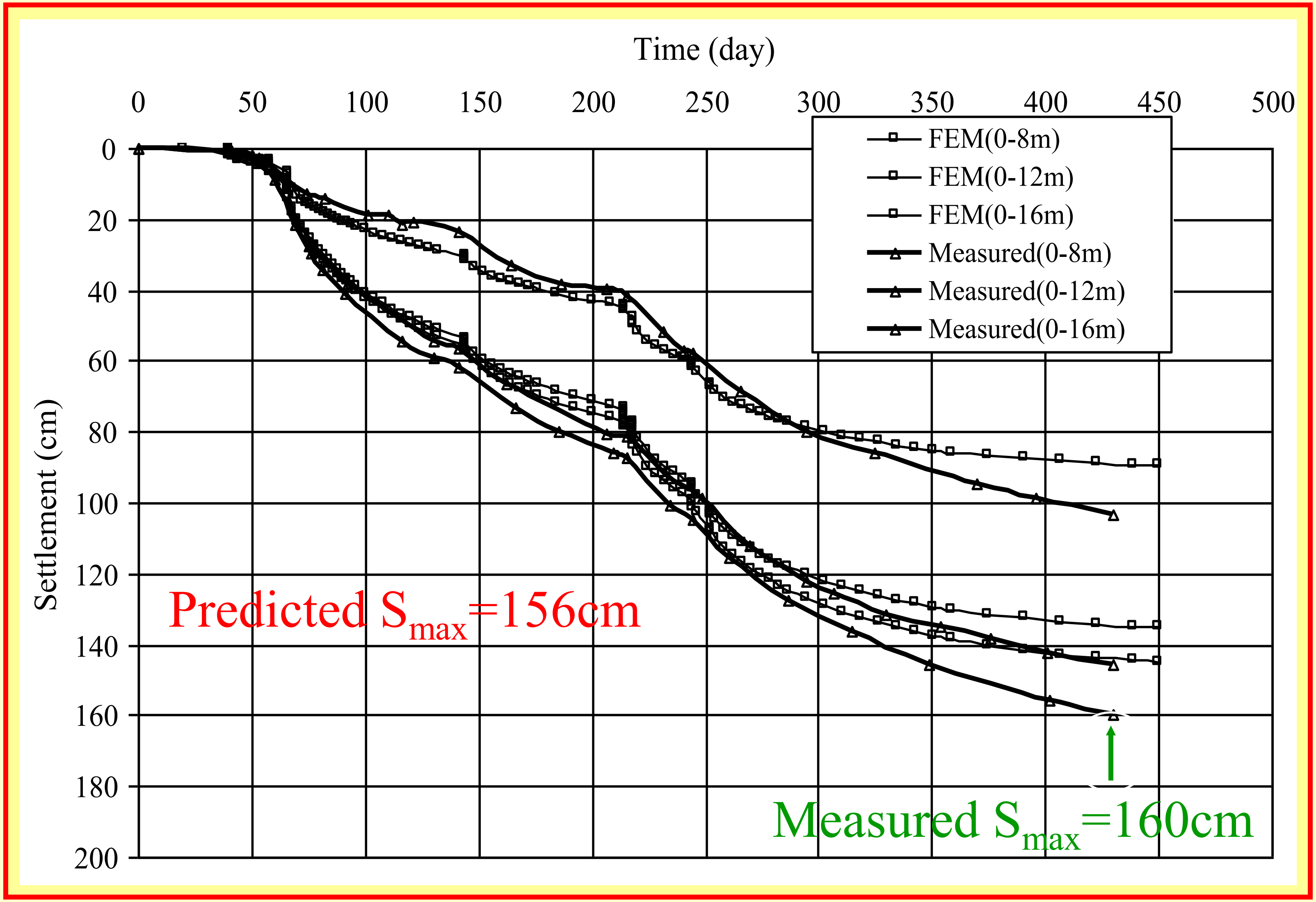
Deformed Mesh of *PVD* Improved Ground in SBIA



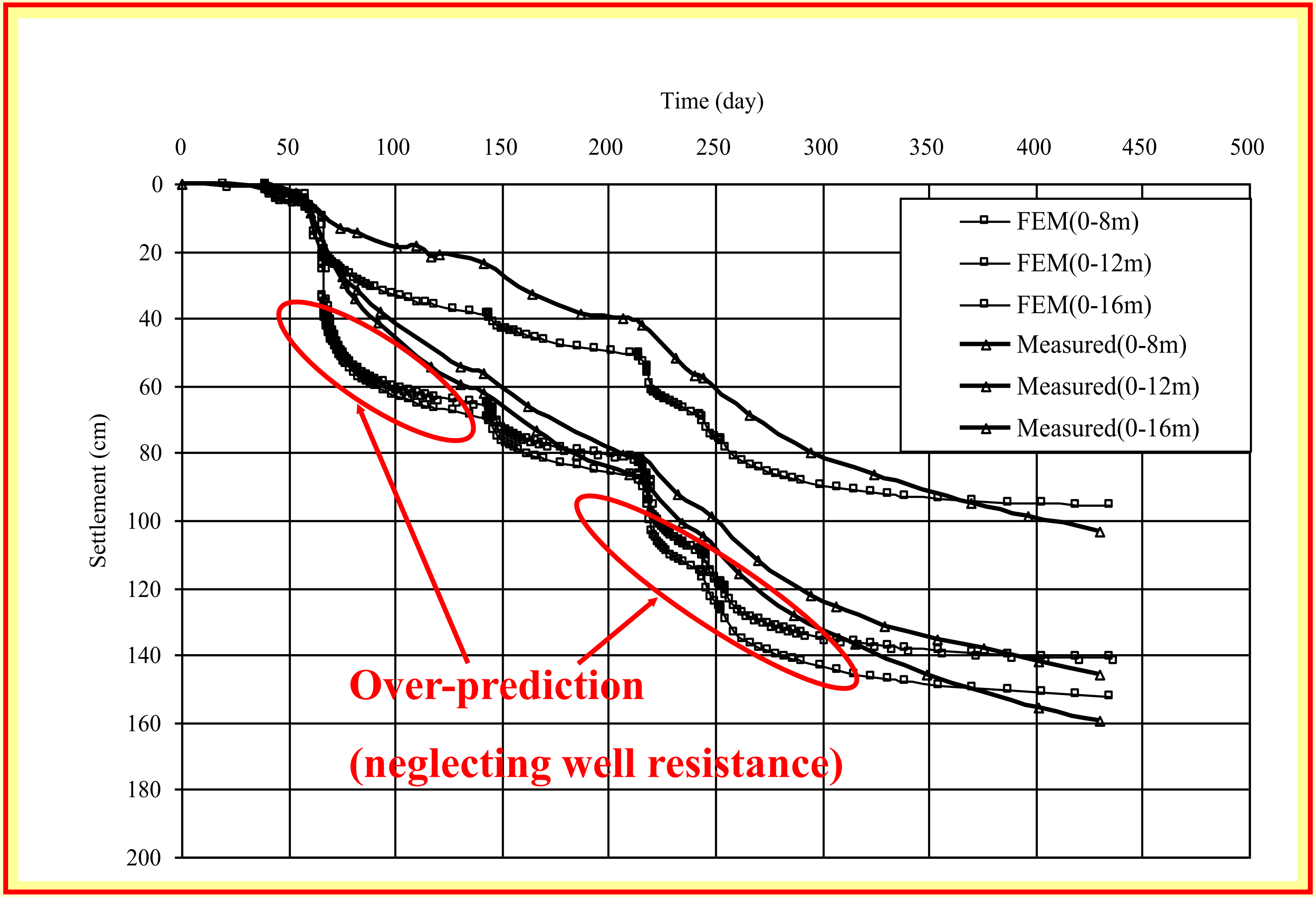
Dissipation of Excess Pore Water Pressure in *PVD* Improved Ground



Finite Element Analysis With Simulations of Smear Effect And Well Resistance



Finite Element Analysis without Considering Well Resistance



CONCLUSIONS

Conclusions

- In a command-driven type of 3-D analysis (Flac^{3D} analysis), the discharge capacity of *PVD* can be varied with the elapsed consolidation time thru a programming technique to consider the time-dependent well resistance effect in calculation.

- The degree of consolidation obtained from settlement rate is constantly higher than that from pore pressure dissipation rate.

Thanks For Your Attention!!

For Steady State Flow

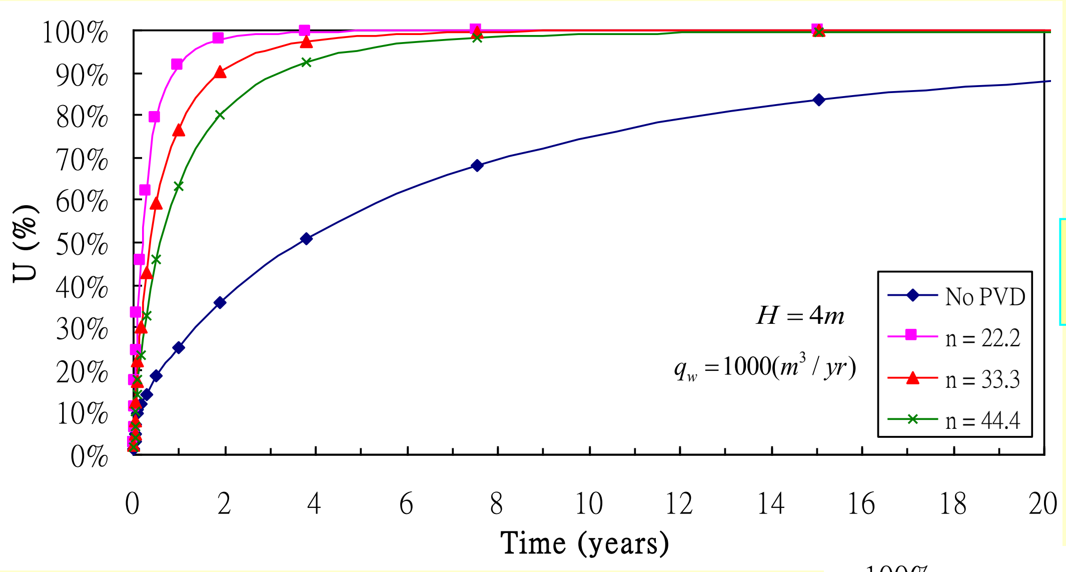
$$q = k_h \times i \times A$$

$$q_1 = 2\pi r H k_h \frac{\partial u_1}{\partial r \, \gamma_w} \quad (r_s \le r \le r_e) \Rightarrow \Delta u_1 = \frac{q_1 \gamma_w}{2\pi H k_h \ln\left(\frac{r_e}{r_s}\right)}$$

$$q_2 = 2\pi r H k_s \frac{\partial u_2}{\partial r \, \gamma_w} \quad (r_w \le r \le r_s) \Rightarrow \Delta u_2 = \frac{q_2 \gamma_w}{2\pi H k_s \ln\left(\frac{r_s}{r_w}\right)}$$

$$q_e = 2\pi r H k_e \frac{\partial u_e}{\partial r \, \gamma_w} \quad (r_w \le r \le r_e) \Rightarrow \Delta u_e = \frac{q_e \gamma_w}{2\pi H k_e \ln\left(\frac{r_e}{r_w}\right)}$$

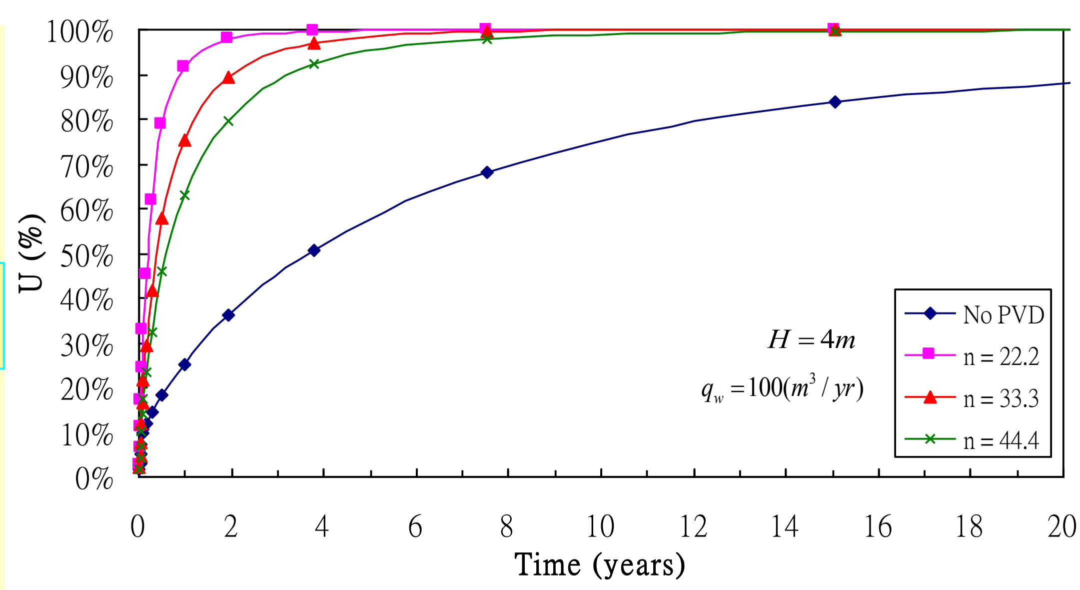
Consolidation Rate of *PVD* Improved Ground for Various Installations Spacing *S*=1*m*, 1.5*m* , 2*m*, No *PVD*



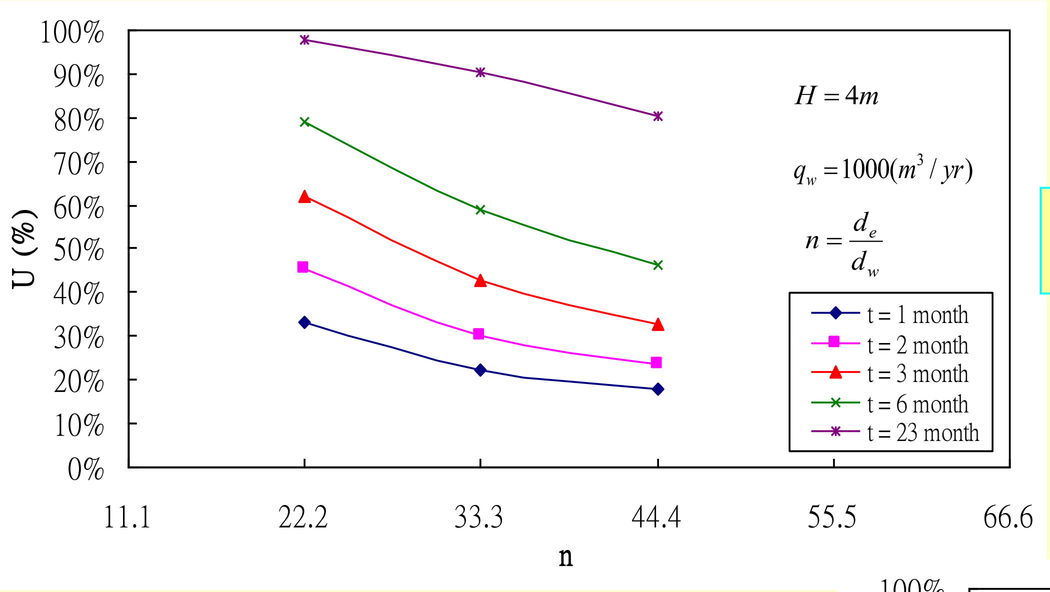
※ $n = d_e / d_w = 1.13S / d_w$

H=4m , q_w=1000(m^3/yr)

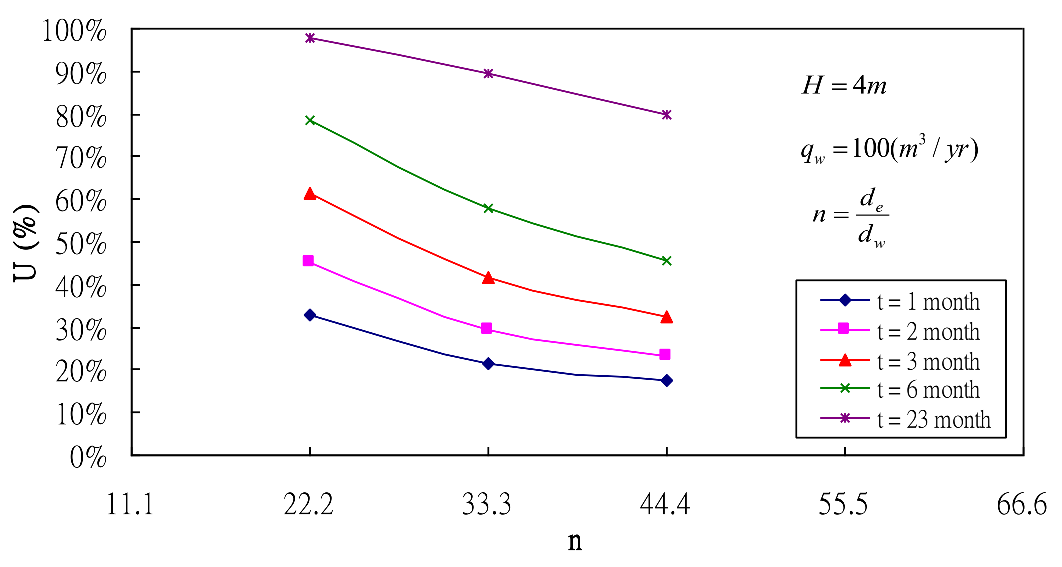
H=4m , q_w=100(m^3/yr)



Consolidation Rate of *PVD* Improved Ground for Various Installation Spacing at t=1mon, 2mon, 3mon, 6mon and 23mon



***H*=4*m* , *q*$_w$=1000(*m*^{3}/yr)**



***H*=4*m* , *q*$_w$=100(*m*^{3}/yr)**