SOFT CLAY IMPROVEMENT USING VERTICAL DRAINS AND VACUUM PRELOADING

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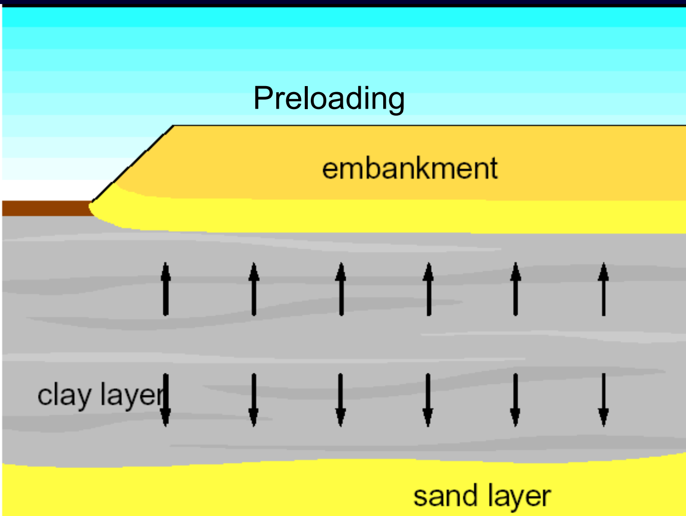
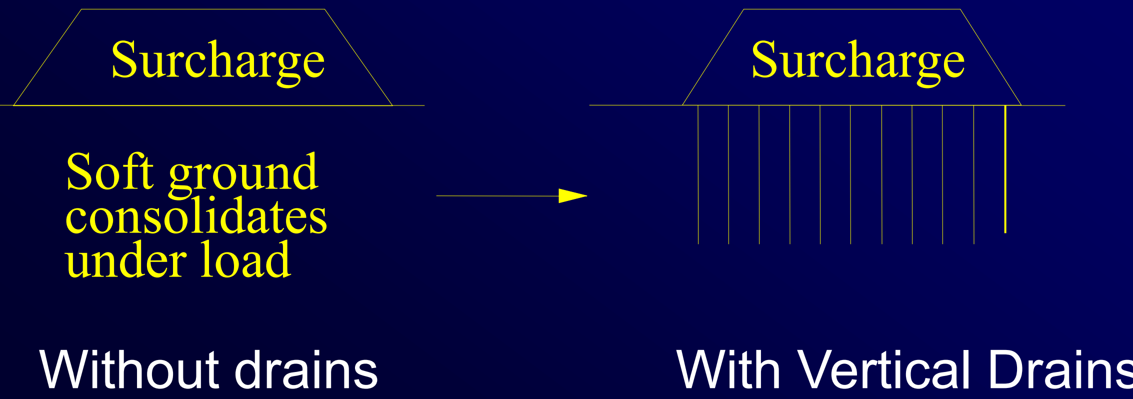
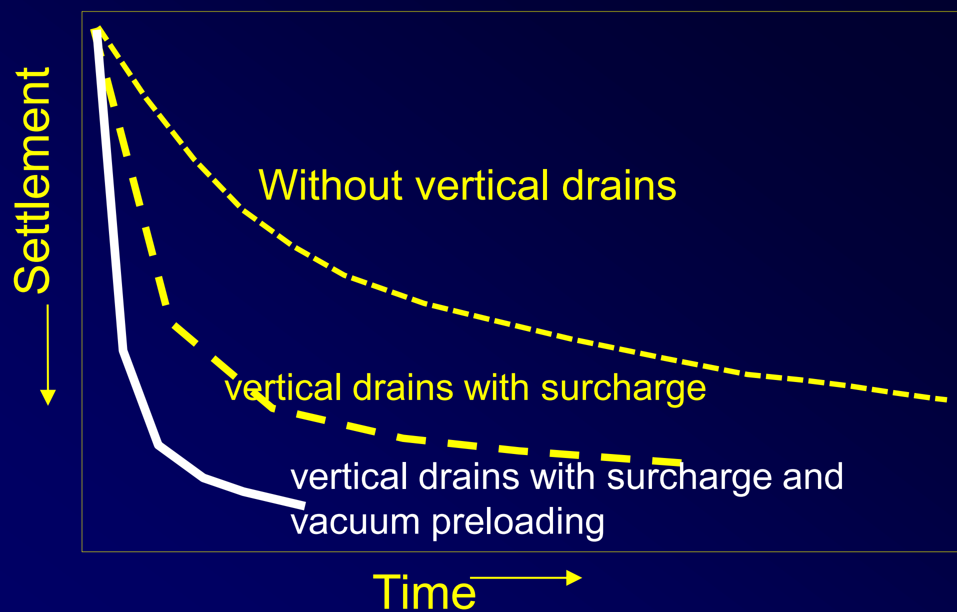
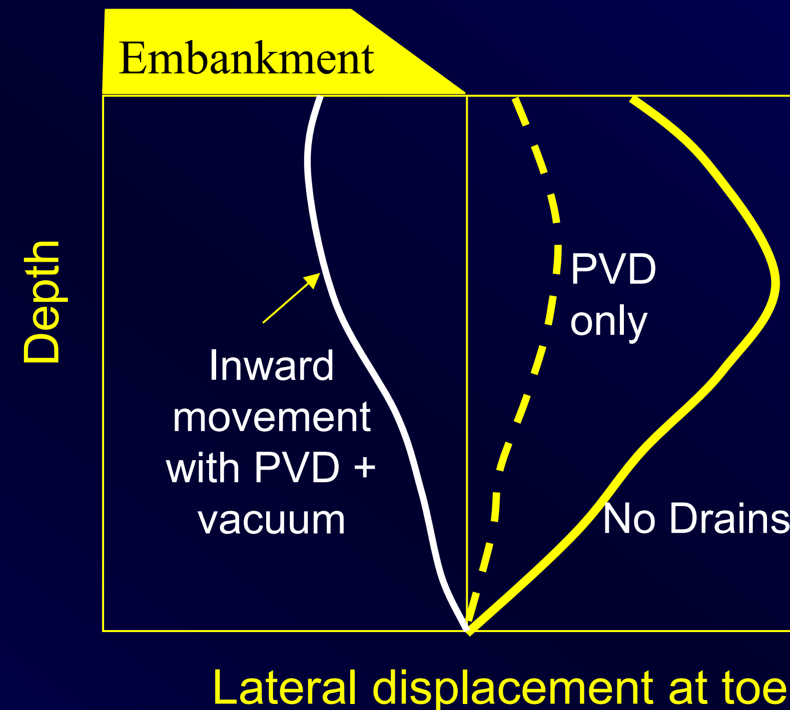
Potential benefits of Subsurface Drainage for Track on Soft Formation clays



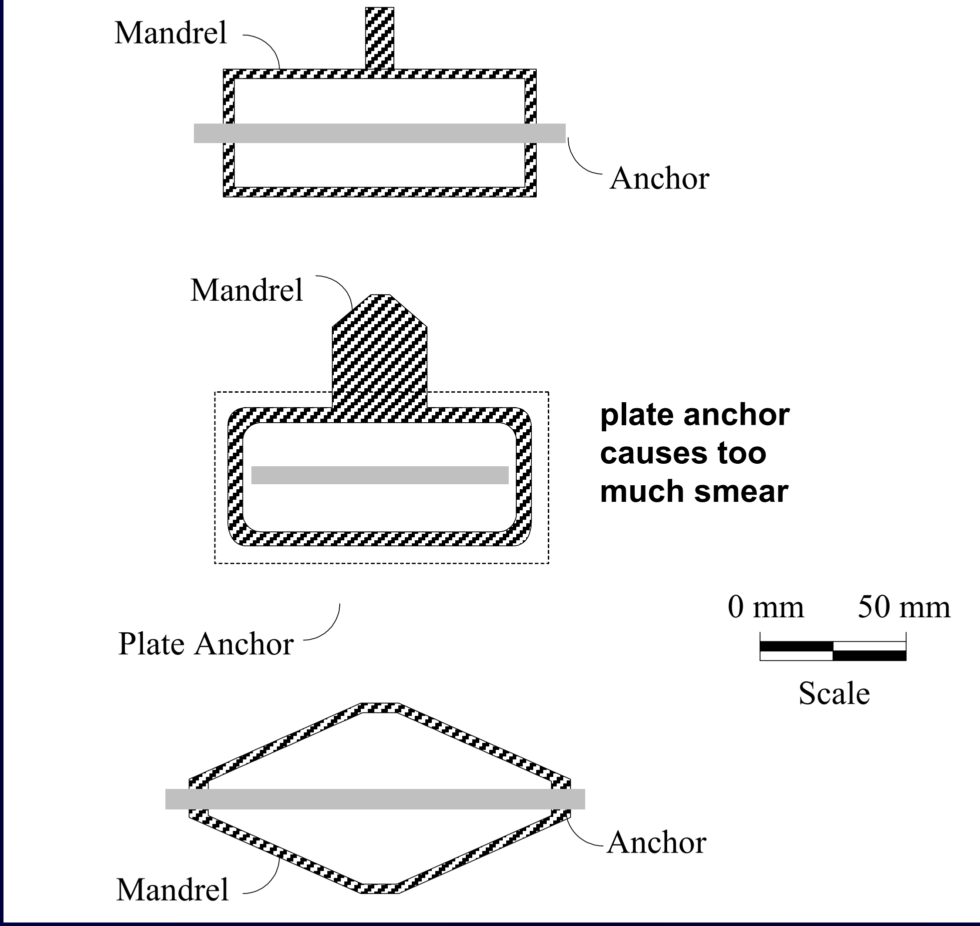






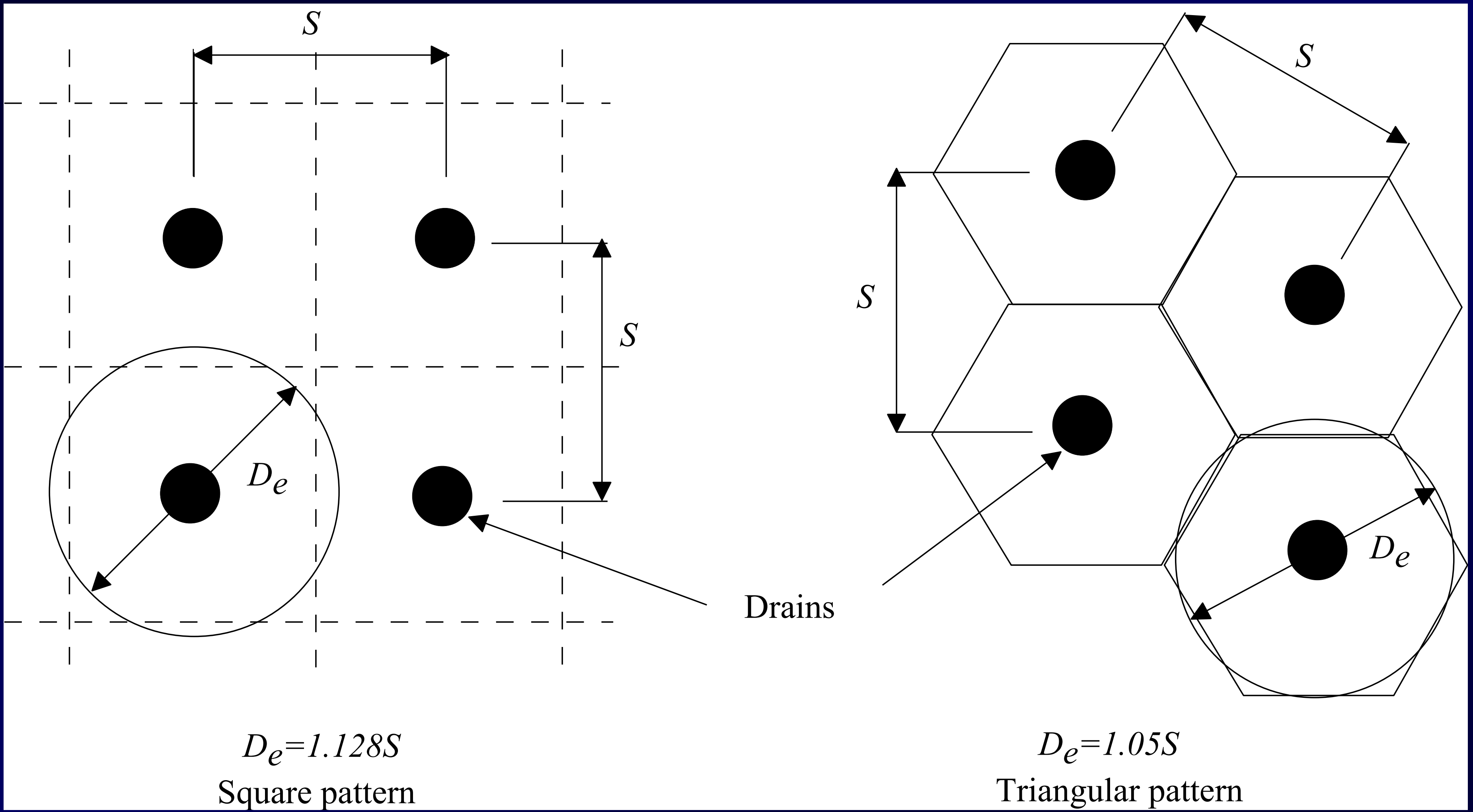
Installation of PVDs

Installation Rig



Drain anchors and Mandrel shapes

Drain Installation Patterns



D_e -equivalent diameter of the influence zone
S -drain spacing

Theory of Radial Consolidation

$$\frac{\partial u}{\partial t} = c_h \left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} \right) + c_v \frac{\partial^2 u}{\partial z^2}$$

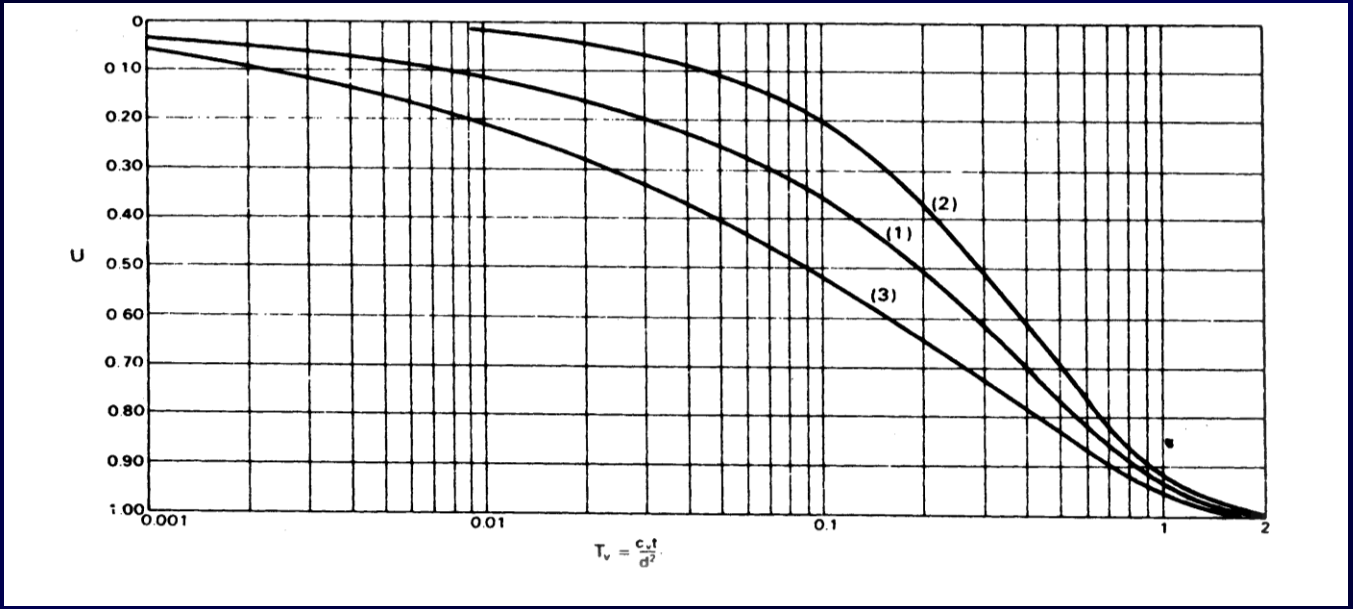
The overall degree of consolidation U is given by:

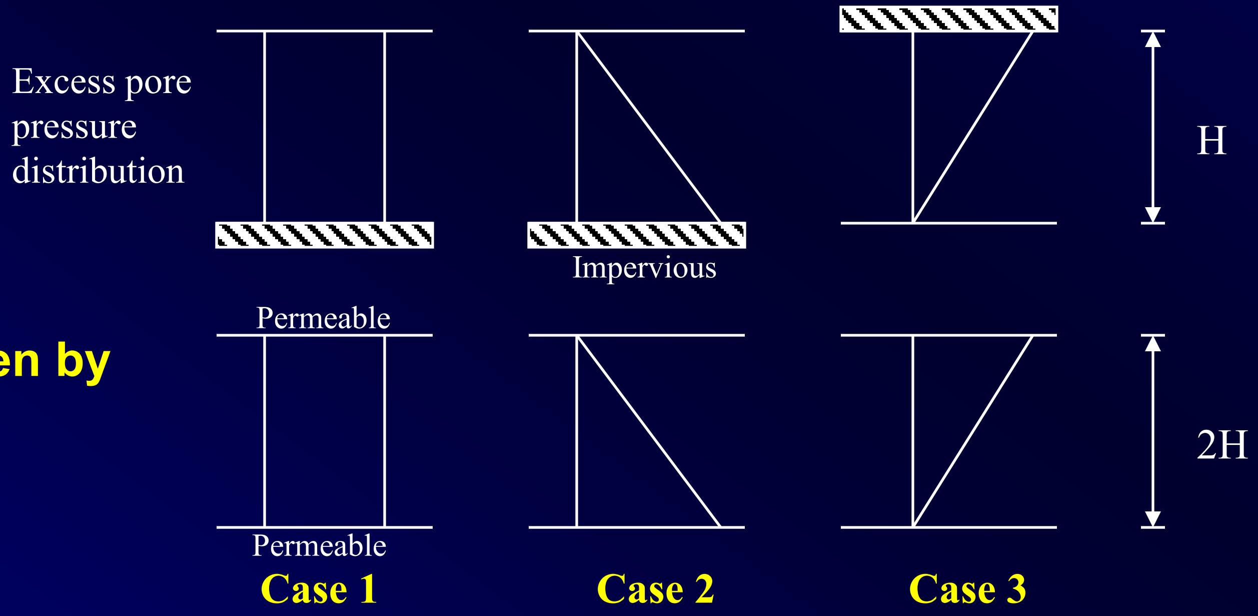
$$1 - U = (1 - U_r)(1 - U_V)$$

u - Excess pore water pressure at time t
c_h - Coefficient of consolidation for radial consolidation
c_v - Coefficient of consolidation for vertical consolidation
U_v - Average degree of consolidation due to vertical flow
U_r - Average degree of consolidation due to radial flow

Consolidation Theory for Vertical Flow

(Terzaghi 1-D theory plotted by Craig 2004)





Time factor T_v is given by

$$T_v = \frac{c_v t}{H^2}$$

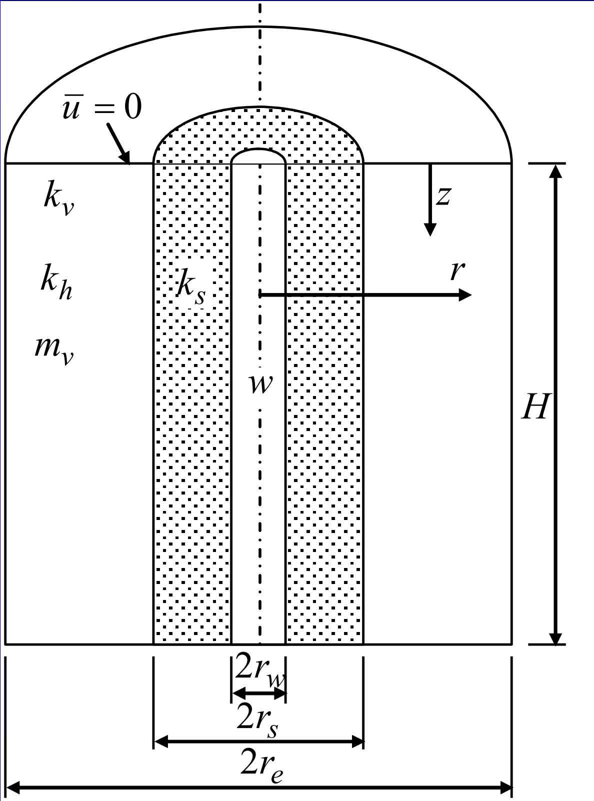
Consolidation Theory for Radial Flow

(Hansbo, 1981)

$$U_r = 1 - exp\left(\frac{-8T_h}{\mu}\right)$$

$$\mu = ln\frac{n}{s} + \frac{k_h}{k_s} ln\, s - 0.75$$

$$T_h = c_h t / d_e^2$$



μ represents the drain geometry and smear effect

n **=** ***d*** $_e$ **/** ***d*** $_w$

s = ***d*** $_s$ **/** ***d*** $_w$

d $_e$ **= equivalent diameter of influence for each drain,**

d $_s$ **= diameter of smear zone (3-4 times the equivalent mandrel diameter)**

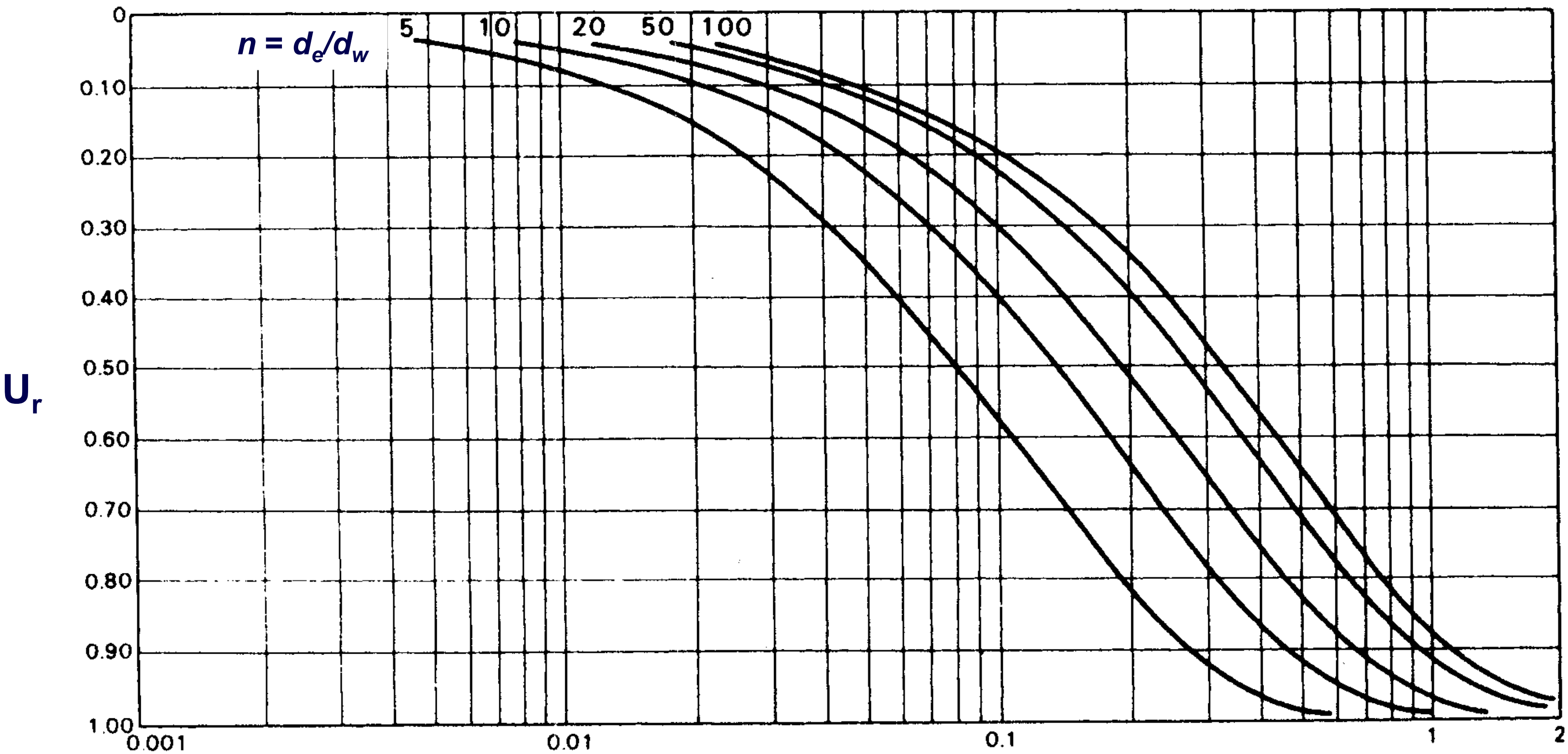
d $_w$ **= equivalent diameter of drain (see later slide)**

k $_h$ **= average horizontal permeability in the undistrubed zone,**

k $_s$ **= average horizontal permeability in the smear zone,**

Consolidation curves for Radial Flow (no smear)

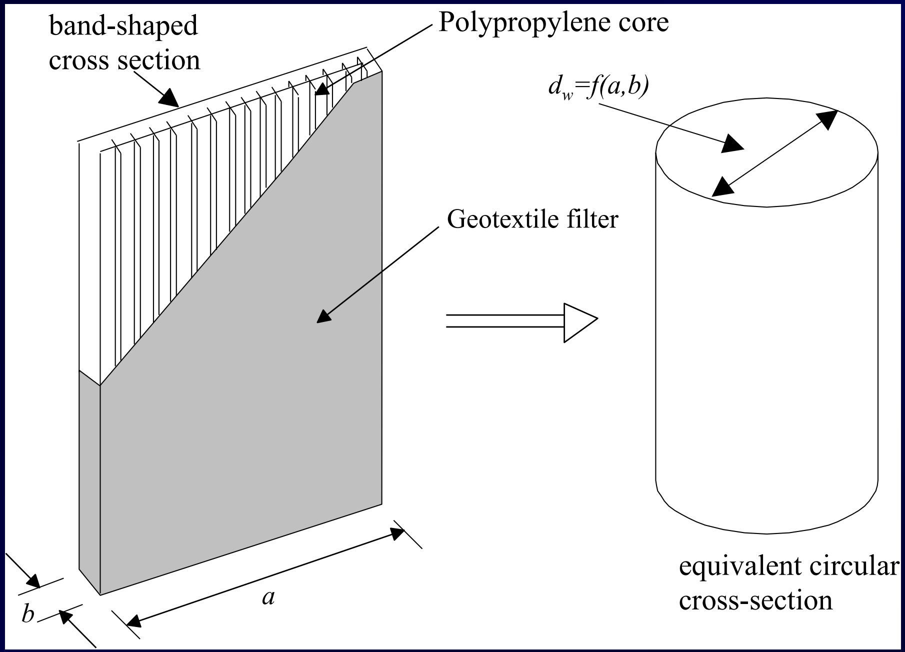
(Hansbo, 1981)



$$T_h = c_h t / d_e^2$$

Parameter Determination

Equivalent drain diameter of band shaped vertical drain



$$d_w = \frac{2(a+b)}{\pi}$$

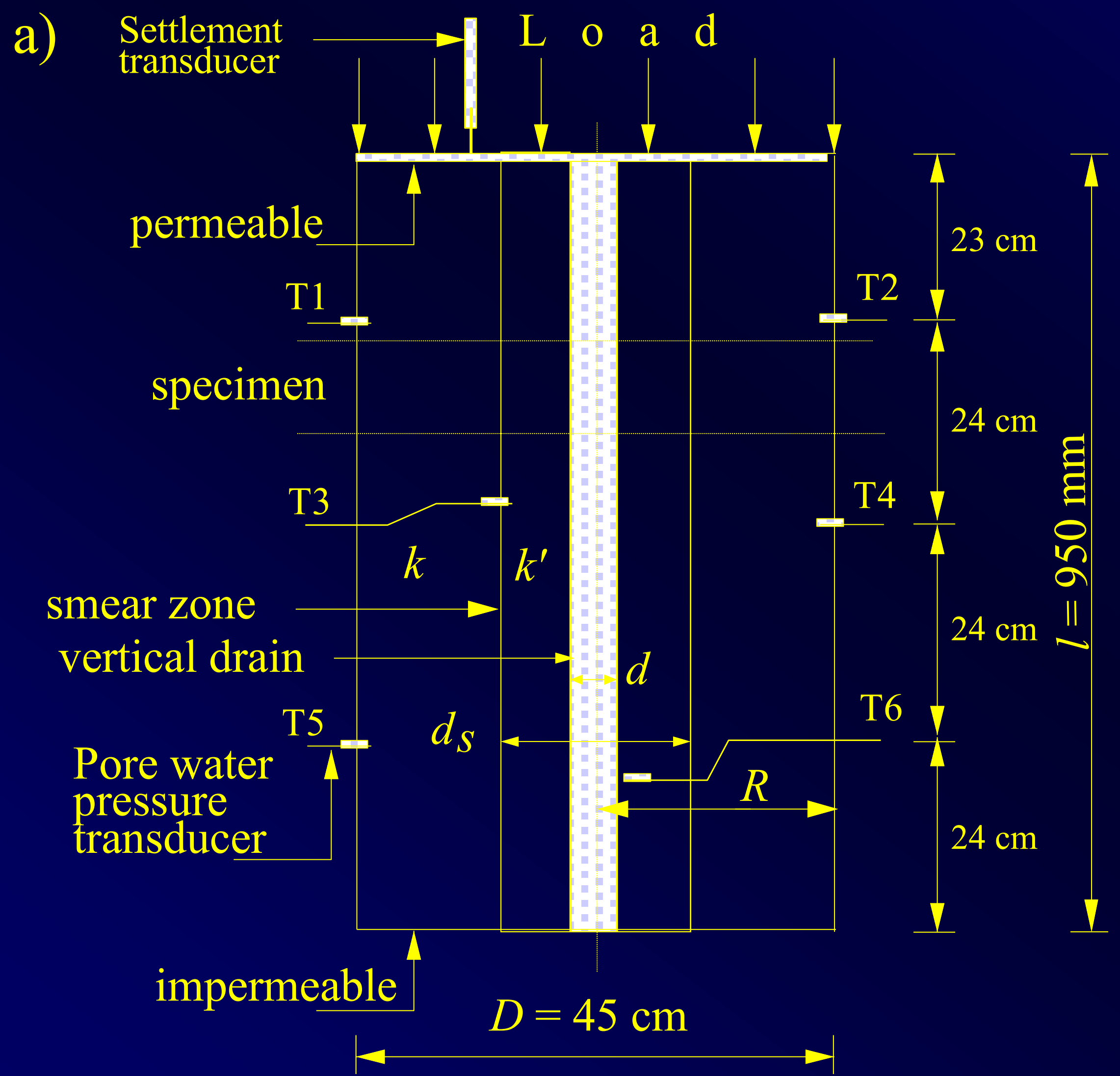
Smear zone permeability and extent of smear zone

d_s = 3-4 d_m (equivalent diameter of mandrel)

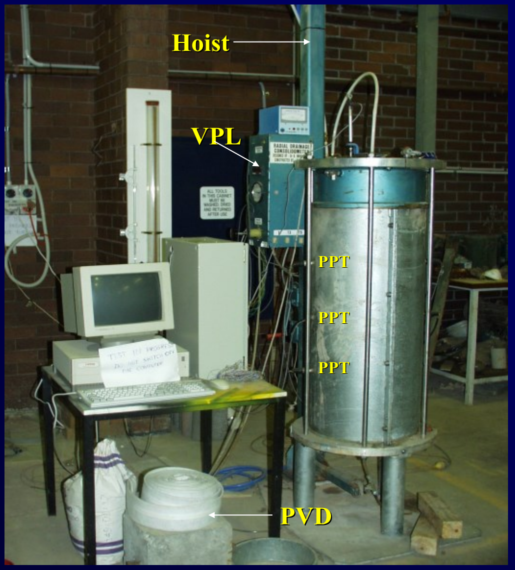
Smear zone permeability, k_s= (0.33-0.5) k_h

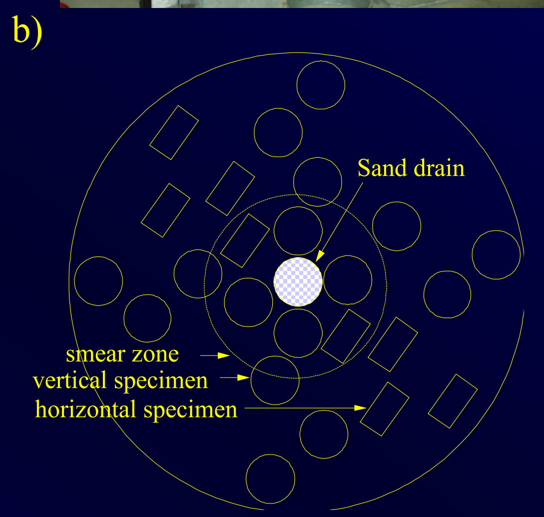
Assessment of the Extent of Smear Zone

(Indraratna & Redana, 1998, Sathananthan & Indraratna 2006)



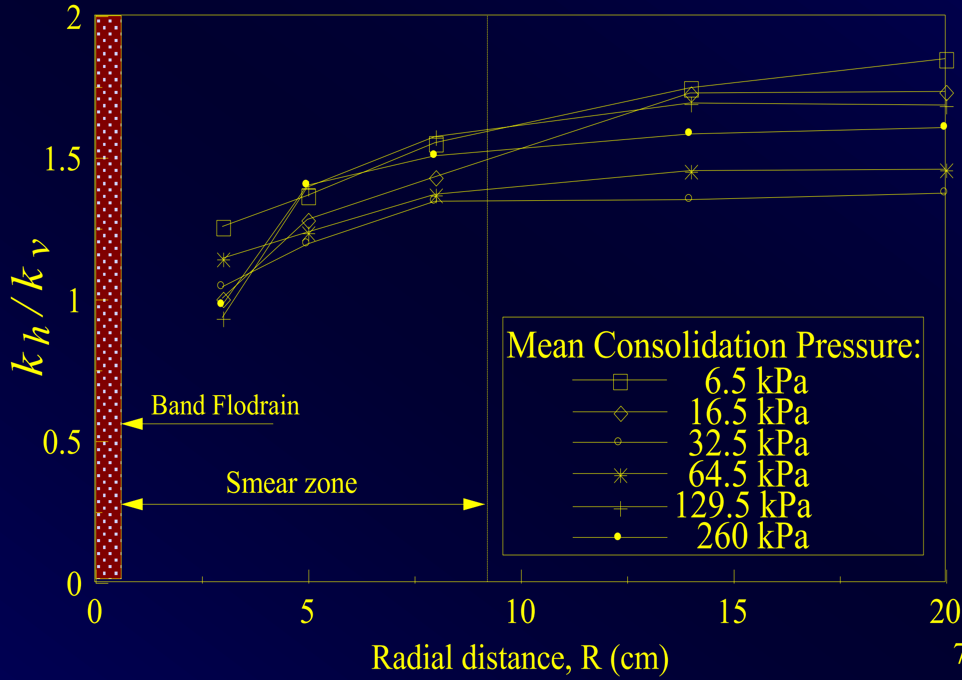
PVD and smear zone





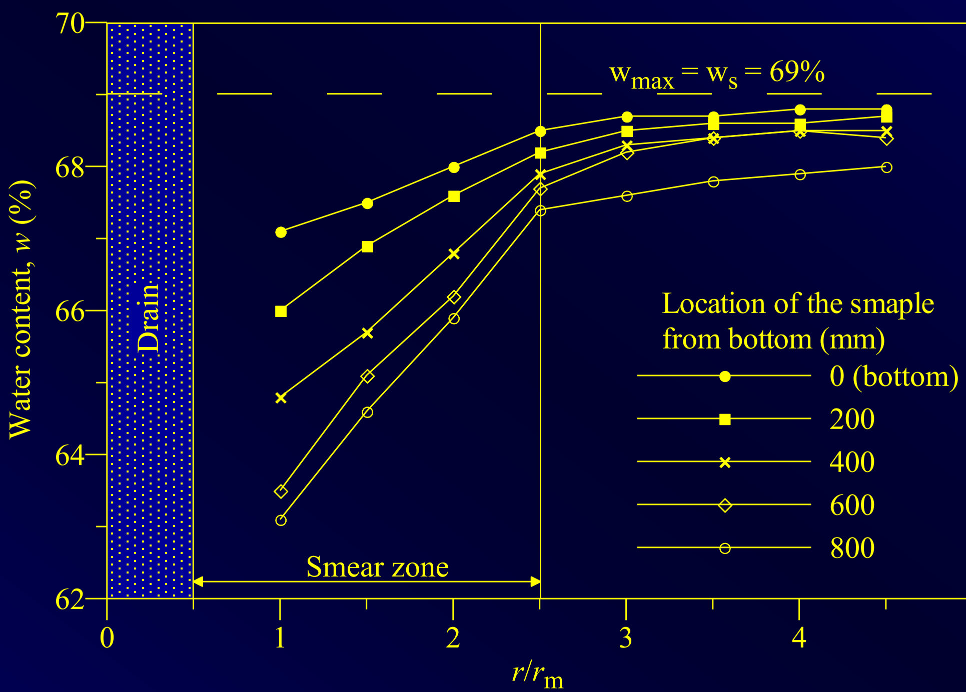
Locations of cored specimens

Smear zone permeability and extent of smear zone



Permeability Approach

Indraratna & Redana, 1998, JGGE, ASCE.

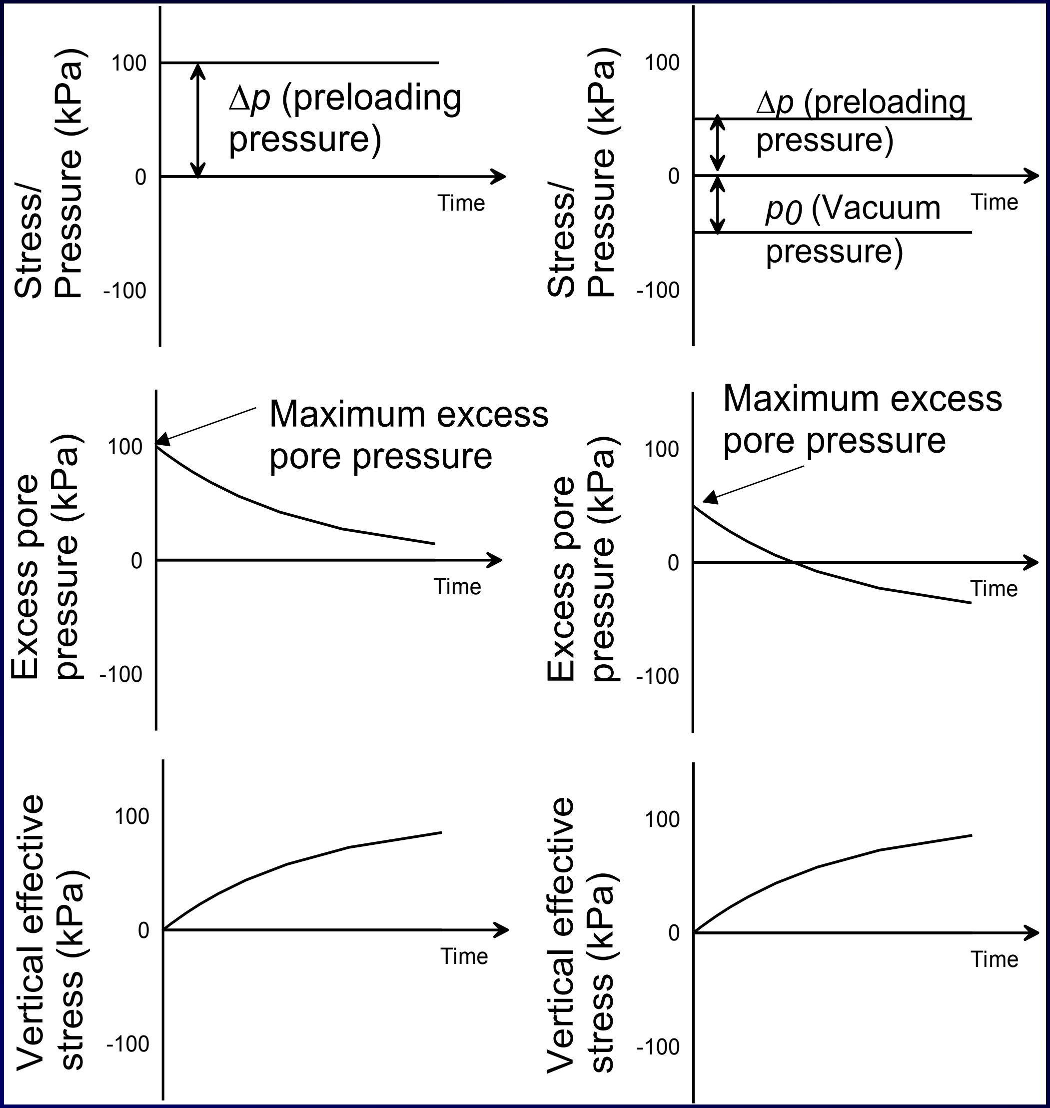


Water Content Approach

Sathananthan & Indraratna 2006, JGGE, ASCE.

Conventional Surcharge vs Vacuum Preloading

(Chu and Yan, 2005; Mohamed-Elhassan and Shang, 2002)



If vacuum pressure is modelled as preloading surcharge, vertical effective stress (hence, settlement) can be matched but not the actual excess pore water pressure

$$u_0 = p_a$$

$$\Delta\sigma = p_a - (u_0 - \Delta u) = \Delta u$$

Note that VP also propagates down the drain length

$\sigma' = \sigma - (-u)$

Site preparation for Vacuum Consolidation

(Courtesy from Austress-Menard)

Drain Installation

Horizontal drain installation

Site preparation for Vacuum Consolidation

(Courtesy from Austress-Menard)

Peripheral bentonite trench

Membrane installation

Site preparation for Vacuum Consolidation

(Courtesy from Austress-Menard)

Completion of membrane installation

Connection between horizontal drainage and vacuum pump

Vacuum Preloading

Factors affecting Performance

- Inward Lateral Movement (possible tension zones on adjacent utilities) Wang and Law, pp. 105-115, 4th ICSSE, 2006.
- Air leaks **(time-dependent suction)-** Bergado et al., 2005

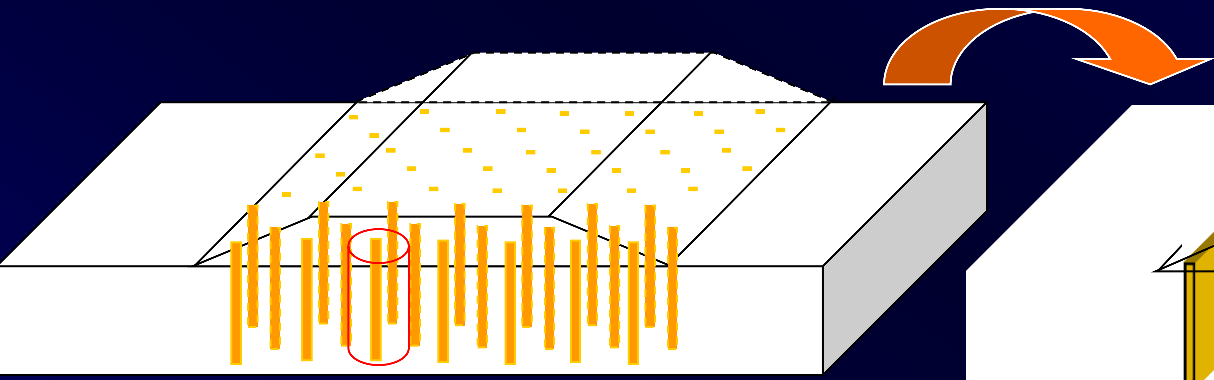
Advantages

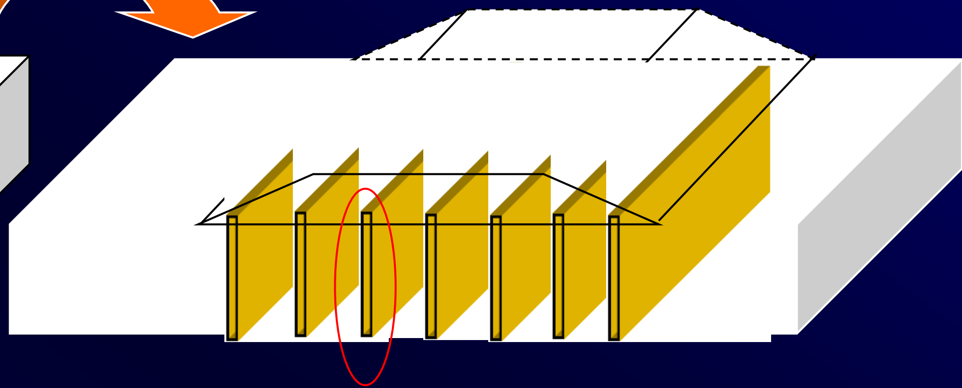
- Lateral movement is less. The risk of shear failure can be minimized at a higher rate of embankment construction.
- The extent of surcharge fill can be decreased to achieve the same amount of consolidation settlement (Chu et al, 2000).
- With vacuum pressure, the unsaturated condition at the soil-drain interface may be improved, resulting in an increased rate of consolidation.

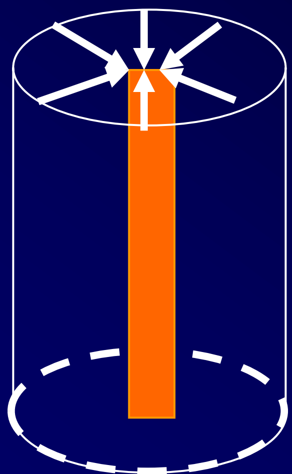
Multi-drain Analysis and Plane strain Conversion

Field condition: Axisymmetric

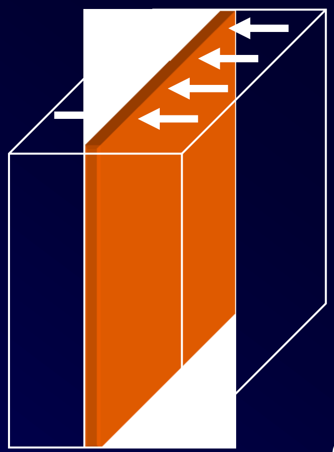
2D plane strain FEM







Maintain geometric equivalence

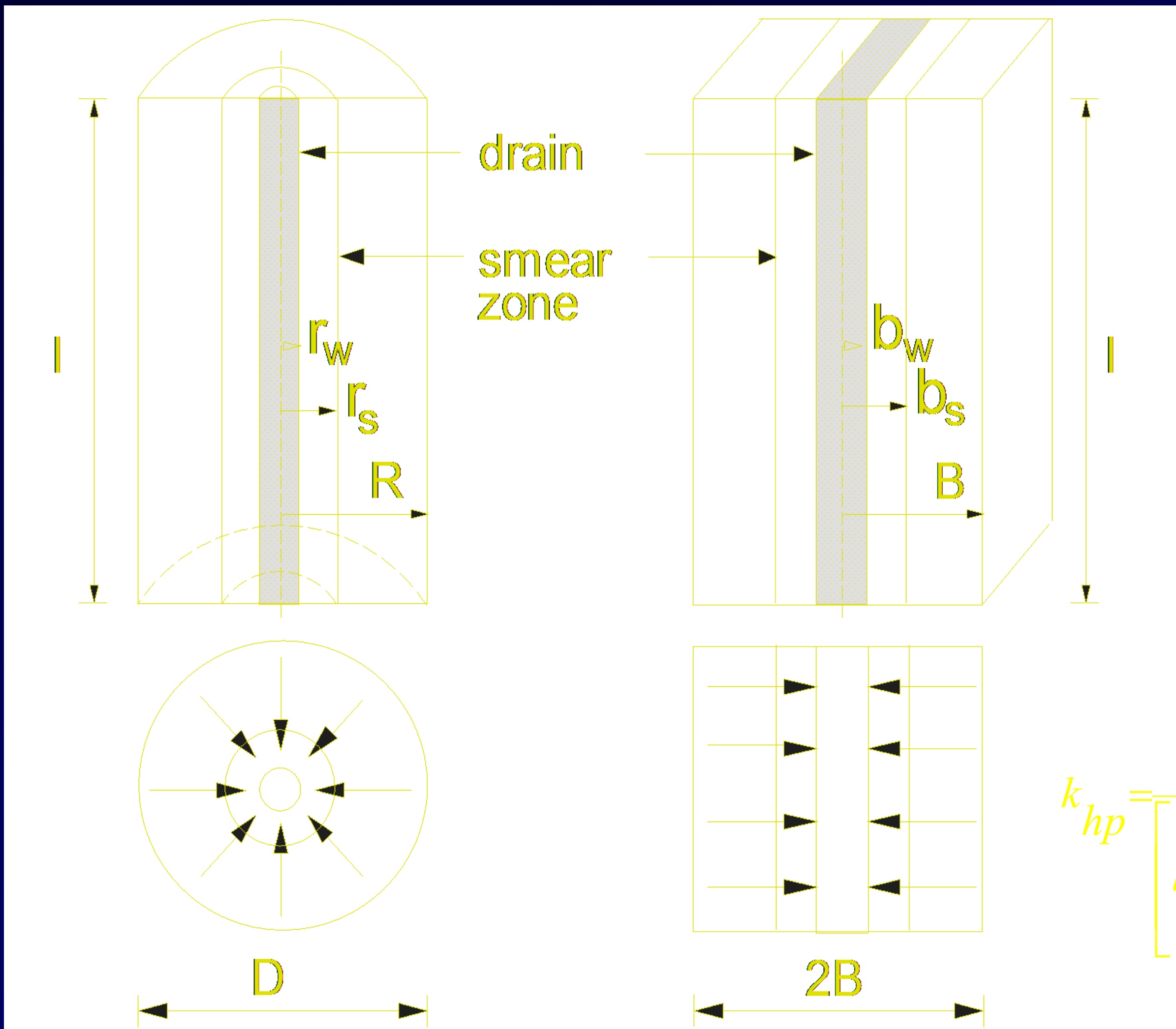


Reduce the convergence time and require less computer memory

Must give the same consolidation response!!

Multi-drain Analysis: Conversion of an Axisymmetric Unit Cell into Plane Strain

Hird et al., 1992; Indraratna et al., 2000 & 2005

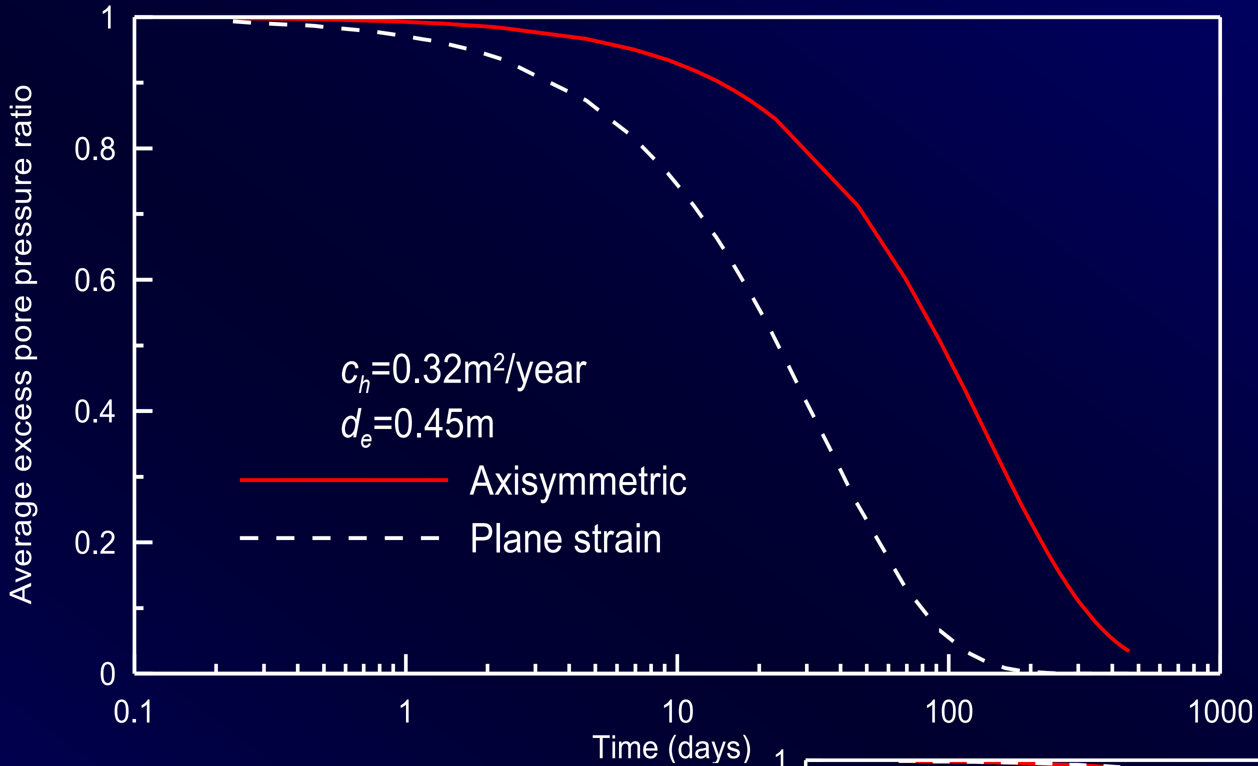


a) Axisymmetric **b) Plane Strain**

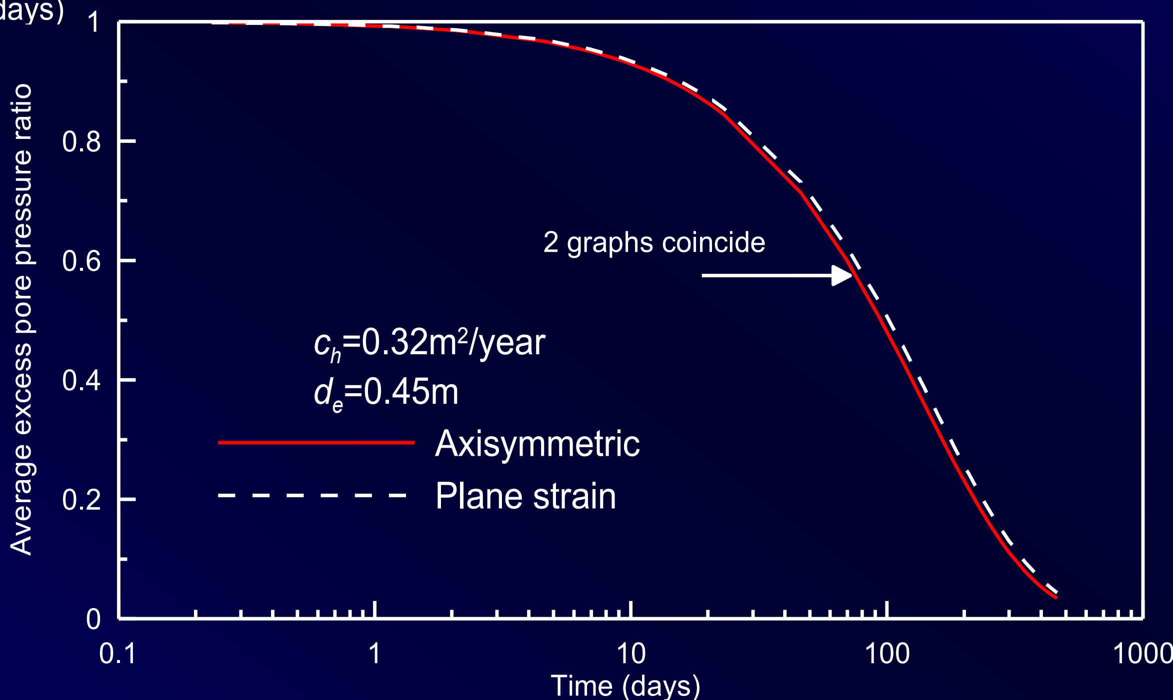
Conversion must give the **SAME** time-settlement curve

$$k_{hp}=\frac{k_h\left[\alpha+(\beta)\dfrac{k_{hp}}{k'_{hp}}+\dfrac{4l^2}{3B}\dfrac{k_{hp}}{q_{wp}}\right]}{\left[\ln\left(\dfrac{n}{s}\right)+\left(\dfrac{k_h}{k'_h}\right)\ln(s)-0.75+\dfrac{2\pi l^2}{3}\dfrac{k_h}{q_w}\right]}$$

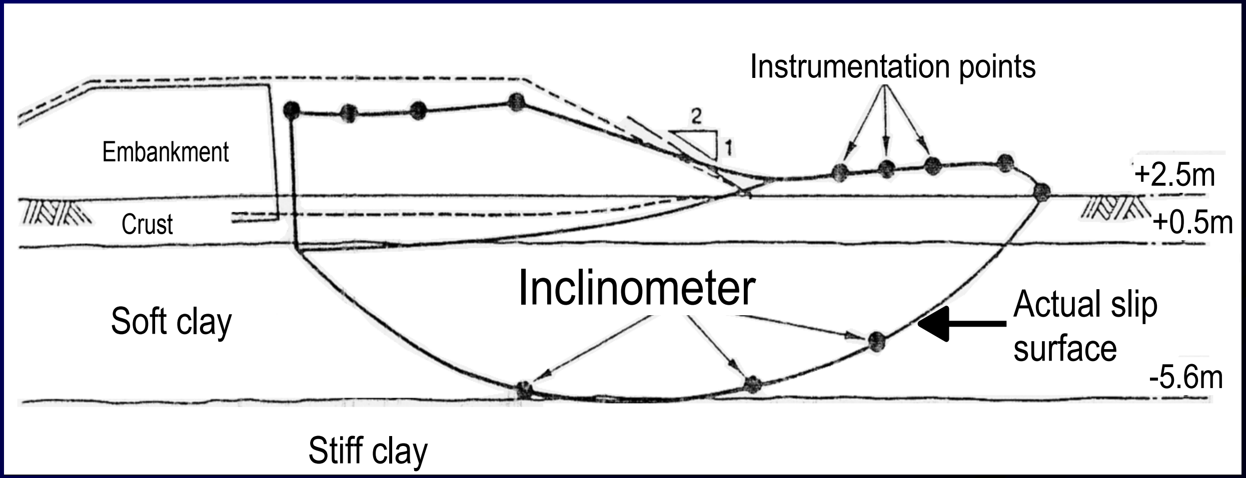
Before conversion



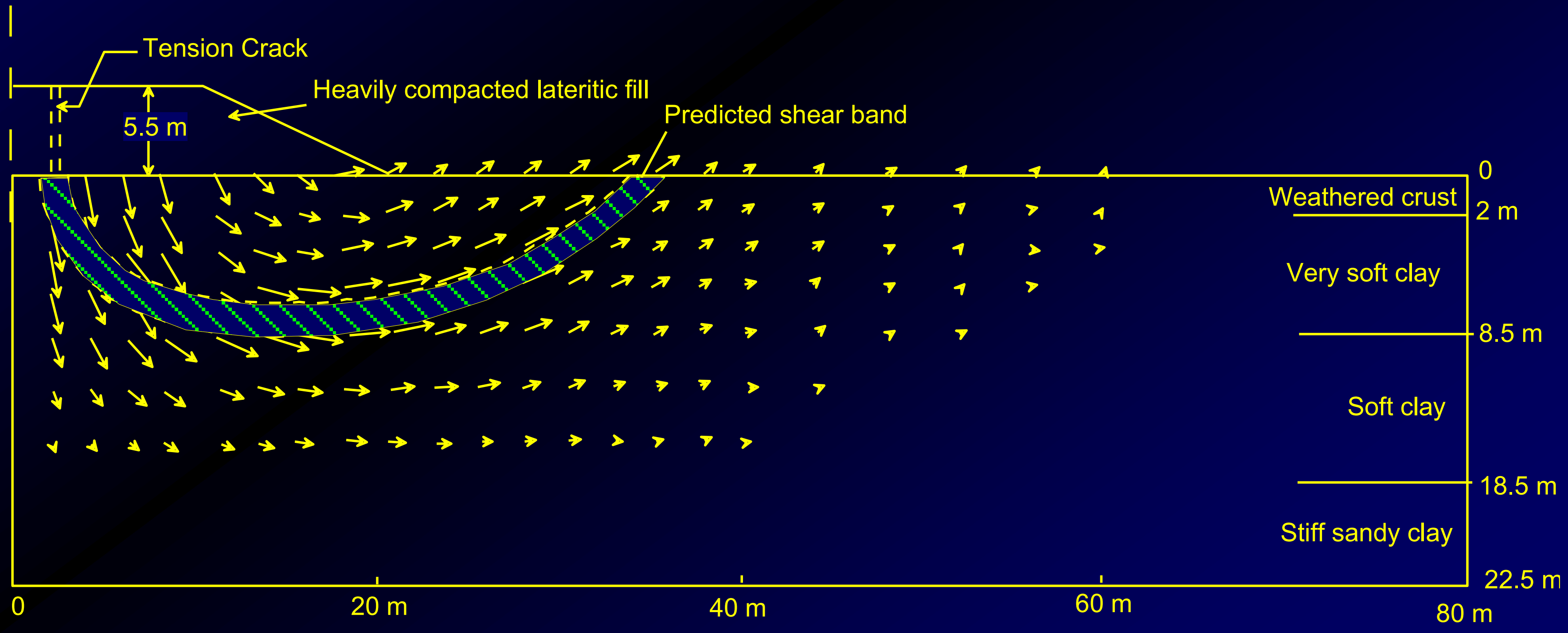
After conversion



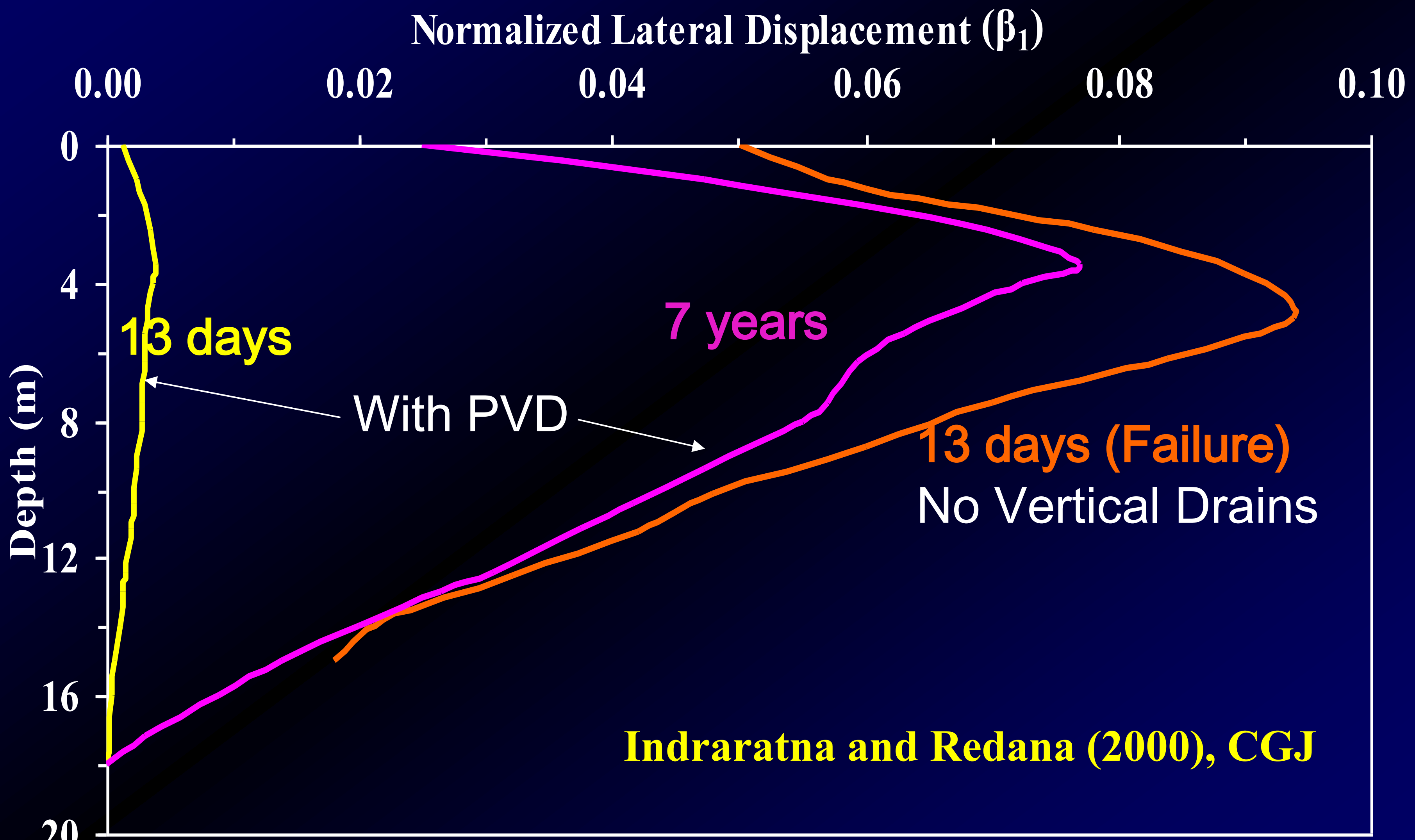
Failure of Embankment without PVD



Failure of Test embankment without PVD, Malaysia (Indraratna et al. 1992, ASCE)

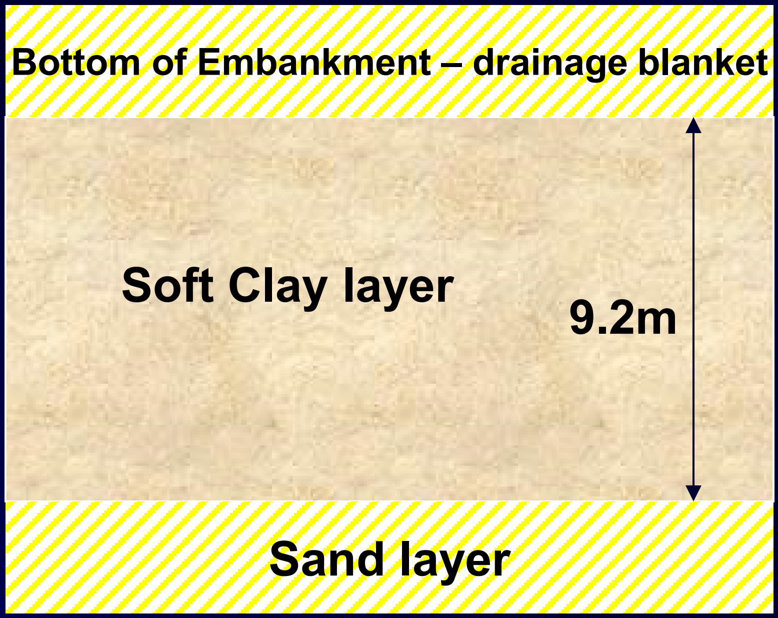


Comparison of Normalized Deformations



Normalized lateral displacement

DESIGN EXAMPLE FOR SOFT CLAY IMPROVED BY VERTICAL DRAINS – no Vacuum pressure



450mm diameter Sand drains (d_w), installed in a square pattern.

c_h = 0.288m²/month

c_v = 0.187m²/month

Degree of consolidation, U = 90%,

Time, t = 9 months

$$T_v = \frac{c_v t}{H^2}$$

H = drainage path = 9.6/2 = 4.6m

$$T_V = \frac{0.187}{4.6^2} \times 9 = 0.08$$

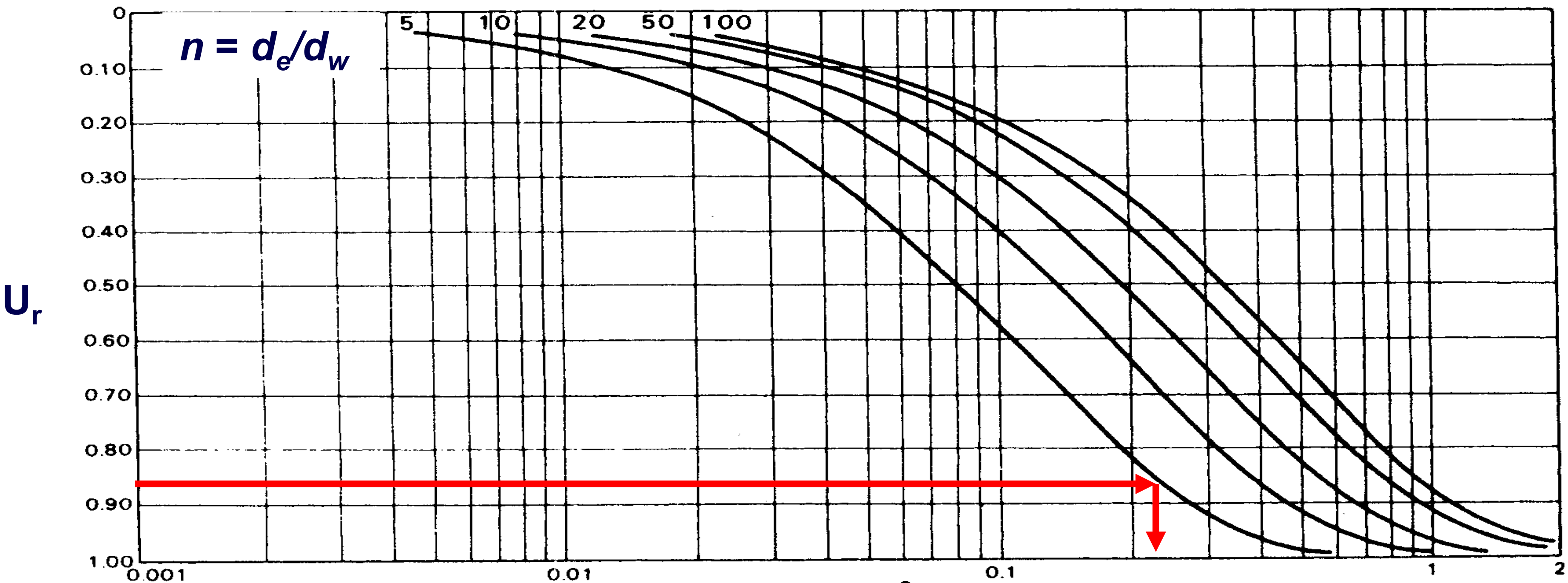
***Uv* = 0.32**

$$1-U=(1-U_r)(1-U_V)$$

Given $U = 0.90$ and $U_v = 0.32$, $U_r = 0.85$

$n = d_e/d_w$,

Assuming $n_1 = 5$, $T_h = 0.25$ (Fig. 10)



$$T_h = c_h t / d_e^2$$

$$d_e = \left(\frac{c_h t}{T_h}\right)^{1/2} = \left(\frac{0.288 \times 9}{0.25}\right)^{1/2} = 3.219\text{m}$$

$n_2 = d_e/d_w = 3.219/0.45 = 7$

$n_2 \neq n_1$

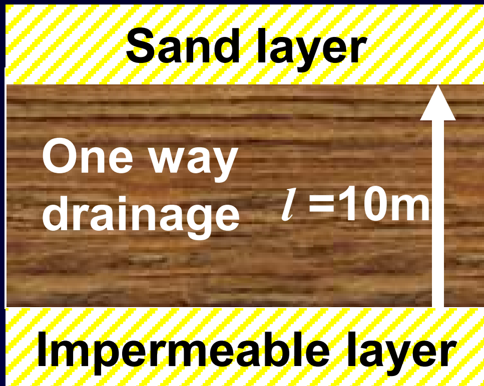
Trial and error, now use $n_3 = 6$

n_{final} = 6.6, also d_w = 0.45m

Hence, d_e=2.98m

Drain spacing, S =2.98/1.13 = 2.63m (square pattern)

DESIGN APPROACH FOR SOFT CLAY IMPROVED BY VERTICAL DRAINS WITH VACUUM PRESSURE



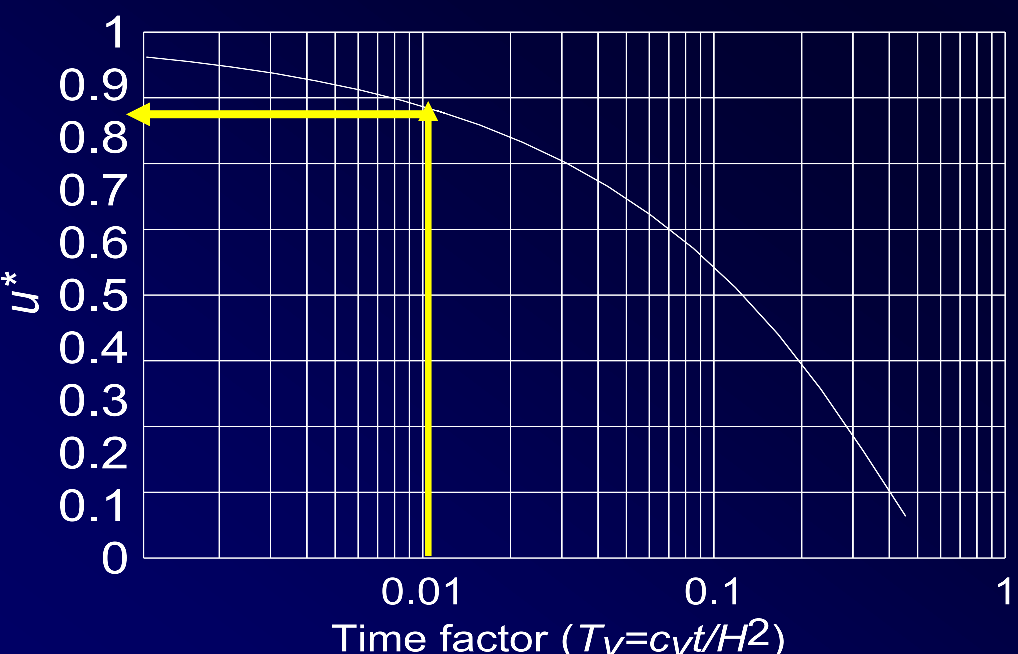
U_t = 90% after t = 1year d_w = 0.06 m

c_h = 2.0 m²/year c_v = 1.0 m²/year

Smear zone, s = d_s/d_w = 3; k_h/k_s=5

Vacuum load =40 kPa

Solution (Indraratna et al, 2007 method):



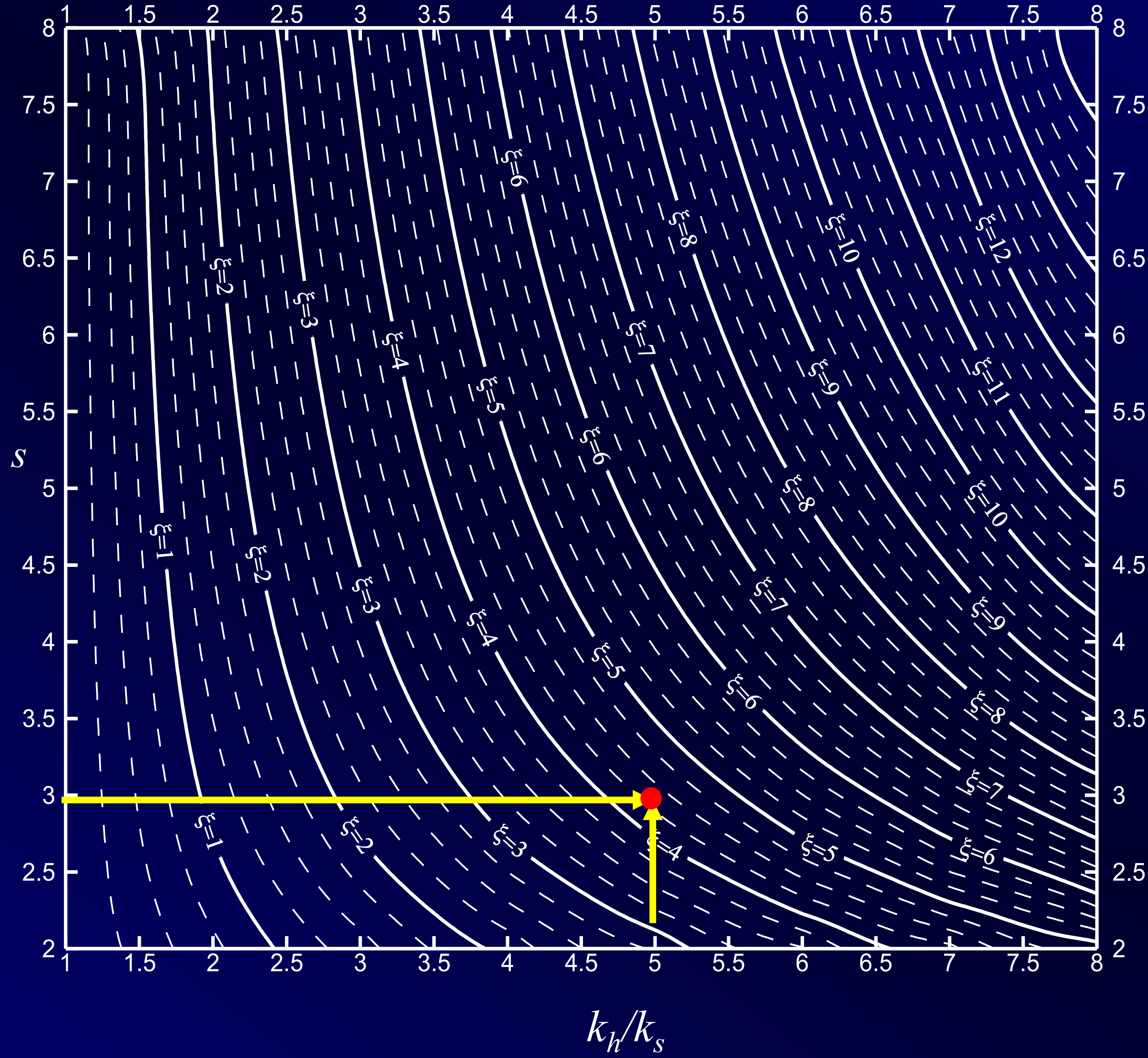
$$T_v = c_v t / l^2 = 1 \times 1/10^2 = 0.01$$

u^*= 0.89

Determine modified time factor based on d_w,

$$T'_h = c_h t / d_w^2 = 2.0 \times 1/0.06^2 = 555.56$$

$$Calculate,\ \gamma = -\frac{8T'_h}{\ln\left(\frac{1-U_t}{u^*}\right)}$$



$$\gamma = -\frac{8 \times 555.56}{\ln\left(\frac{1-0.9}{0.89}\right)} = 2036.07$$

Making $\gamma = 2036$,

Now determine ξ from LHS plot

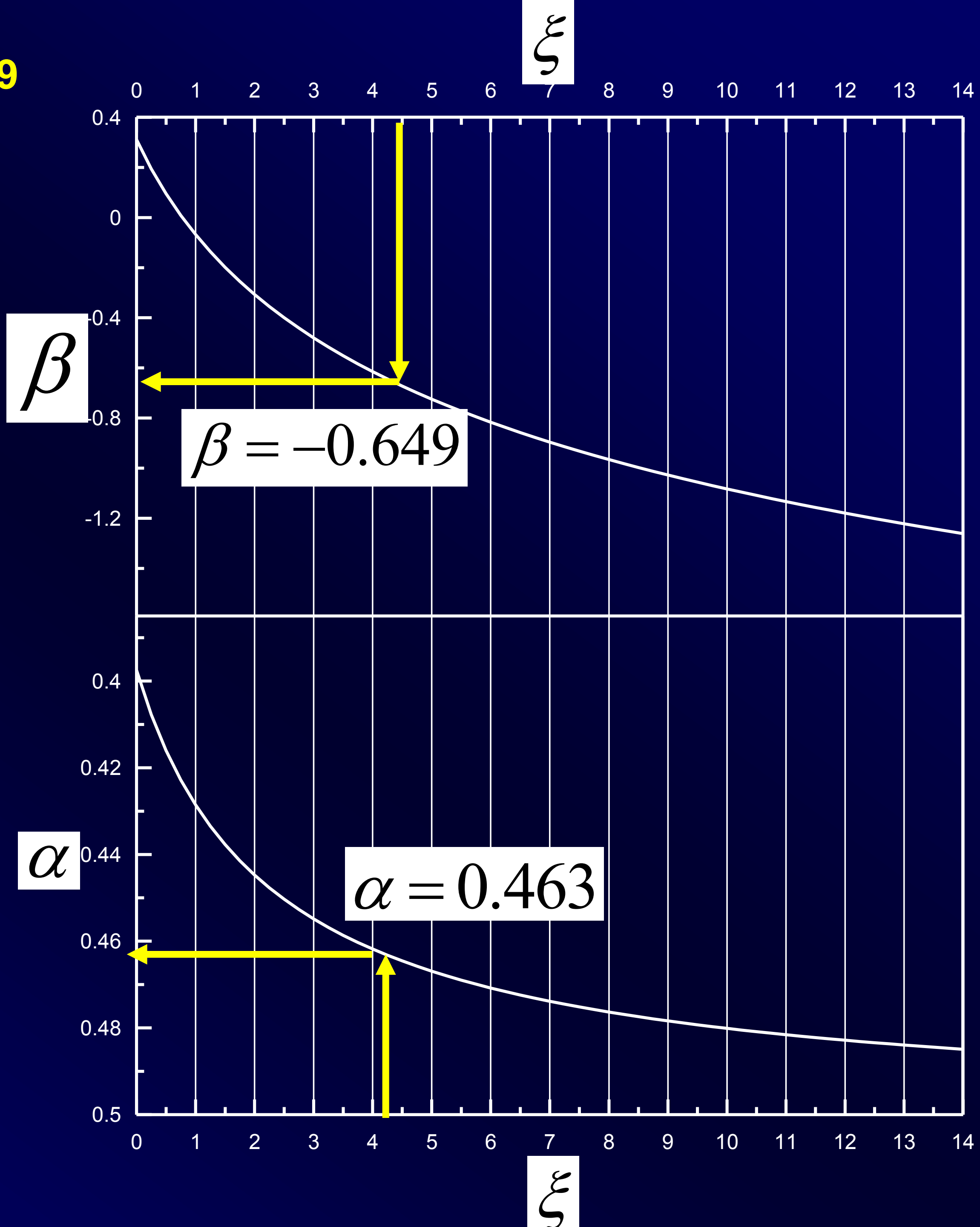
ξ= 4.39 for
s= d_s/d_w =3, and
k_h/k_s=5

$$n = \exp(\alpha \ln \gamma + \beta)$$

Now determine (α, β) *to get n*

Indraratna et al., 2007

Determine (α, β) *from* ξ = 4.39



Indraratna et al., 2007

$$n = \exp(\alpha \ln \gamma + \beta) = \exp(0.463 \times \ln 2036.07 - 0.649) = 18$$

but, $n = d_e/d_w$ *where* $d_w = 0.06m$

Hence, $\boldsymbol{d_e = 18 \times 0.06 = 1.08\ \mathrm{m}}$

Drain spacing, $S = d_e/1.128$ for square pattern

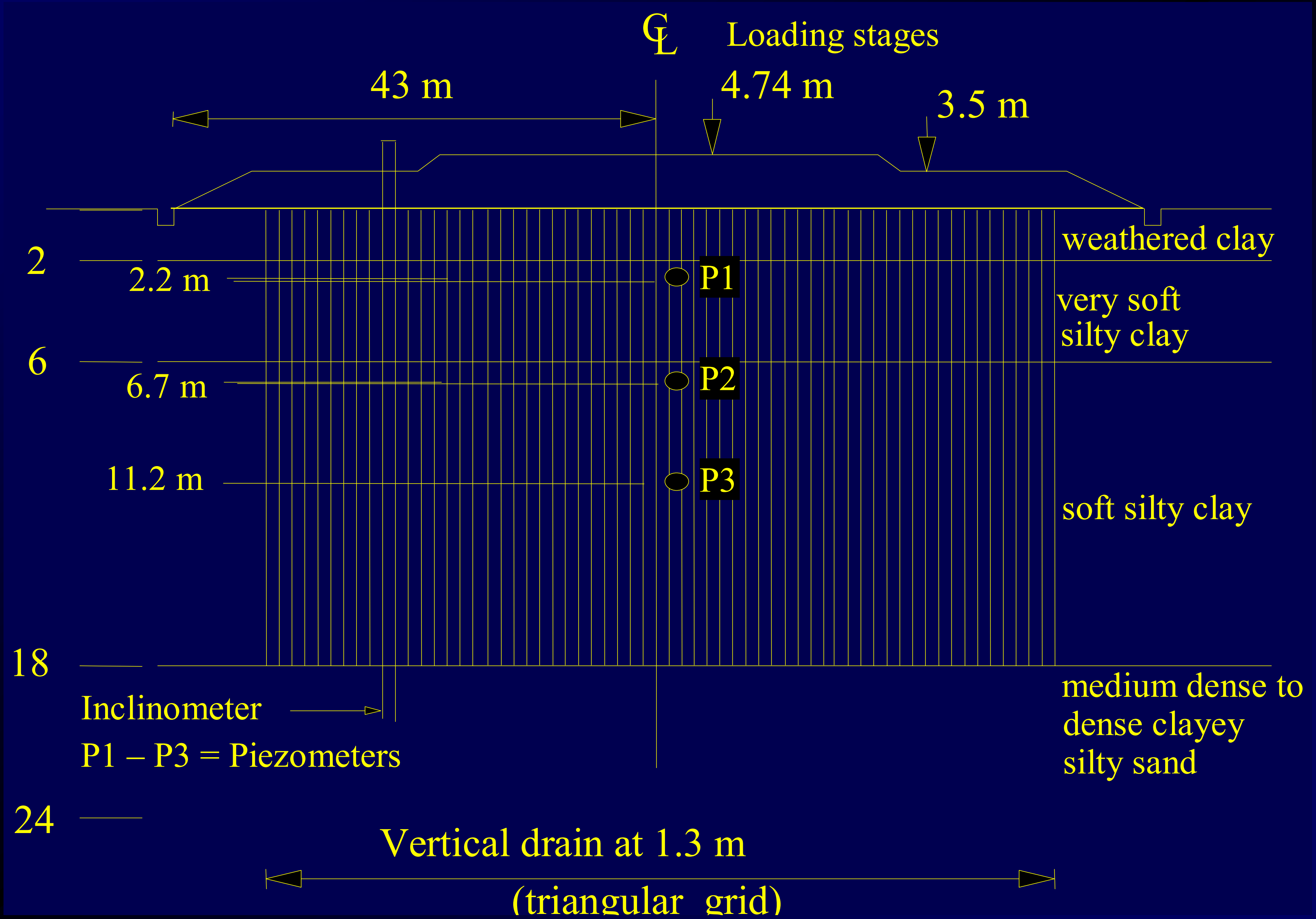
$S = d_e/1.05$ for triangular pattern

Drain Spacing of about 1m is OK for any pattern

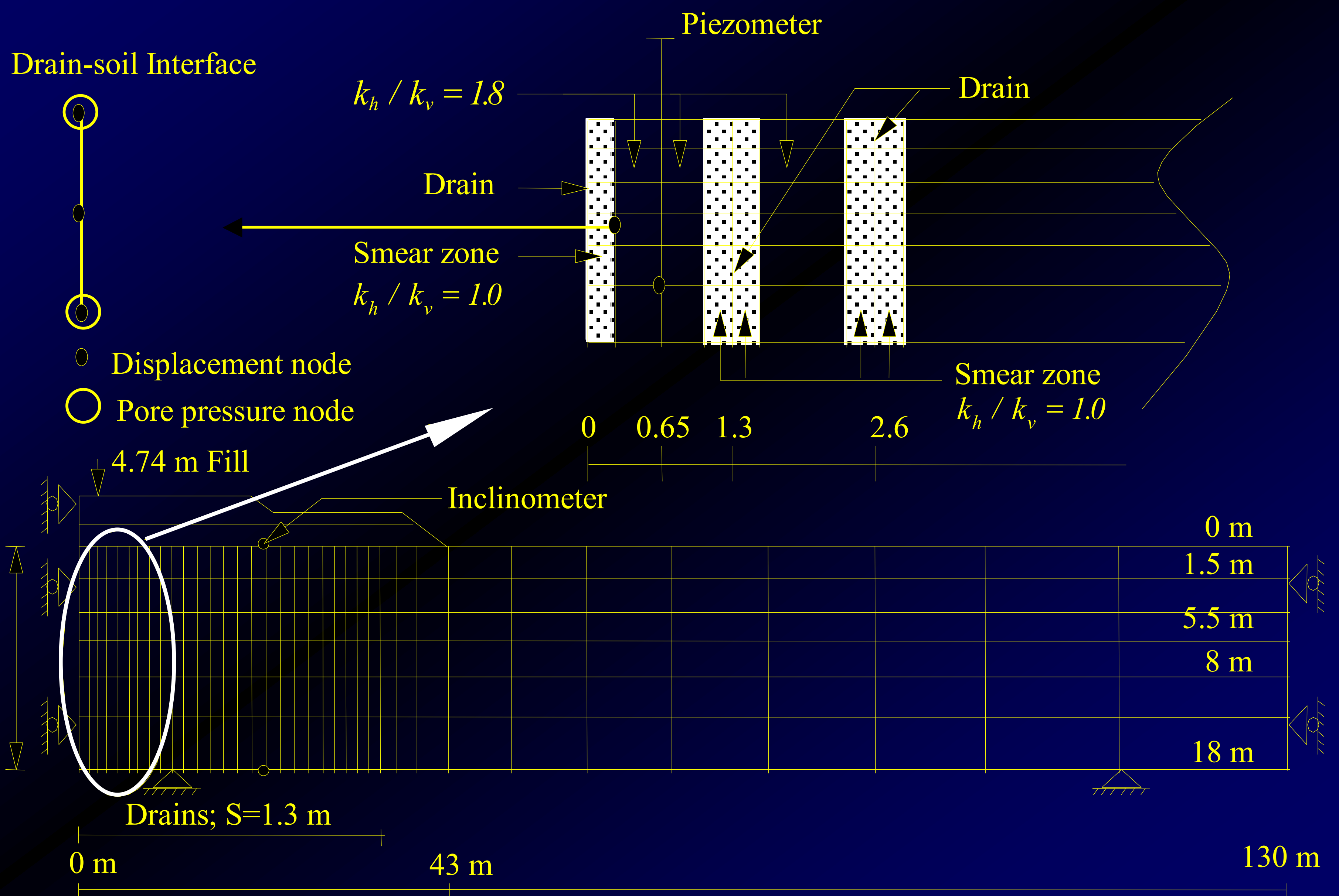
S less than 1m is not practical due to excessive smear

Test Embankment Stabilized with PVDs – No Vacuum

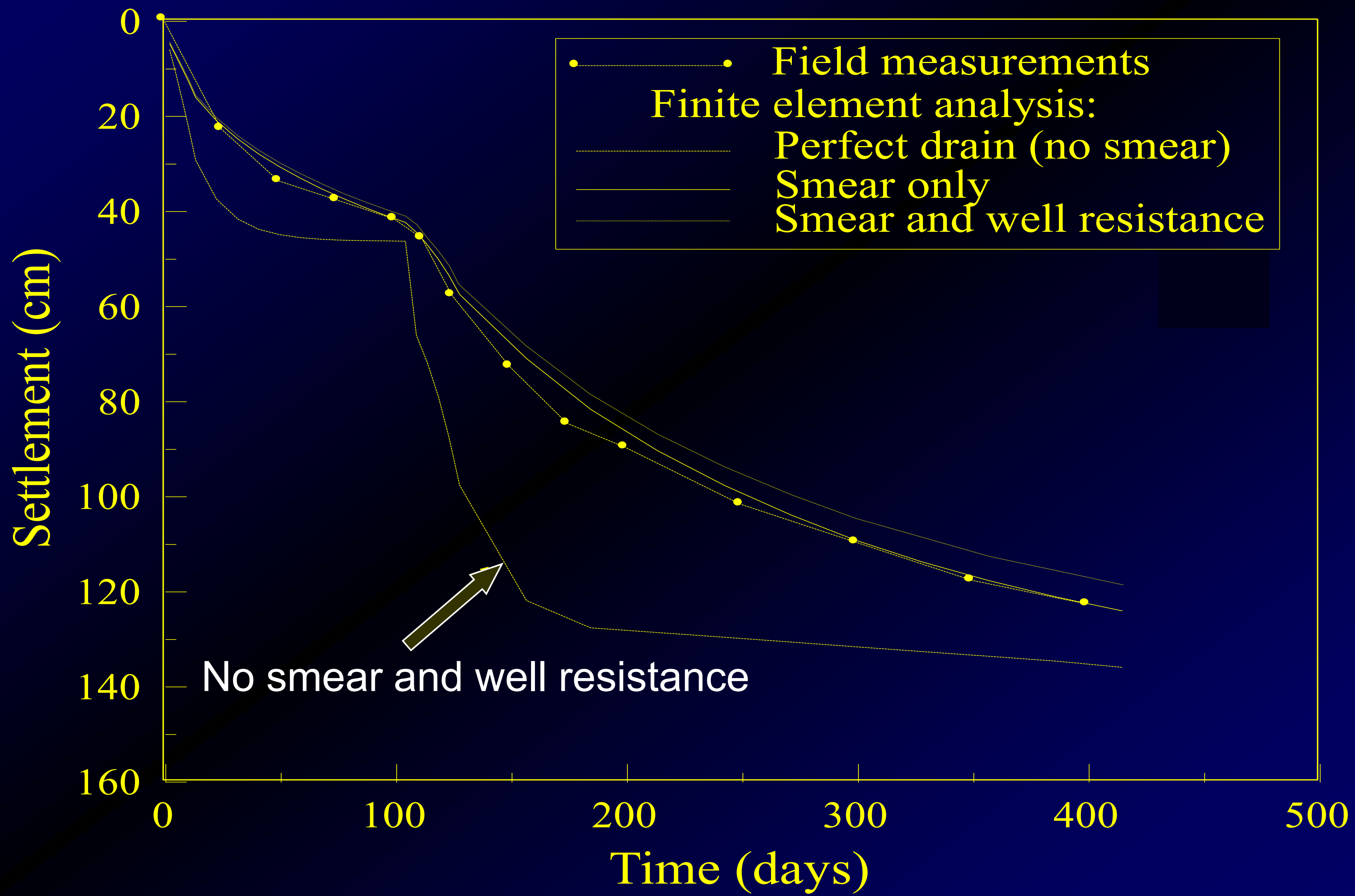
(Indraratna and Redana 2000, CGJ)



Finite Element Mesh of Embankment for Plane Strain Analysis

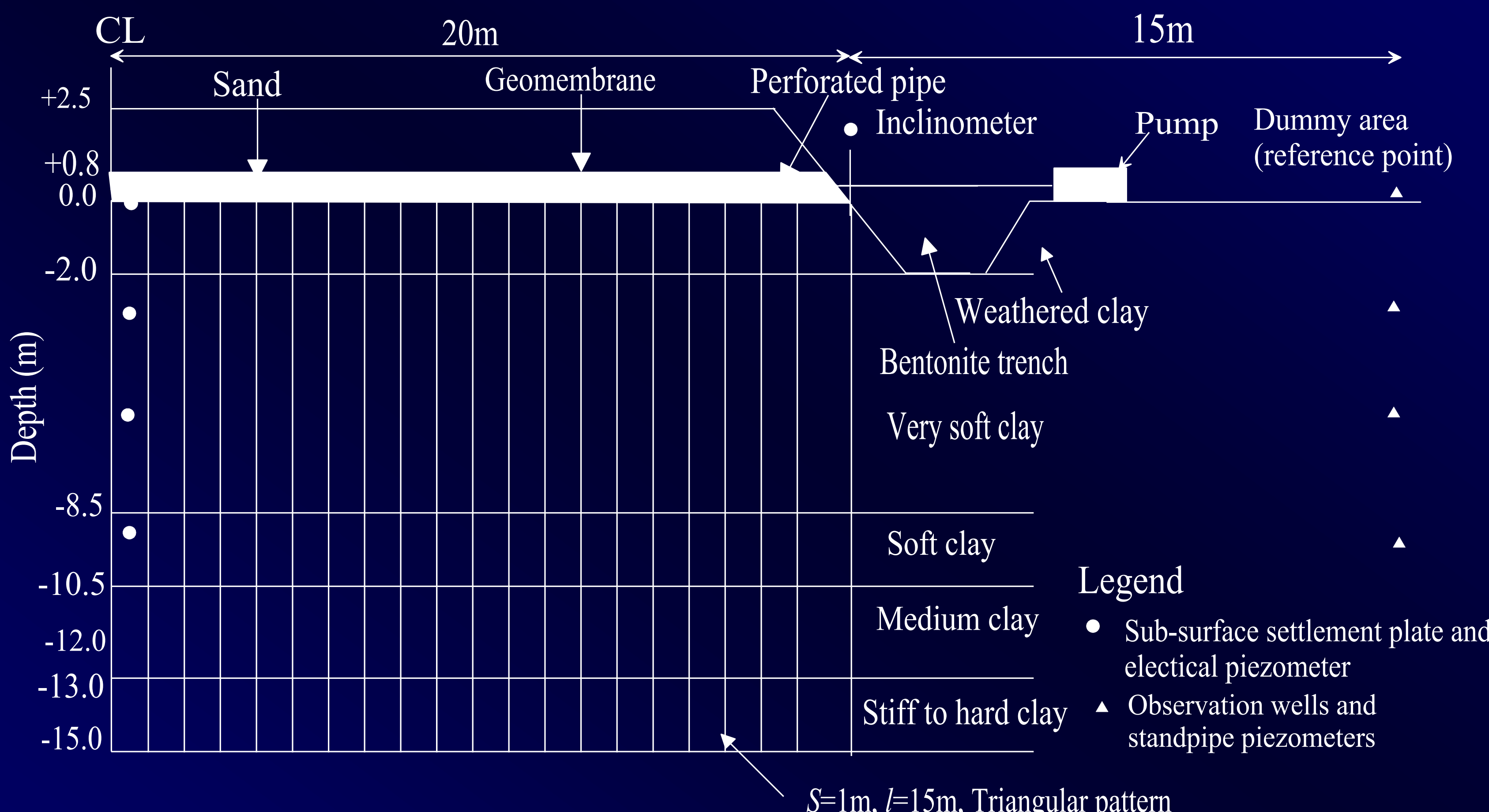


Surface settlement at embankment centreline



FEM Application: Test Embankment Stabilized with PVD and Vacuum Preloading in Soft Bangkok Clay, Thailand

(Indraratna et al 2005, Int. J. of Geomechanics, ASCE, 114-124)

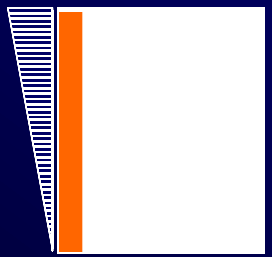


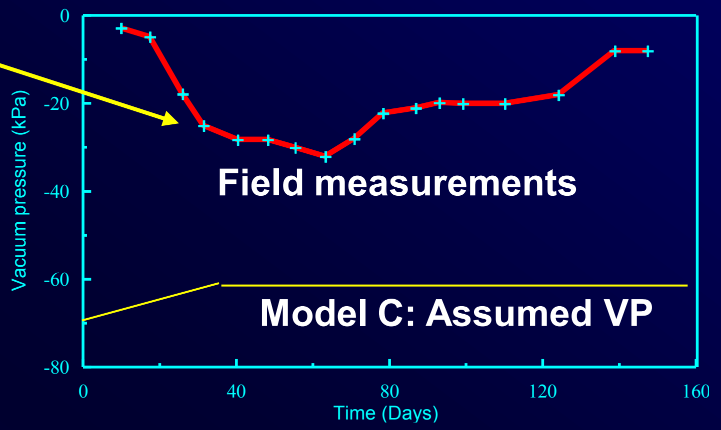
-70 kPa vacuum and 2.5 m surcharge applied at this site

Case History: Vacuum Simulation

Model A: Conventional analysis (i.e., no vacuum; only surcharge application)

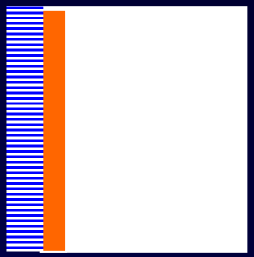
Model B: Vacuum pressure is adjusted according to field measurement and reduces linearly to zero at the bottom of the drain ($k_1 = 0$)



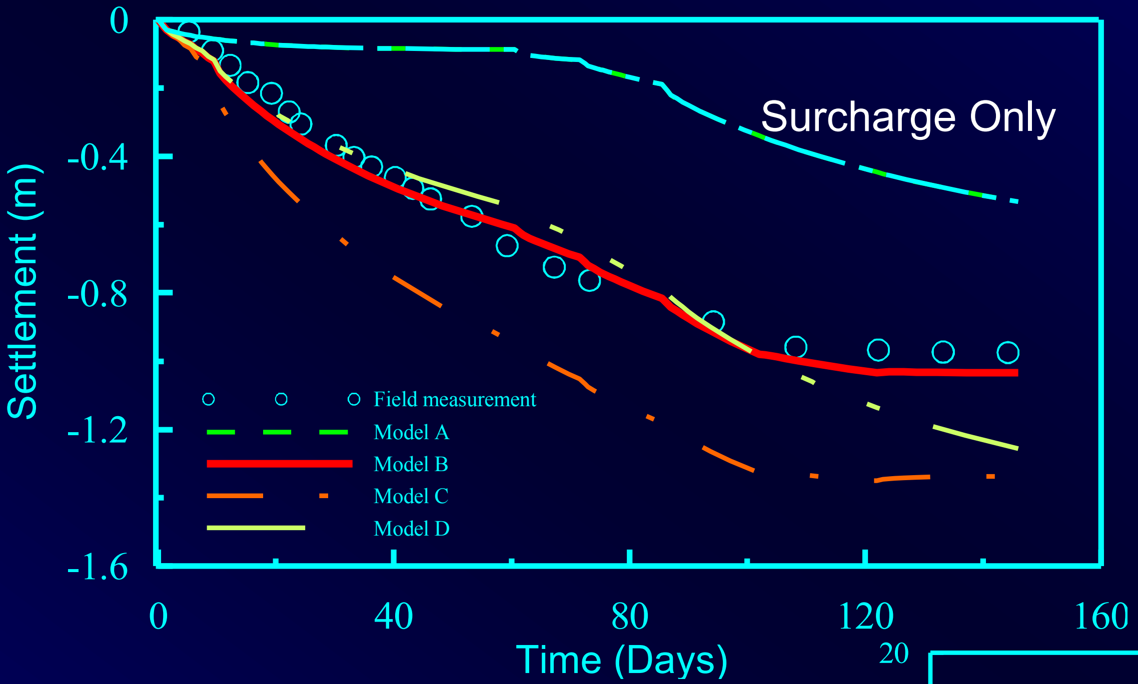


Model C: Perfect seal (i.e. vacuum pressure was kept constant at -60kPa after 40 days); vacuum pressure varies linearly to zero along the drain length ($k_1 = 0$)

Model D: No vacuum loss along the drain length ($k_1 = 1$)

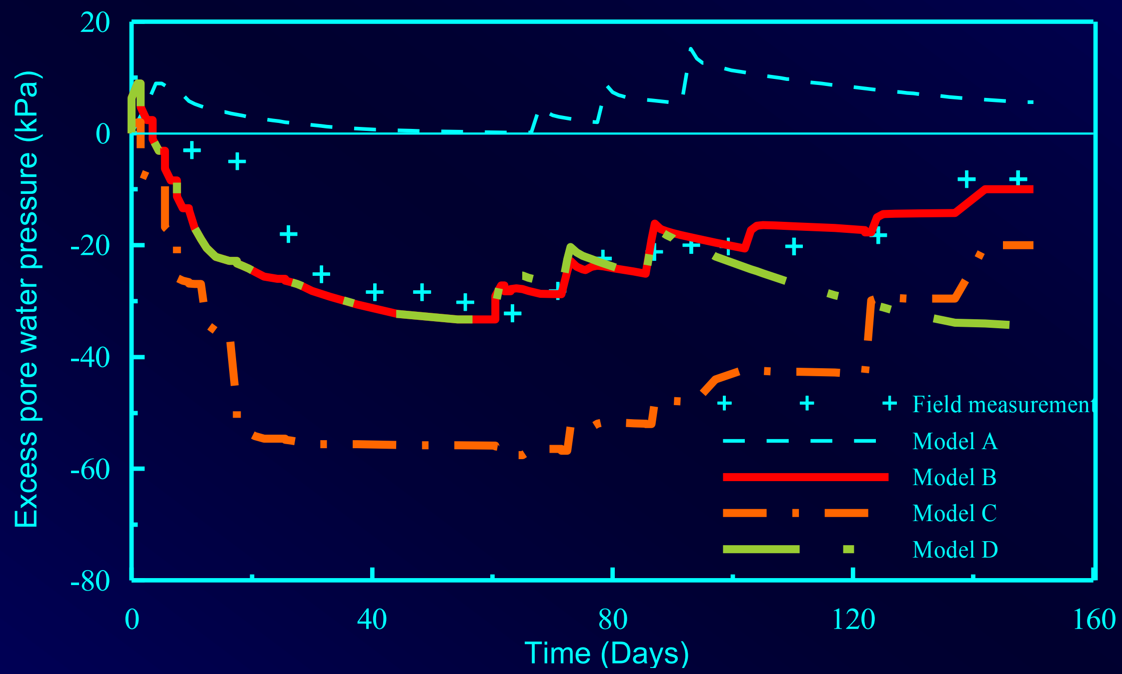


Case History: Results and Discussion

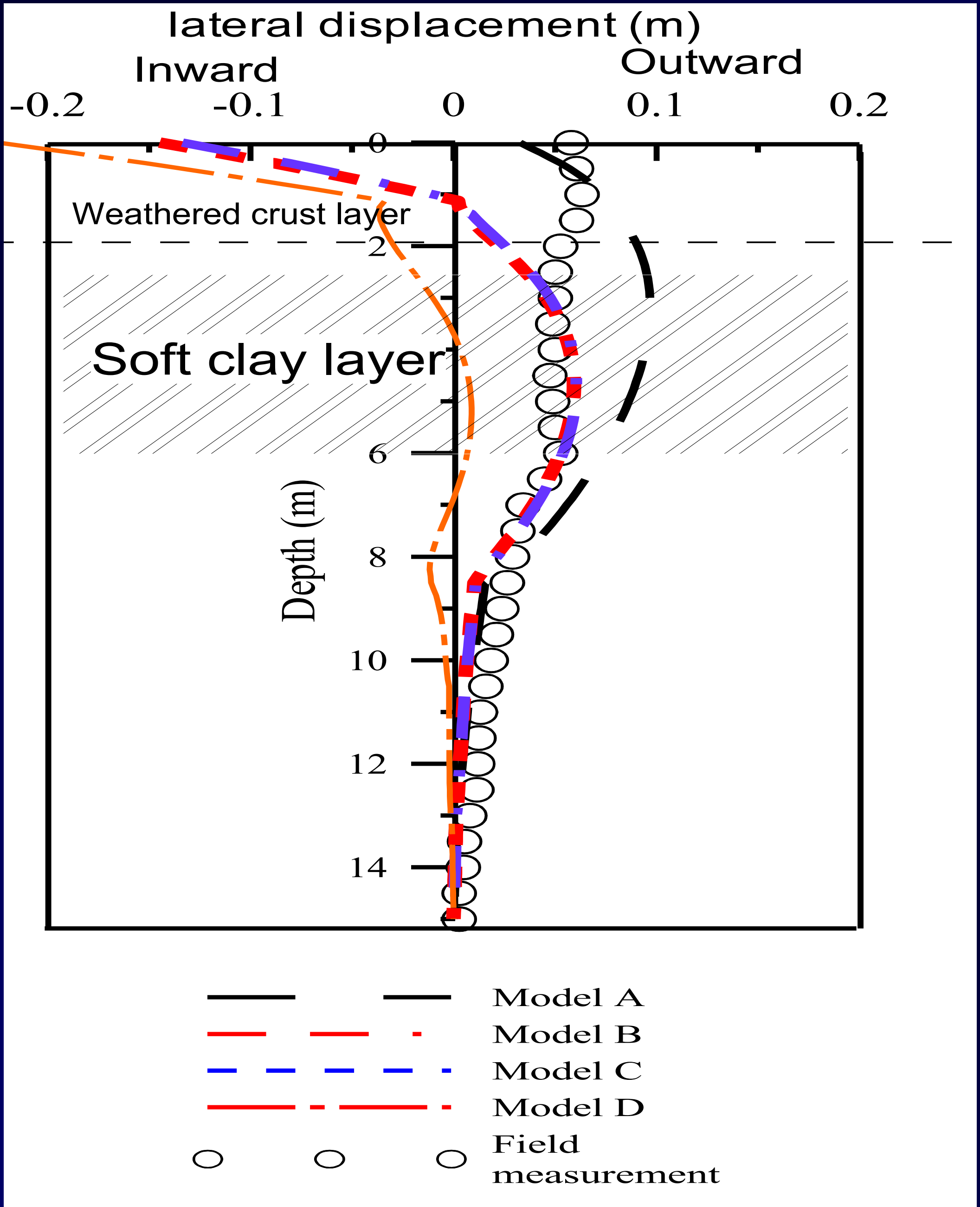


Settlements

Excess pore pressures



Case History: Results and Discussions



Lateral Movements at Embankment Toe

Weathered Crust is less stiffer than laboratory based properties

Advantages

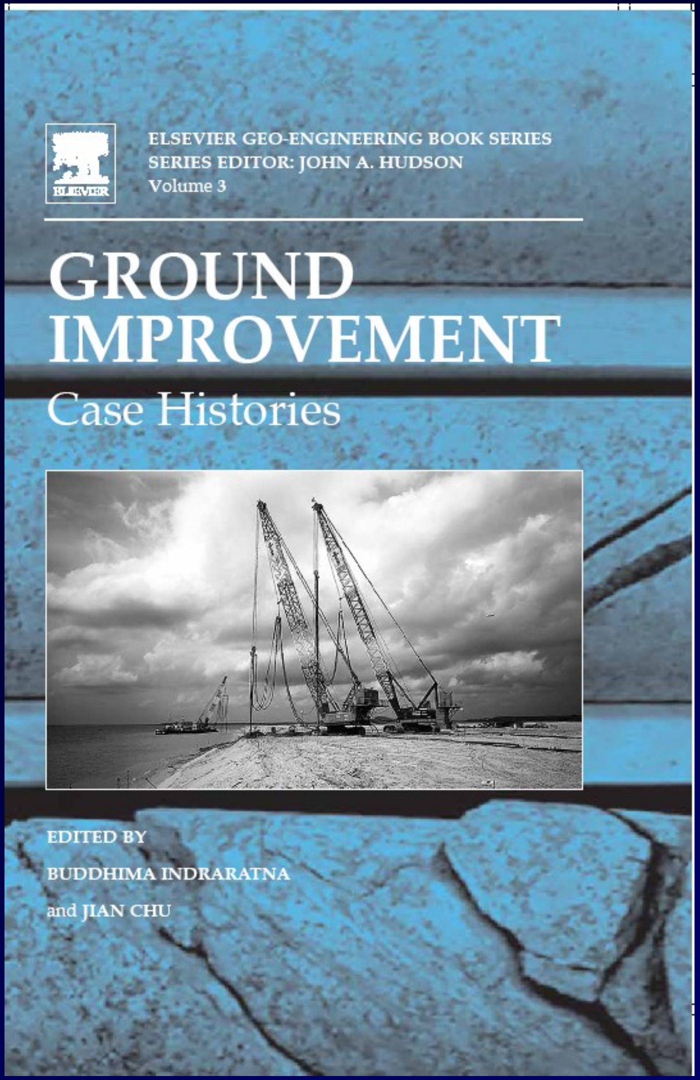
- **Embankment height reduction from 4.0m to 2.5 m**
- **Time reduction from 12 months to 4 months**

Acknowledgements

➢Past and Present research students and Research Associates (Dr. I. Redana, Dr. C. Bamunawita, Dr. I. Sathananthan, Dr. R. Walker, Dr. C. Rujikiatkamjorn, Dr. H. khabbaz, A. Attya, and others.)

➢Reference for PVDs design Procedure

Rujikiatkamjorn C. and Indraratna, B. (2007). Analytical solutions and design curves for vacuum-assisted consolidation with both vertical and horizontal drainage. Canadian Geotechnical Journal, Vol.44, 188-200.



Installation methods

Displacement Type

Use of steel mandrel (popular method)

Soil is not removed from the hole; pushed aside or displaced (e.g. PVDs)

Significant soil disturbance around the drain

Non-displacement Type

Soil is removed from the hole (e.g. Sand drains)

Less soil disturbance around the drain