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Use of Pressuremeter Tests for Land Reclamation Projects in Singapore

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Outline

- Part 1. Land reclamation methods
- Part 2. Use of pressuremeter tests in marine clay
- Part 3. Use of pressuremeter tests in sandfill
(presented by Dr Laifa CAO)

A satellite image of Singapore, showing the island's urban landscape, green spaces, and surrounding waters. The word "Singapore" is overlaid in white text in the center of the island.

Singapore

1960s: 600 km²

2000s: 700 km²

Population: 5.4M

Tunisia: 163,610 km²



Tuas

>3000 ha

Jurong Island

~3000 ha

2nd container port

Marina bay

Changi East

>2000ha

Tekong

2000ha



Changi International Airport



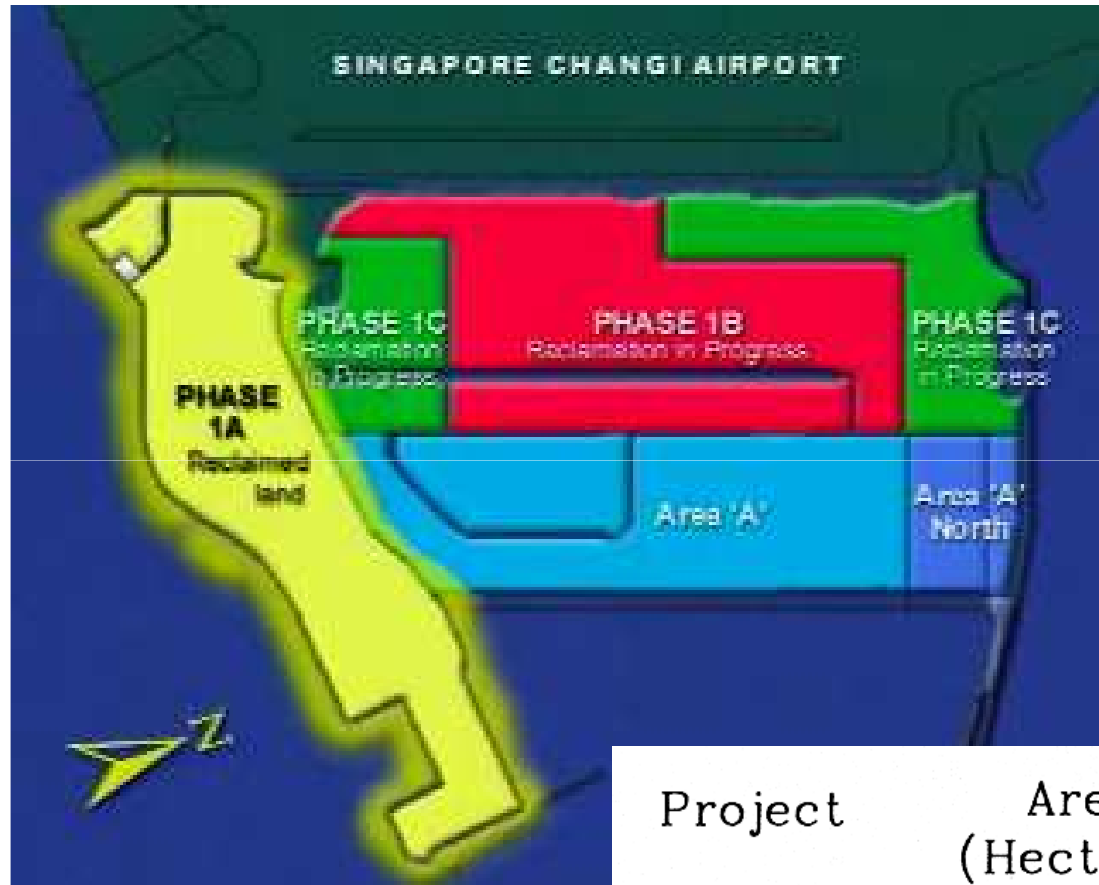
**Changi East
Land
Reclamation
Project**

Hill cut soil used for the Changi Airport



- 870 hectares ~ 56 million m³
- Earth cut from nearby hills (200 hectares)

Changi East Land Reclamation Project



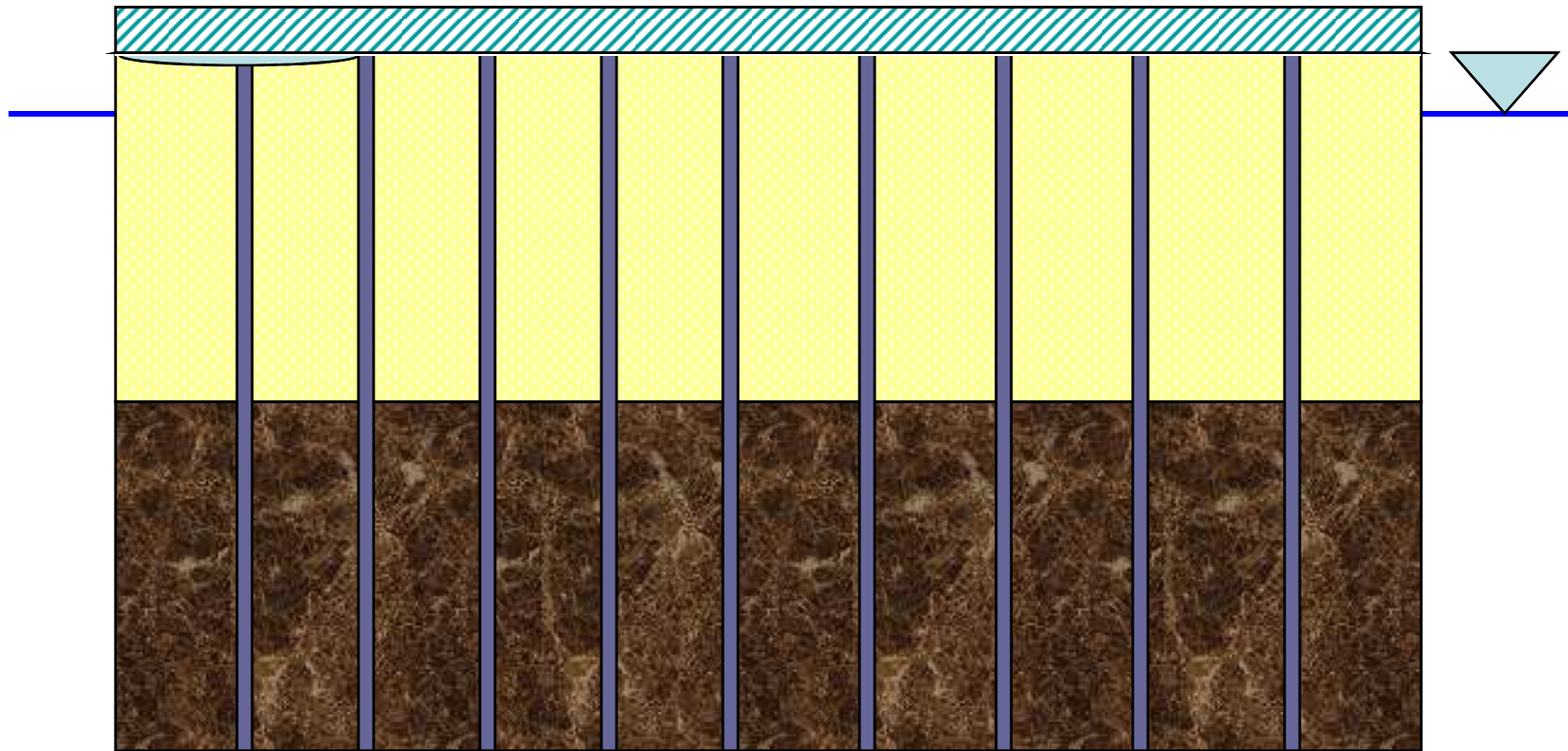
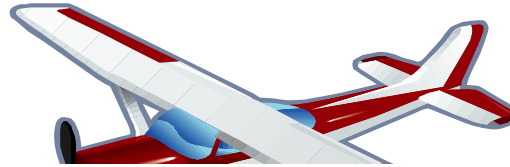
Area = 2086 ha (8 mi²)

Sand = 272 M m³

PVD = 140 Mm

Project	Area (Hectares)	Volume of Sand (Mm ³)	Length of Vertical Drain (Mm)
PHASE 1A	501	65	—
PHASE 1B	520	75	28
PHASE 1C	451	68	49
AREA "A" – NORTH	90.7	12	13.3
AREA "A" – SOUTH	450	52	50.4

Offshore Land Reclamation Process



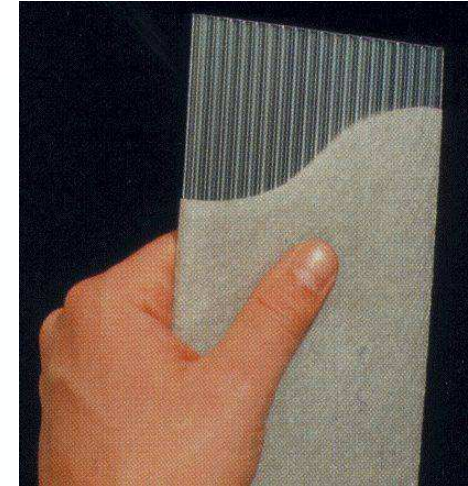


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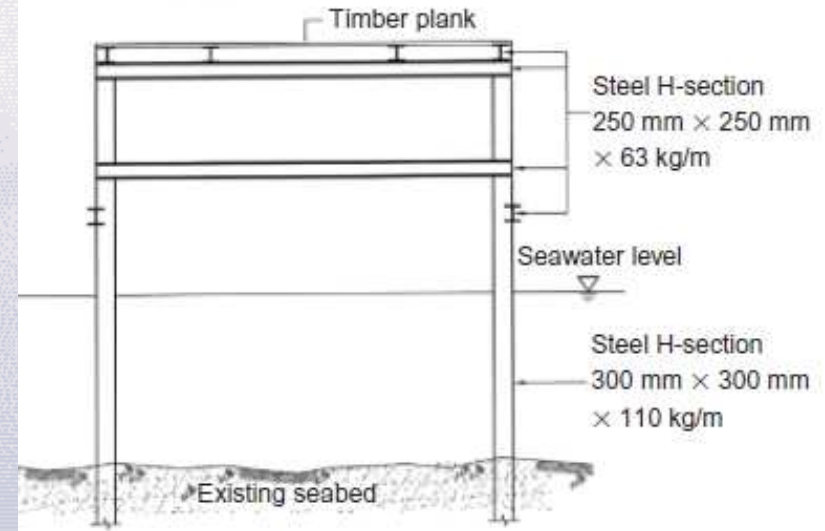
Placement of Sand Fill



Installation of Vertical Drains

Piezometers = 2144
Settlement gauges = 4691

...
Total = 7246

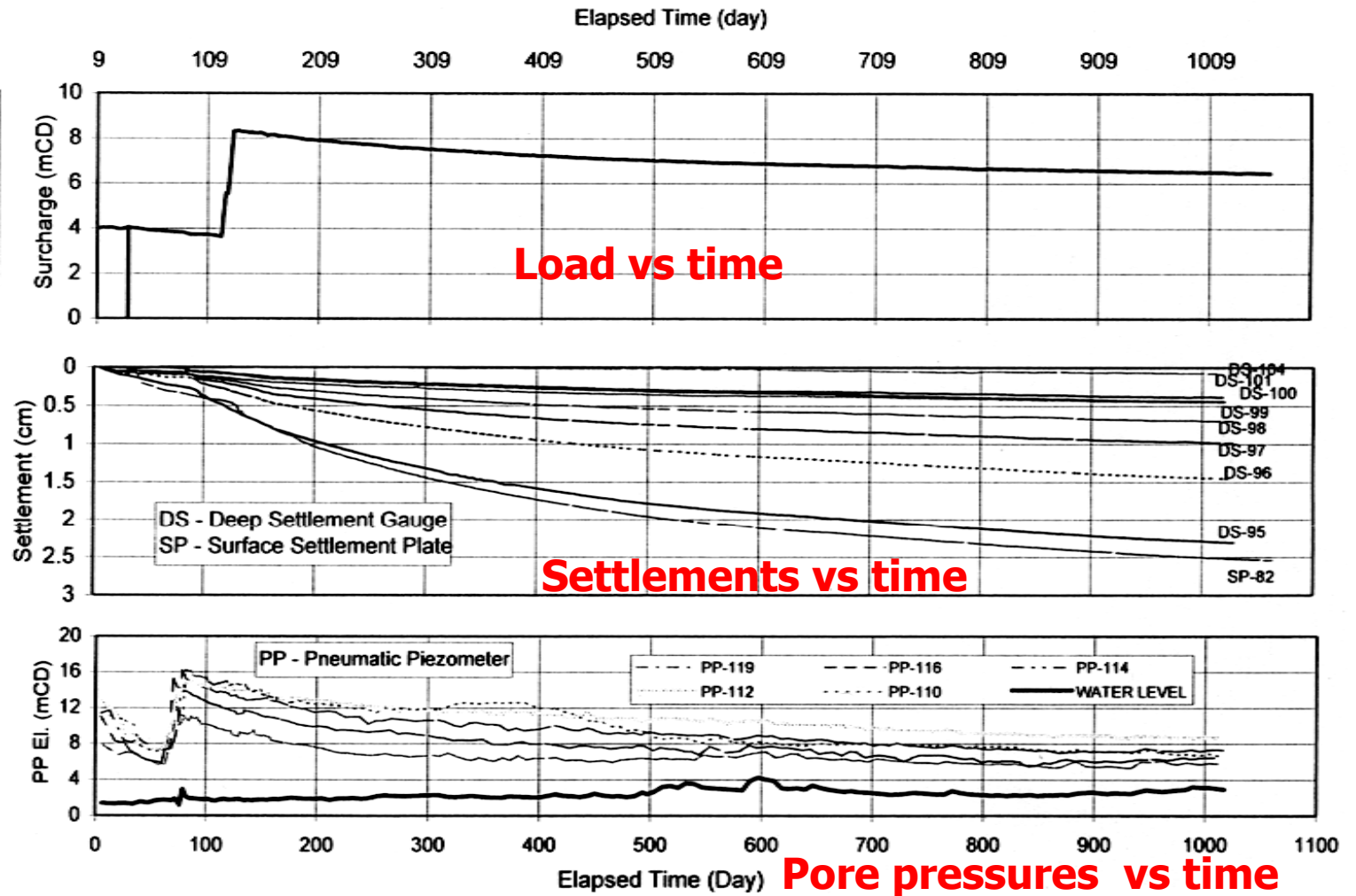


Instrumentation Clusters



Application of Surcharge

SOIL PROFILE			SOIL TYPE	SOIL INSTRUMENT E.L. (mCD)
REF. BOREHOLE	DC-013	DEPT (m)		
E.L. (mCD)				
4		0	SAND	SP-082 (3.51)
-8.4		12.4	CLAY	DS-095 (-8.4)
				PP-110 (-10)
				DS-096 (-14)
				PP-112 (-18)
				DS-097 (-20)
				DS-098 (-24)
				PP-114 (-25.8)
				DS-099 (-27.8)
-28.02		32.02	SAND	
-29.88		33.88	CLAY	PP-116 (-35)
				DS-101 (-36)
-38.93		42.93	SILT	
				PP-119 (-47)
-57.4		61.4	SAND	DS-104 (-57.4)
-63		67		



Settlements and pore pressures measured at different depths and different times

Densification of Sand fill using Dynamic Compaction (DC) or Vibro-compaction



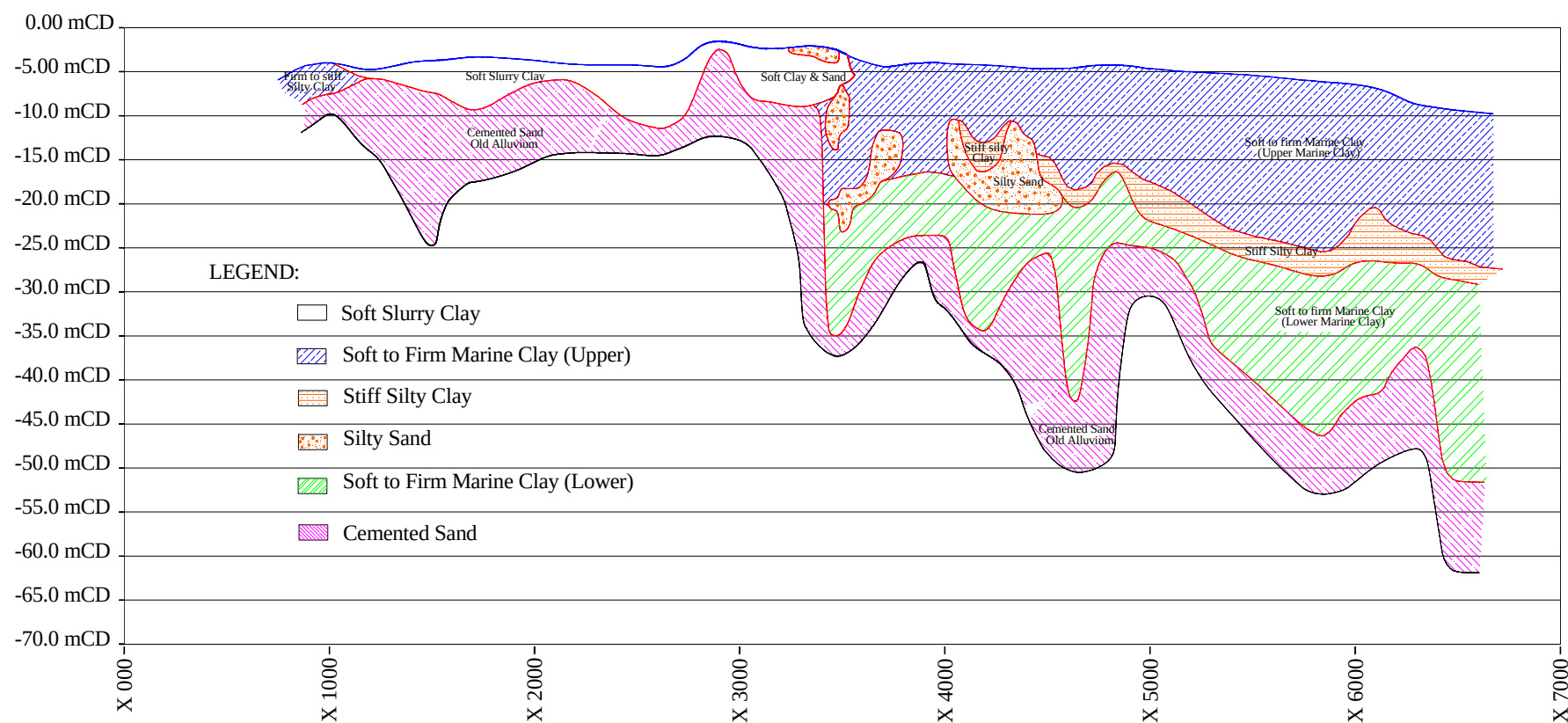
Muller resonance
compaction (MRC)



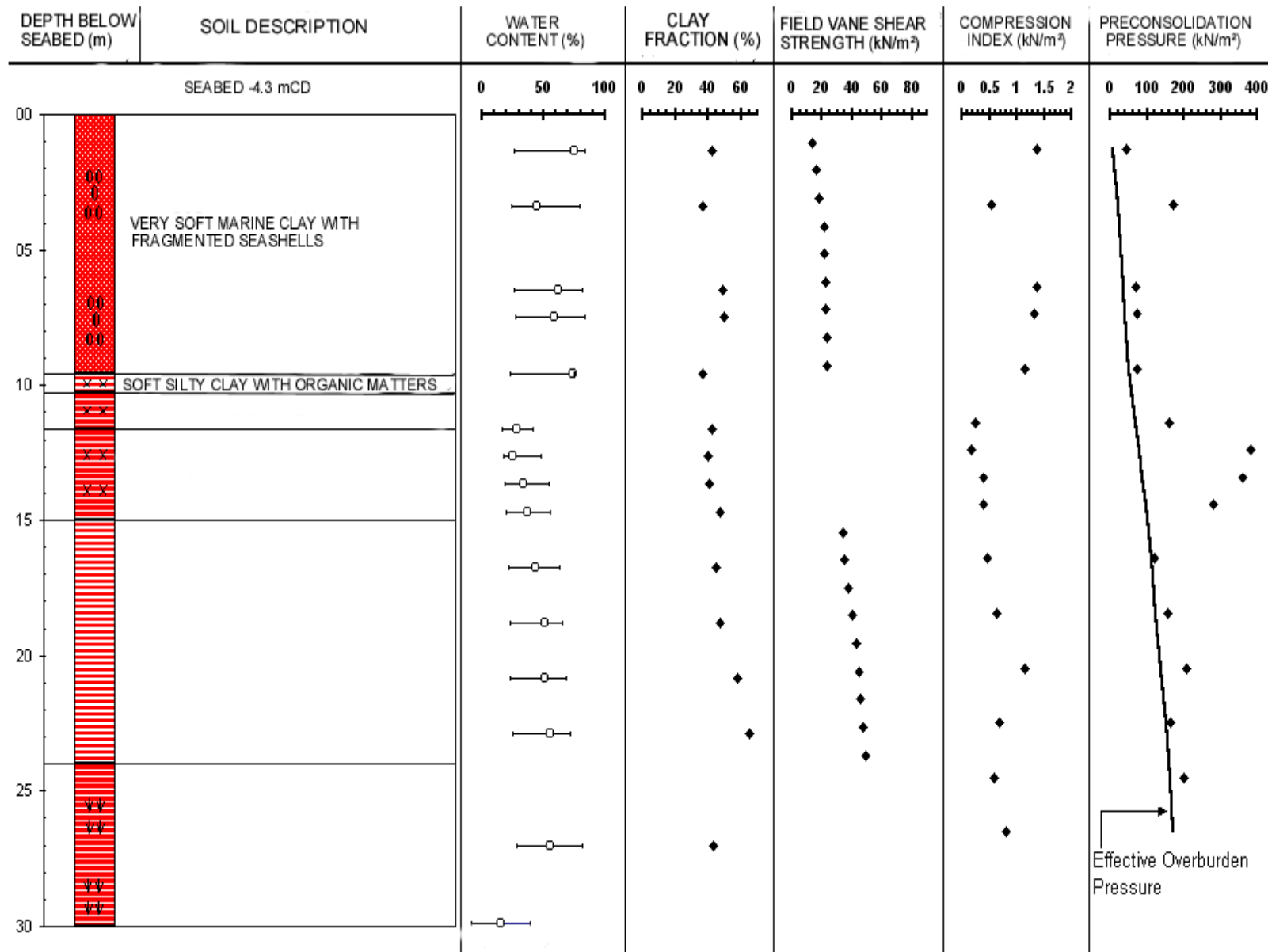
Initial $q_c = 5 \sim 7$ MPa. Improved q_c **15 MPa** for the runway and **12 MPa** for the taxiway areas or approximately equivalent to relative densities of 75% and 70% respectively.

Table 1. Summary of in situ tests conducted

Tests	FVT	SPT	CPT ^a	DMT ^b	SBPT ^c	Seismic cone	CPMT ^d	k ^e	RAM ^f
Number	864	8342	16726	27	27	3	116	67	1784



Soil profile along Section A-A'



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- Part 1. Overview of land reclamation methods
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Use of Menard pressuremeter for reclaimed land



Effect of C_h value on PVD Design

Given $c_v = 2.0 \text{ m}^2/\text{yr}$, $c_h = 4.0 \text{ m}^2/\text{yr}$, $H = 20 \text{ m}$, PVD $104 \times 5 \text{ mm}$, the permeability in the smear zone is $1/2$ of the undisturbed clay and the smear zone diameter is 4 times of the drain diameter, the time available for consolidation is 9 months, and the degree of consolidation specified is 90%. What will be the drain spacing?

For $c_h = 4.0 \text{ m}^2/\text{yr}$, to achieve $U_{vh} = 90\%$, the min. The PVD spacing is 1.5 m in square pattern

If $c_h = 3.0 \text{ m}^2/\text{yr}$, $U_{vh} = 82\%$ in 9 mths

To achieve $U_{vh} = 90\%$, the PVD spacing has to be reduced to 1.3 m → An increase in project cost of 30%!

Or

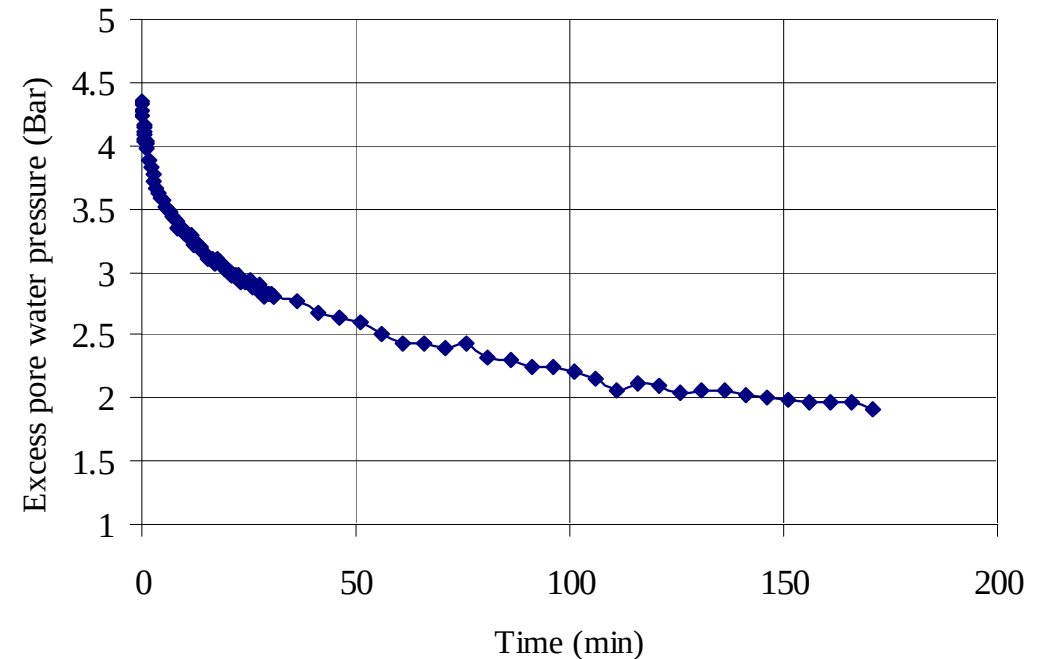
To wait for another 3 mths (i.e. 12 mths) to achieve $U_{vh} = 90\%$

In-situ Tests to measure coefficient of consolidation

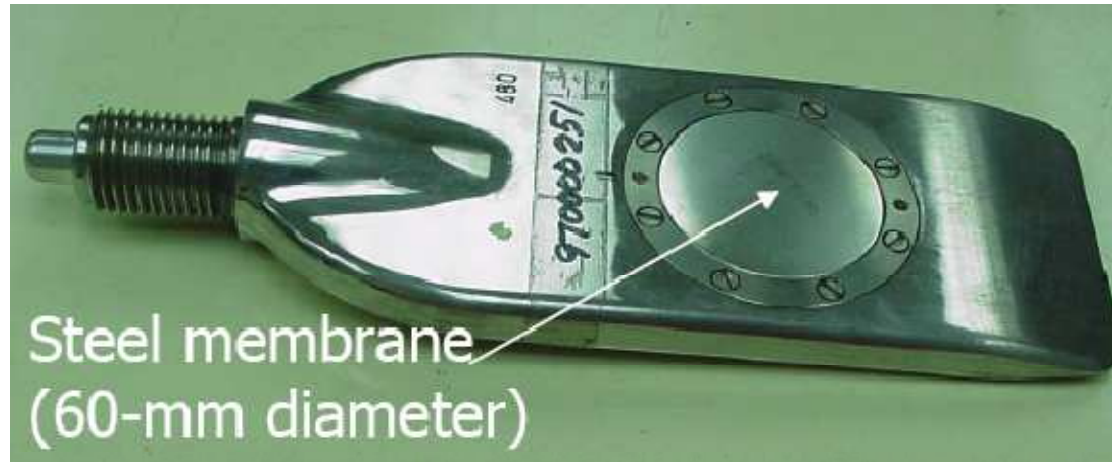
Name of test	Parameter determined	Remarks
Piezocene dissipation test (CPTU)	c_h and k_h (indirect measurement)	Based on pore water pressure dissipation.
Pressuremeter or self-boring pressuremeter (SBPM) test	c_h and k_h (indirect measurement)	Based on lateral pressure change or pore water pressure dissipation.
Flat dilatometer test (DMT)	c_h and k_h (indirect measurement)	Based on lateral stress change.

CPTU Dissipation Test

The test involves penetration of a piezocone to a selected depth, holding it in place, and observing the change in the pore pressure at selected time intervals.



Dilatometer Dissipation Test



Three readings are taken:

A: lift-off pressure, P_0

B: move the centre of the membrane for 1.0 mm, P_1

C: return of the membrane to the lift-off position, P_2 .

c_h can be estimated from either the A-reading (DMTA) or the C-reading (DMTC).

Self-boring pressuremeter (SBPM)



Cambridge SBPT MKX(D) was used. The probe was **83 mm in diameter** and 1.4 meters long and made of mainly stainless steel and brass. The pore water pressure cell was located 43 mm below the centre of probe (see Fig. 1).

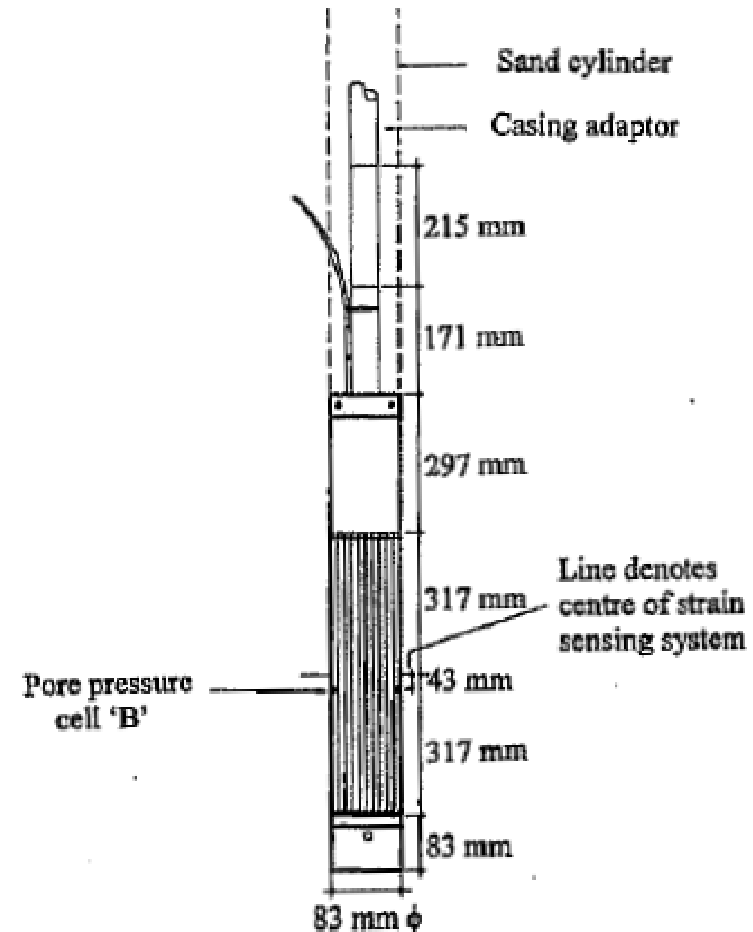


Figure 1 Dimensions of the Cambridge self-boring pressuremeter (Cambridge In-situ, 1993)

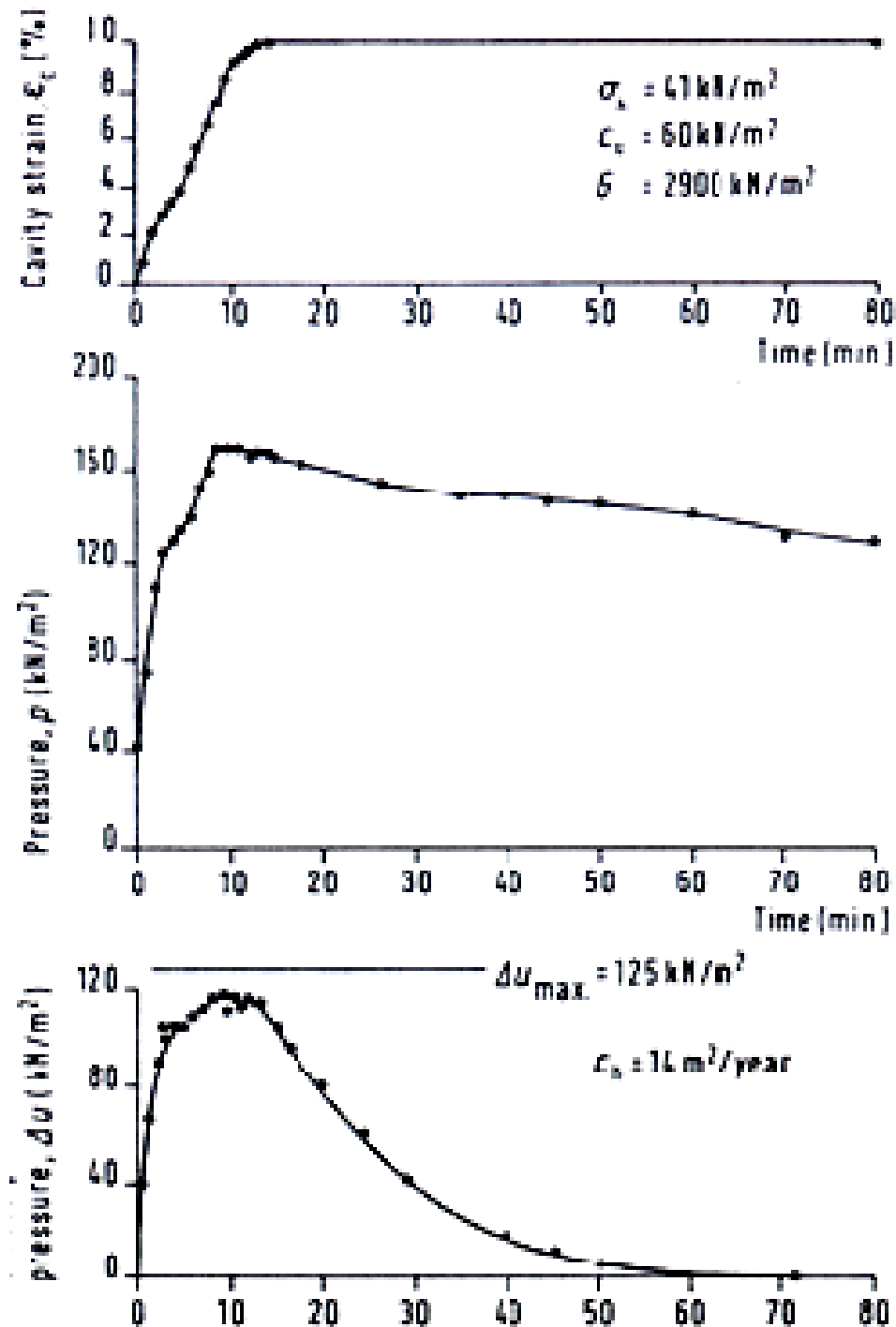
Conducting SBPM tests from a floating pontoon



Self-boring pressuremeter (SBPM) holding test

During a holding test, the expanded cavity is held fixed at the current dimensions. The excess pore water pressure generated by the preceding expansion will begin to drain and the decay of pore water pressure is monitored and recorded. When the level of excess pore pressure has fallen by half, the test is terminated.

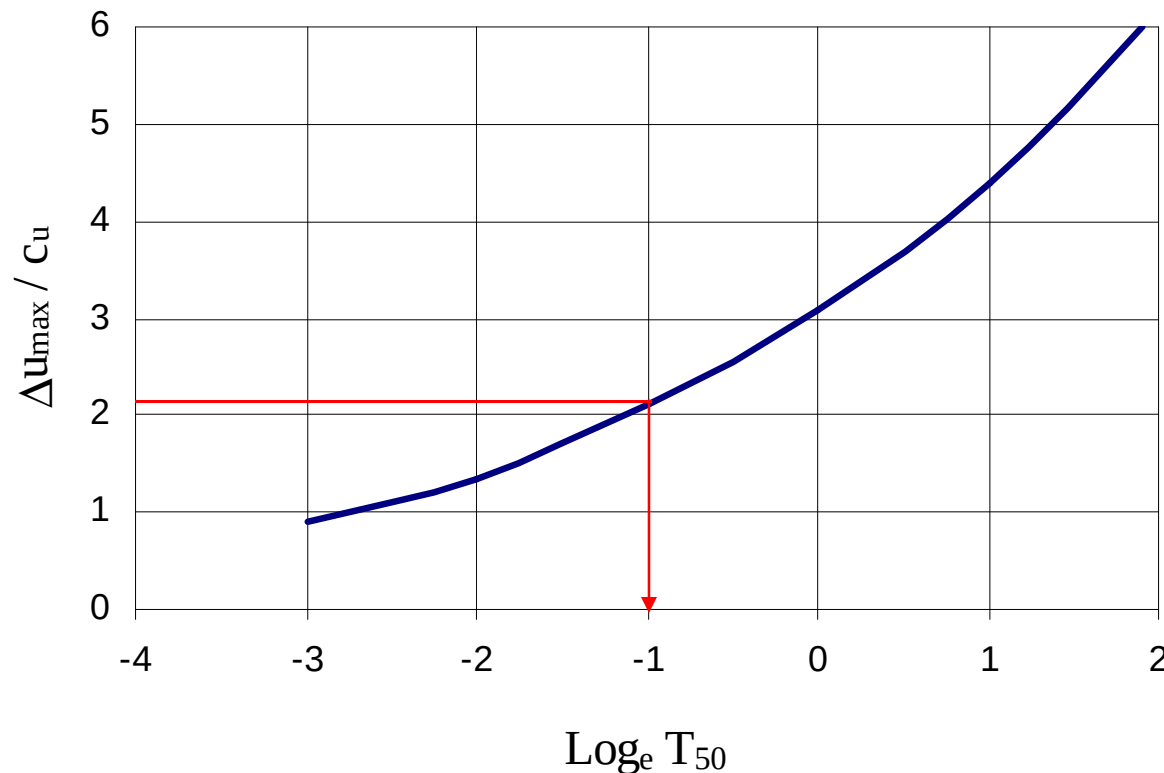
**Typical holding
test results**
(Clarke et al, 1979)



Determination of c_h

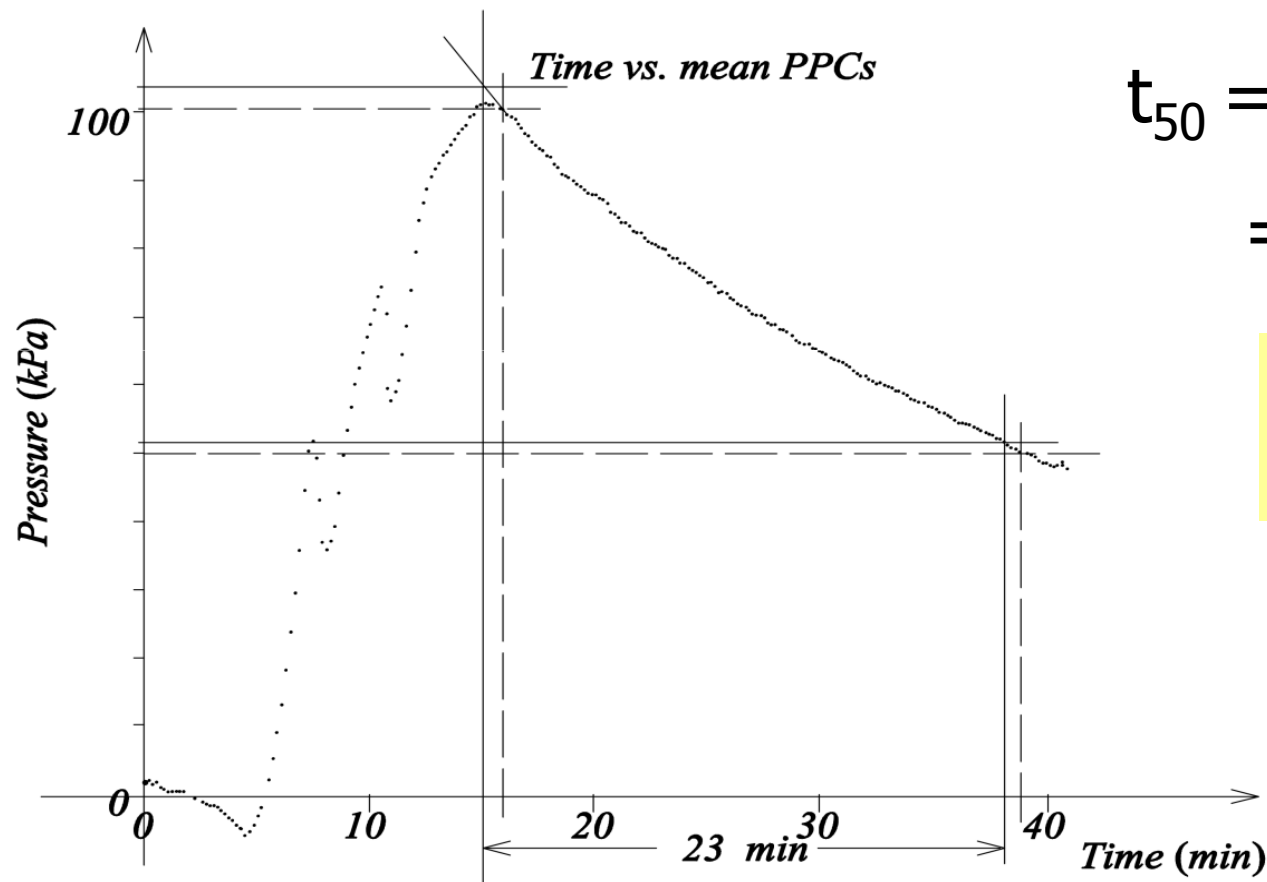
Radius of the PMT

$$c_h(SBPT) = \frac{T_{50} R_r^2}{t_{50}} \quad (1)$$



$$\begin{aligned} \Delta u_{\max} / c_u &= 125/60 \\ &= 2.1 \\ \Rightarrow \ln T_{50} &= -1 \\ \Rightarrow T_{50} &= 0.368 \end{aligned}$$

Typical pore pressure dissipation versus time curve



$$t_{50} = 23 \text{ min}$$

$$= 4.37 \times 10^{-5} \text{ yr}$$

$$c_h(SBPT) = \frac{T_{50} R_r^2}{t_{50}}$$

Conversion of C_h

c_h calculated from Eq. (1) corresponds to the unloading and reloading, that is, OC state. To obtain the c_h value for NC state, a conversion has to be made. One suggestion made by Baligh and Levadoux (1986) for CPTU is:

$$c_h(NC) = \frac{RR}{CR} c_h \quad (2)$$

$$RR = \frac{C_r}{1 + e_0}$$

$$CR = \frac{C_c}{1 + e_0}$$

$$Cr/Cc = 0.05 \text{ to } 0.10$$

$$k_h = \frac{\gamma_w}{2.3\sigma_{v0}'} RRC_h$$

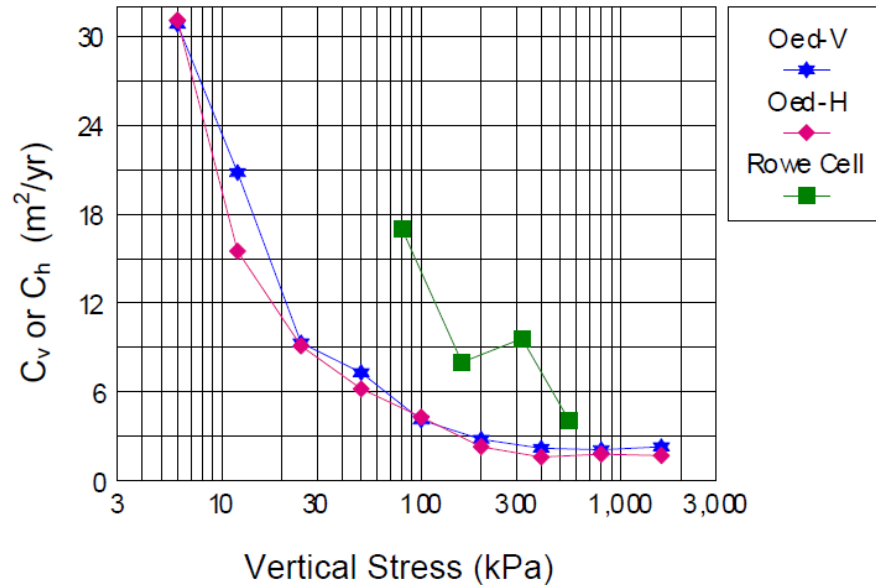
(3)

$$\frac{c_v}{c_h} = \frac{k_v}{k_h}$$

(4)

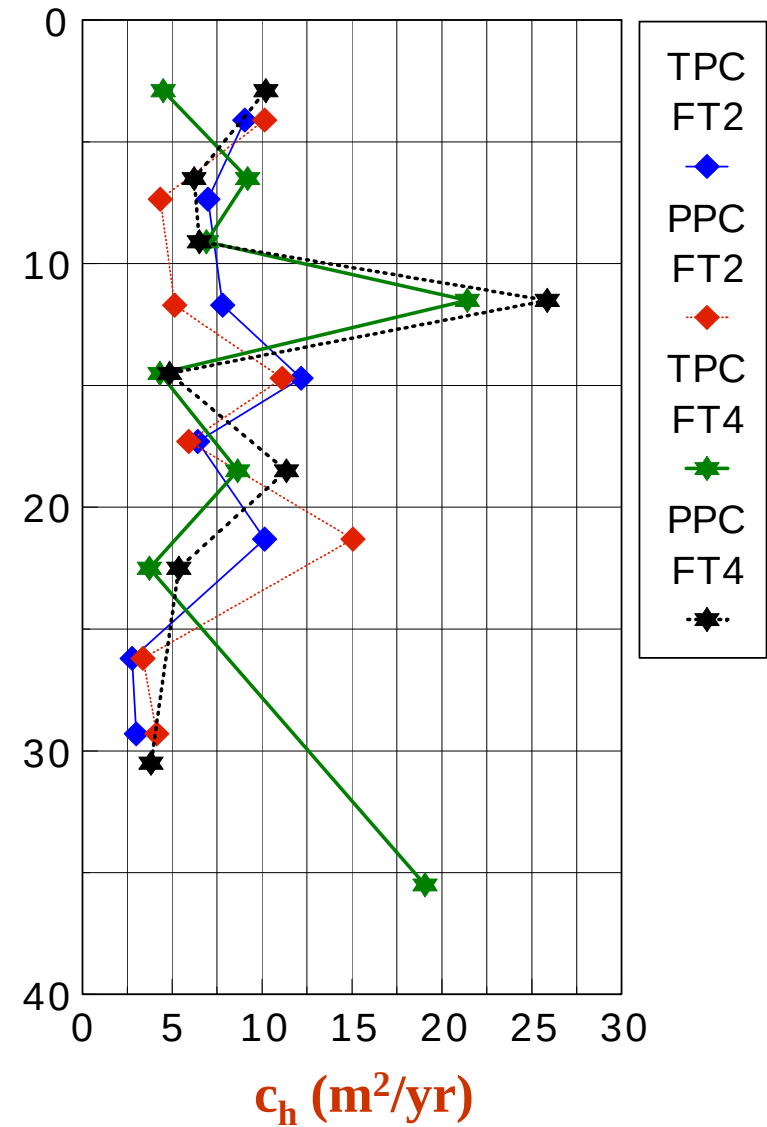
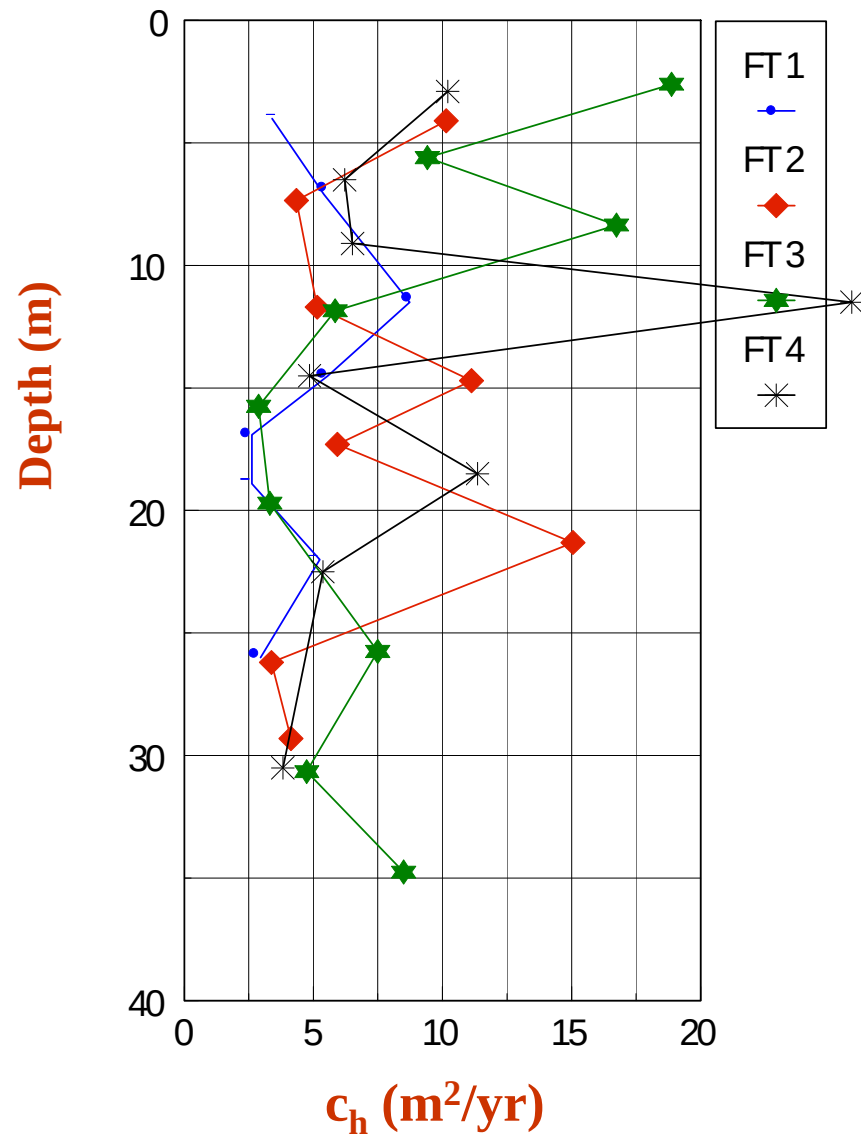
Conversion of C_h (cont'd)

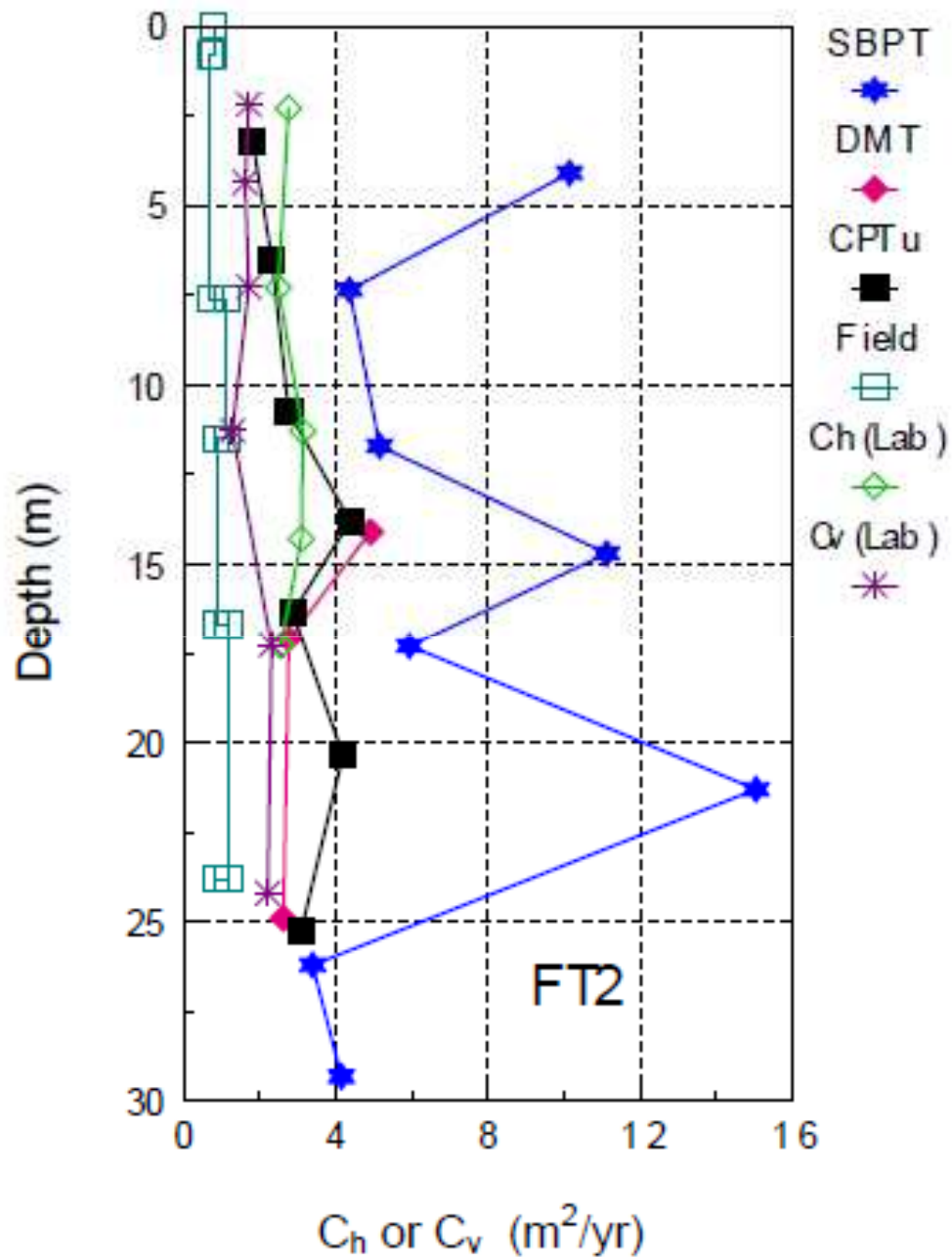
Typical k_h/k_v values for soil



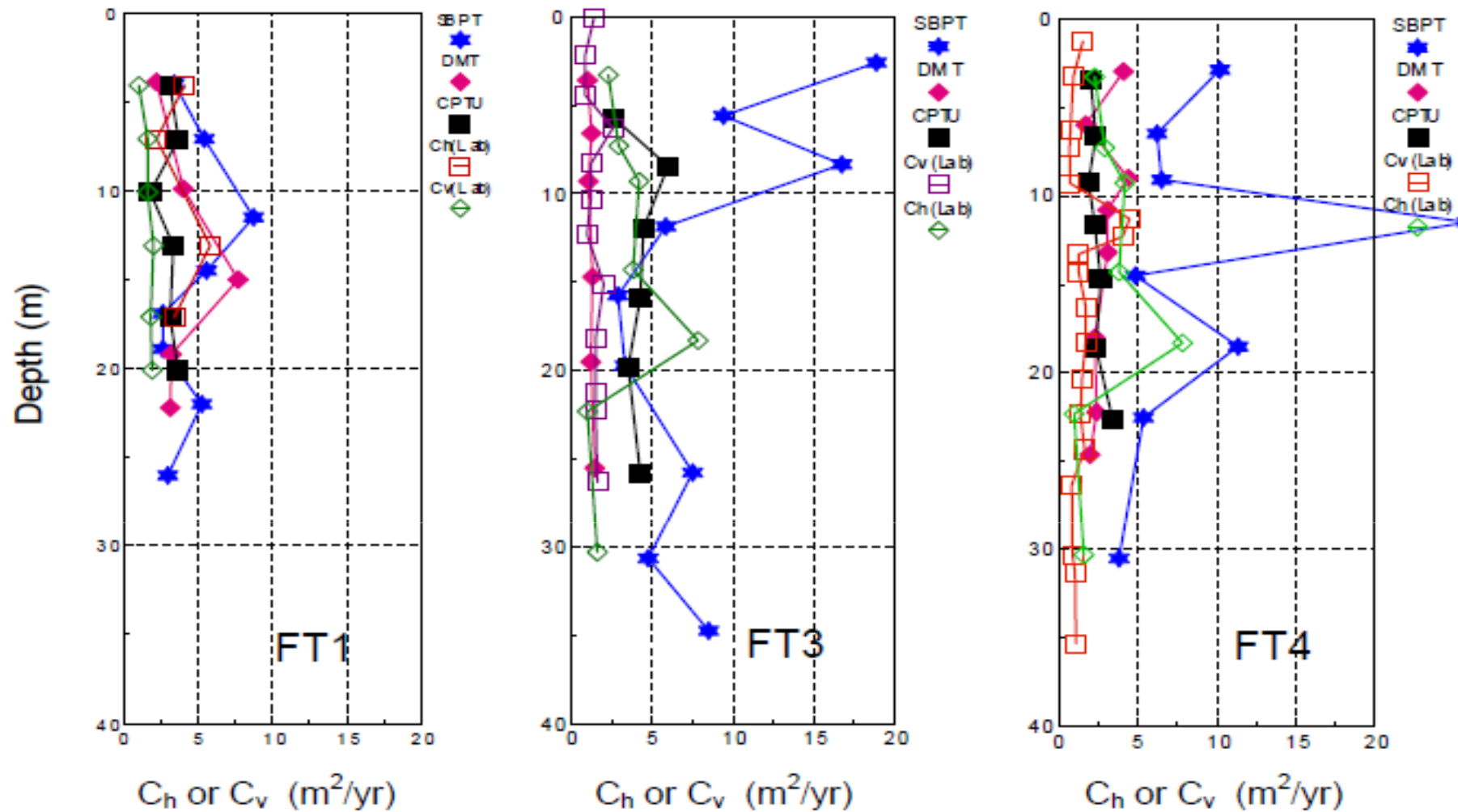
Nature of Clay	k_h/k_v	References
Nearly homogeneous clay or massive marine clay	1 ~ 2	Olson & Daniel (1981), Leroueil et al. (1990), Bo et al. (1998)
Some macrofabric, e.g., marine clay with lenses etc	2 ~ 4	Chan & Kenney (1973)
Deposits containing embedded and more or less continuous permeable layers	3 ~15	Olson & Daniel (1981), Jamiokowski et al. (1985), Baligh & Levadoux (1986).

c_h from SBPT





**Comparison of
different
 C_v or C_h
measurements
for Singapore
marine clay**



Possible reasons for a higher C_h value by SBPM tests:

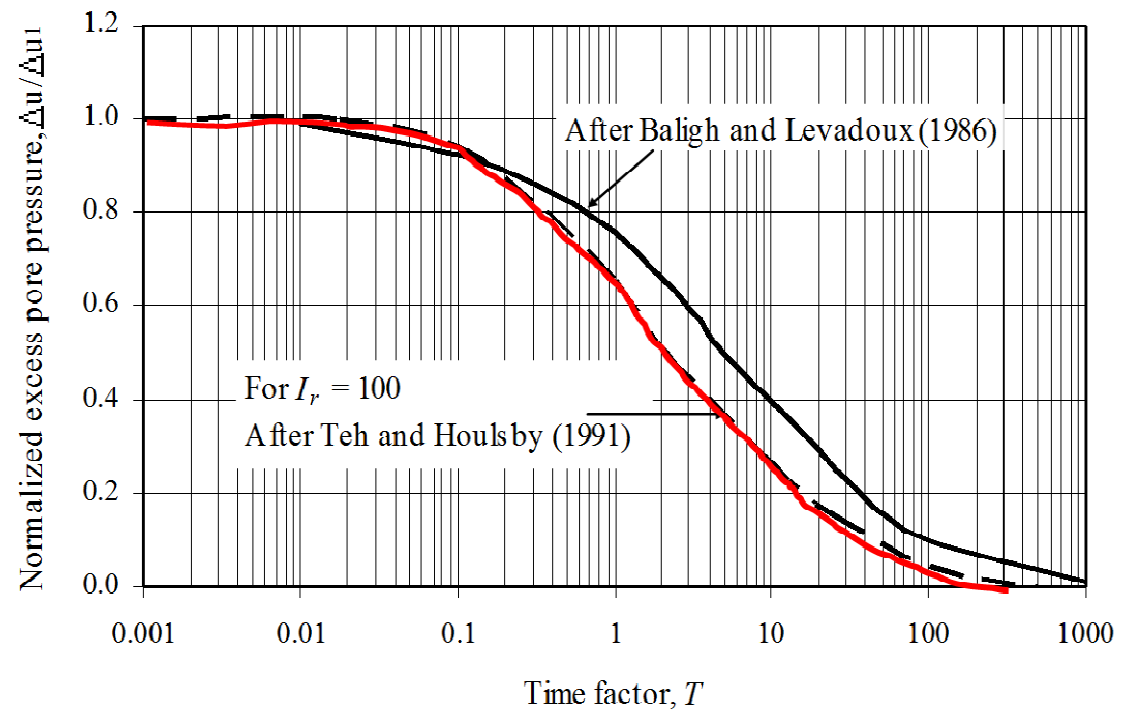
- 1). Less smear effect due to the selfboring process and loosening of borehole wall
- 2). A better interpretation or conversion method may be required

Rigidity index of the soil should be taken into consideration

For CPTU, Teh and Houlsby (1991) has proposed a solution to take the rigidity index $I_r = G/c_u$ into consideration through the use of modified time factor T^* :

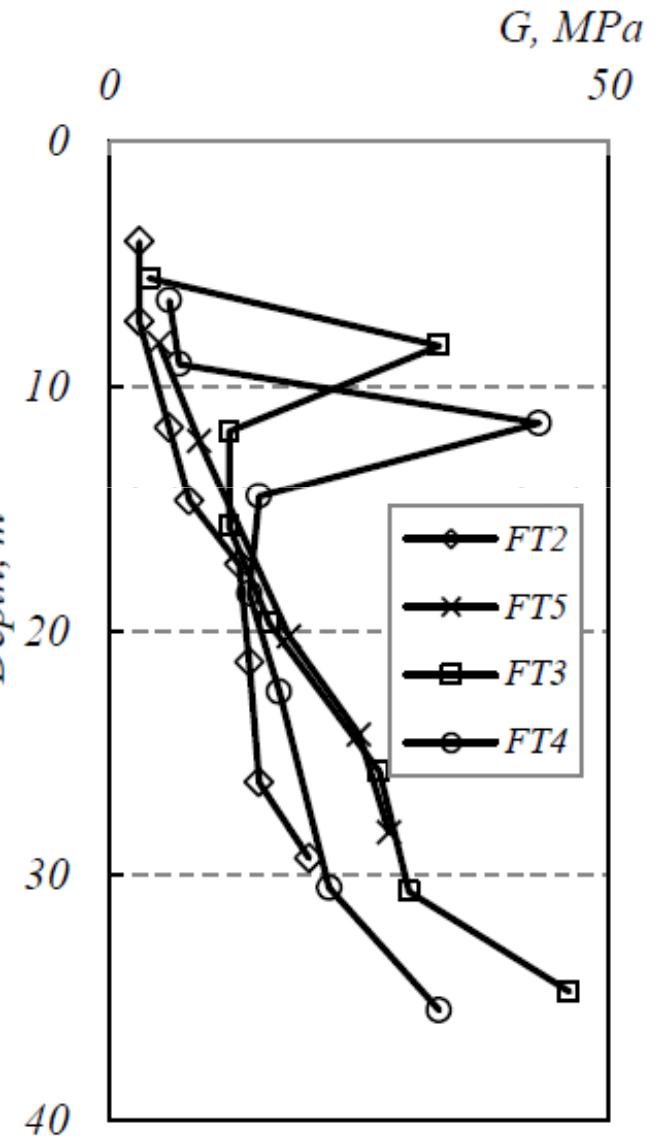
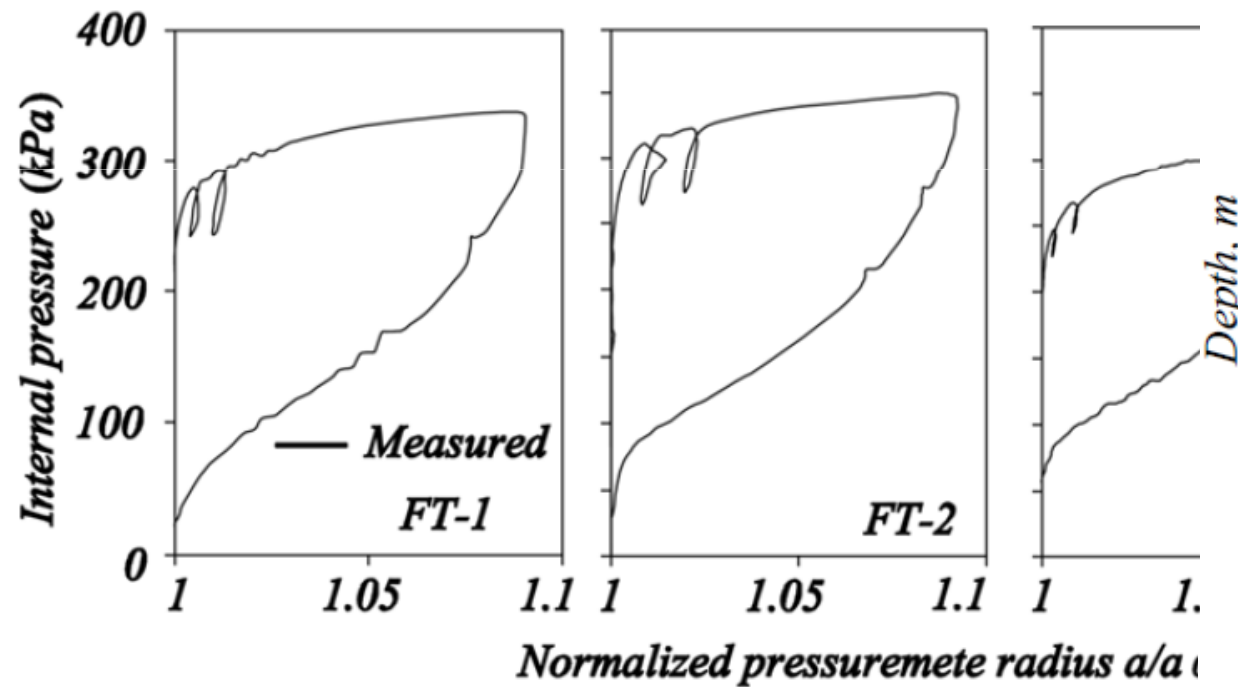
$$T^* = \frac{c_h t}{R_r^2 \sqrt{I_r}}$$

If a similar modification can be made, the C_h obtained by SBPM tests will be smaller.



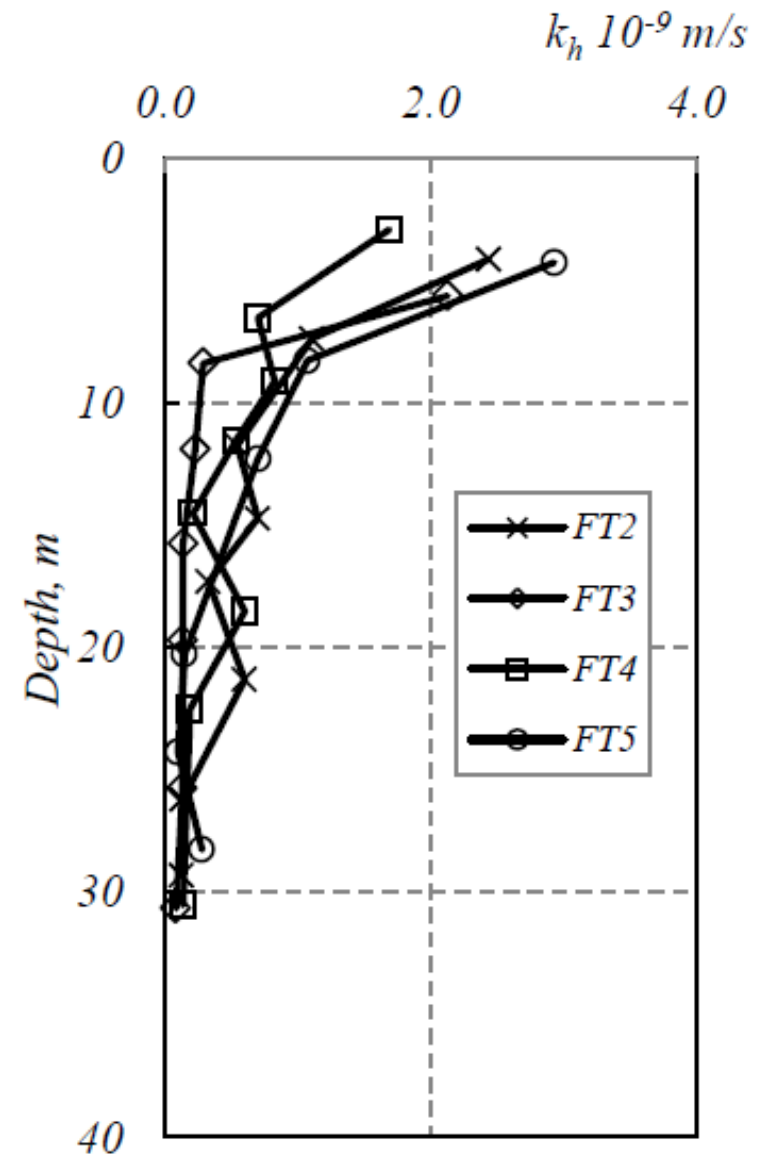
Shear Modulus Determination

$$2G = \frac{\Delta p}{\Delta \varepsilon} = \frac{2\Delta \tau}{\Delta \gamma}$$

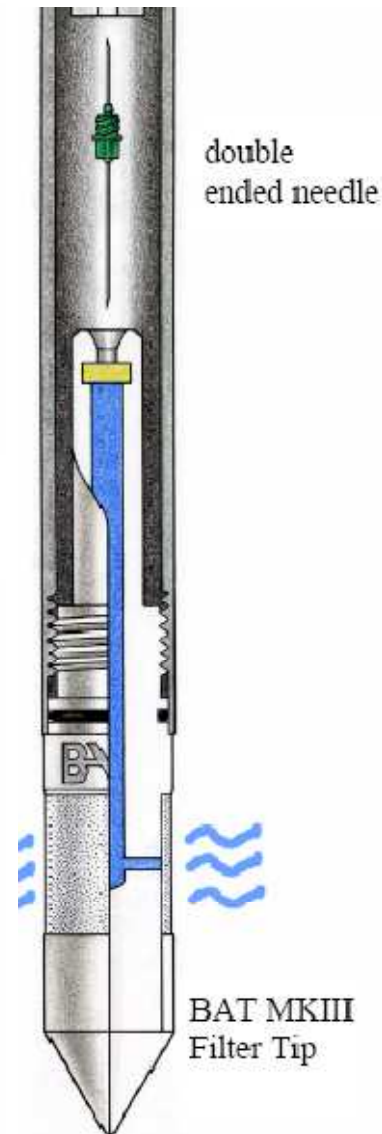
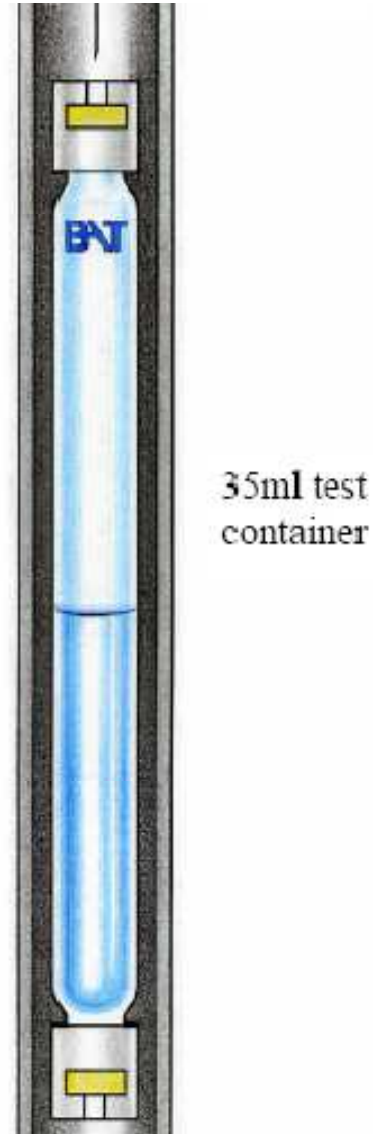
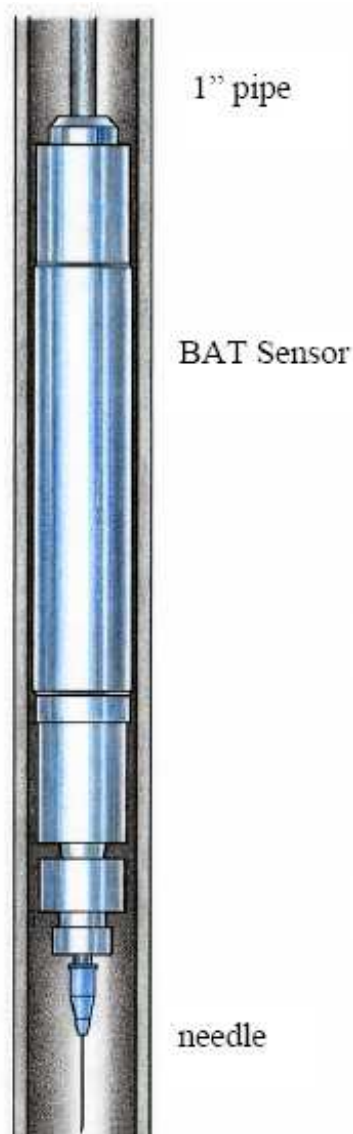
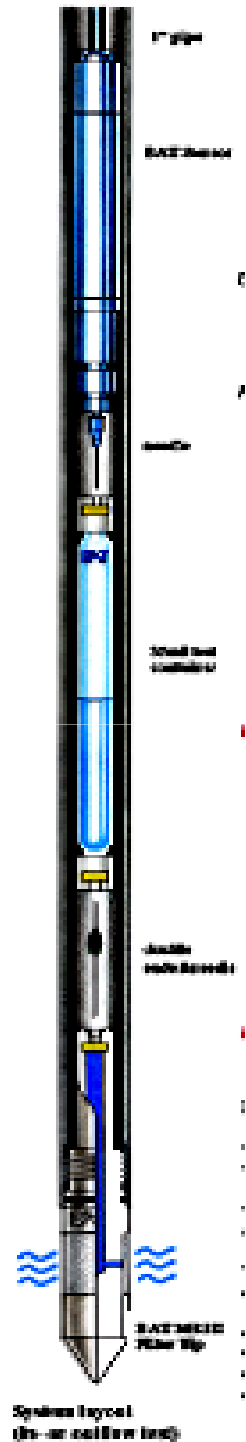


Coefficient of Permeability Determination

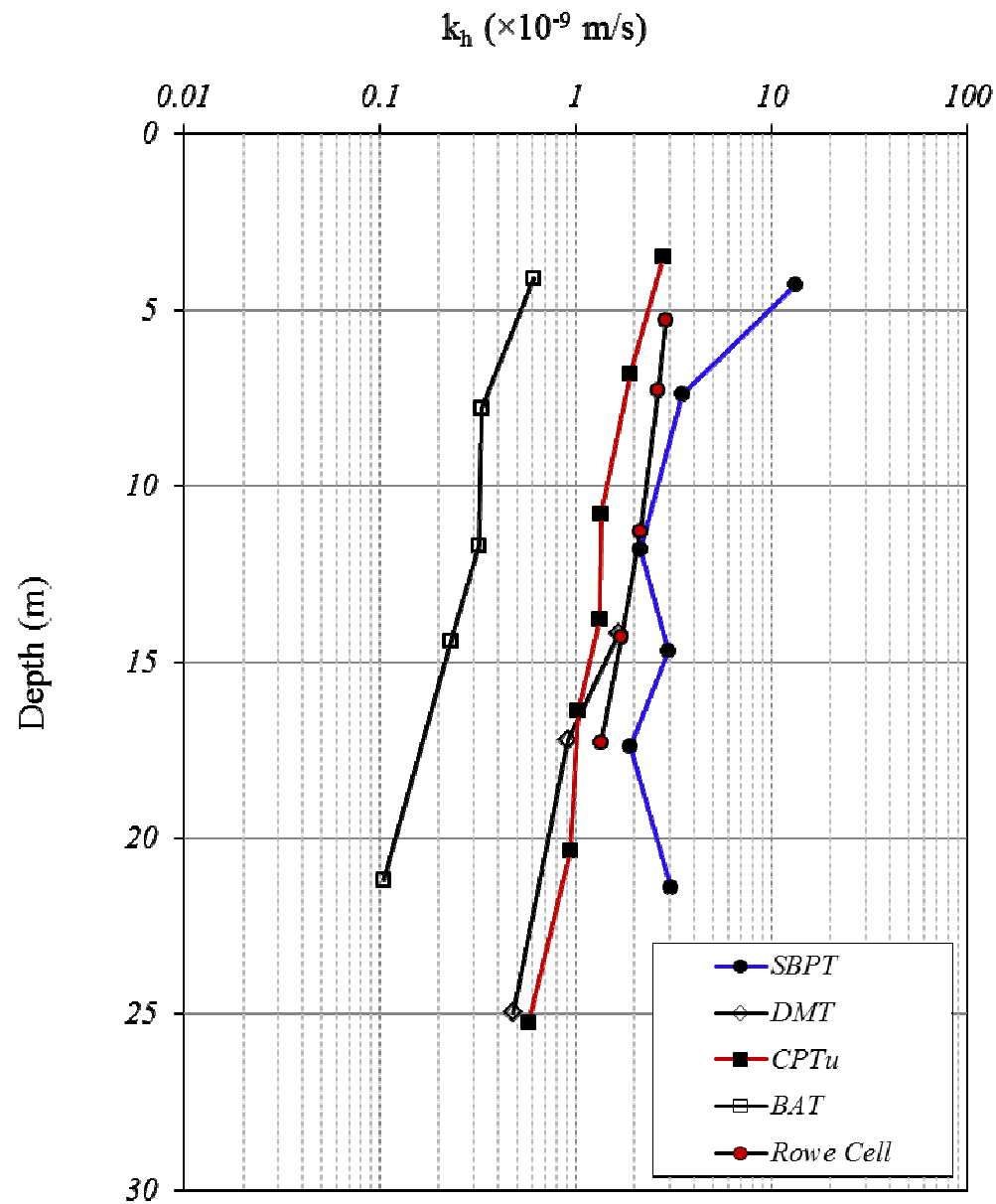
$$c_h(SBPM) = \frac{k_h}{\gamma_w} 2G \left(\frac{1 - \nu'}{1 - 2\nu'} \right)$$



BAT Permeameter Test



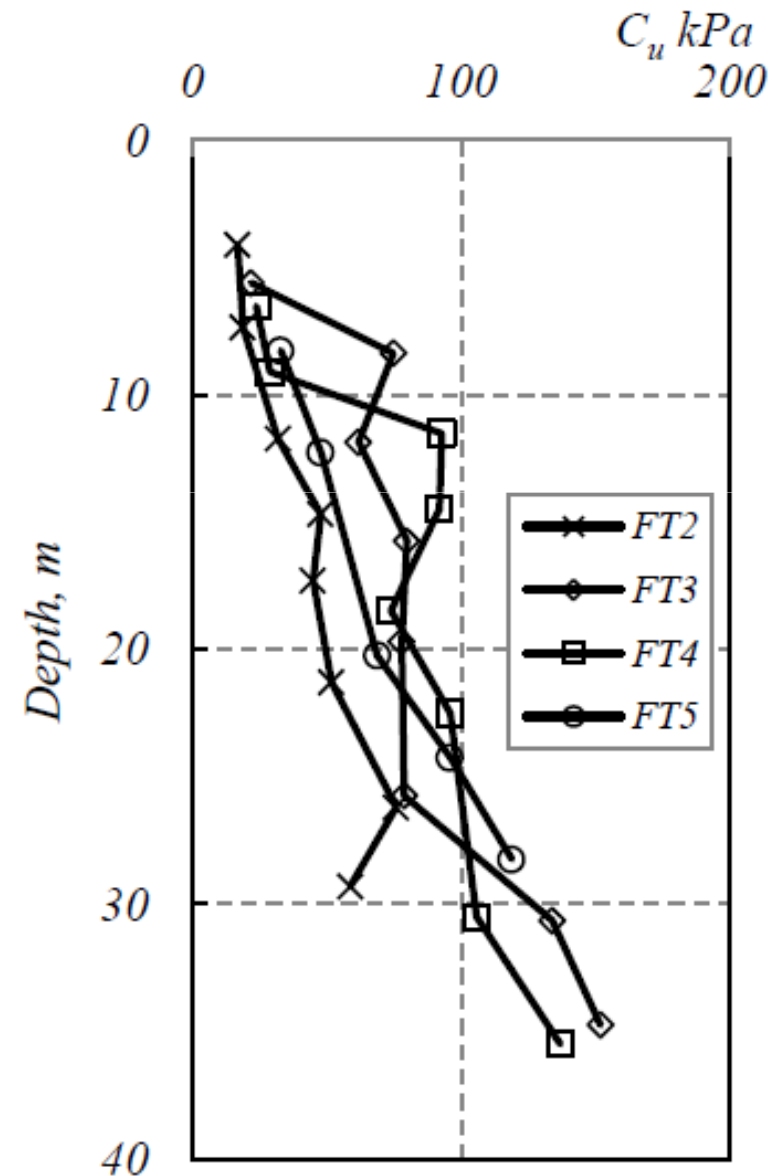
<http://www.bat-gms.com/pdf/In%20situ%20permeability%20measurement%20with%20the%20BAT%20Permeameter.pdf>

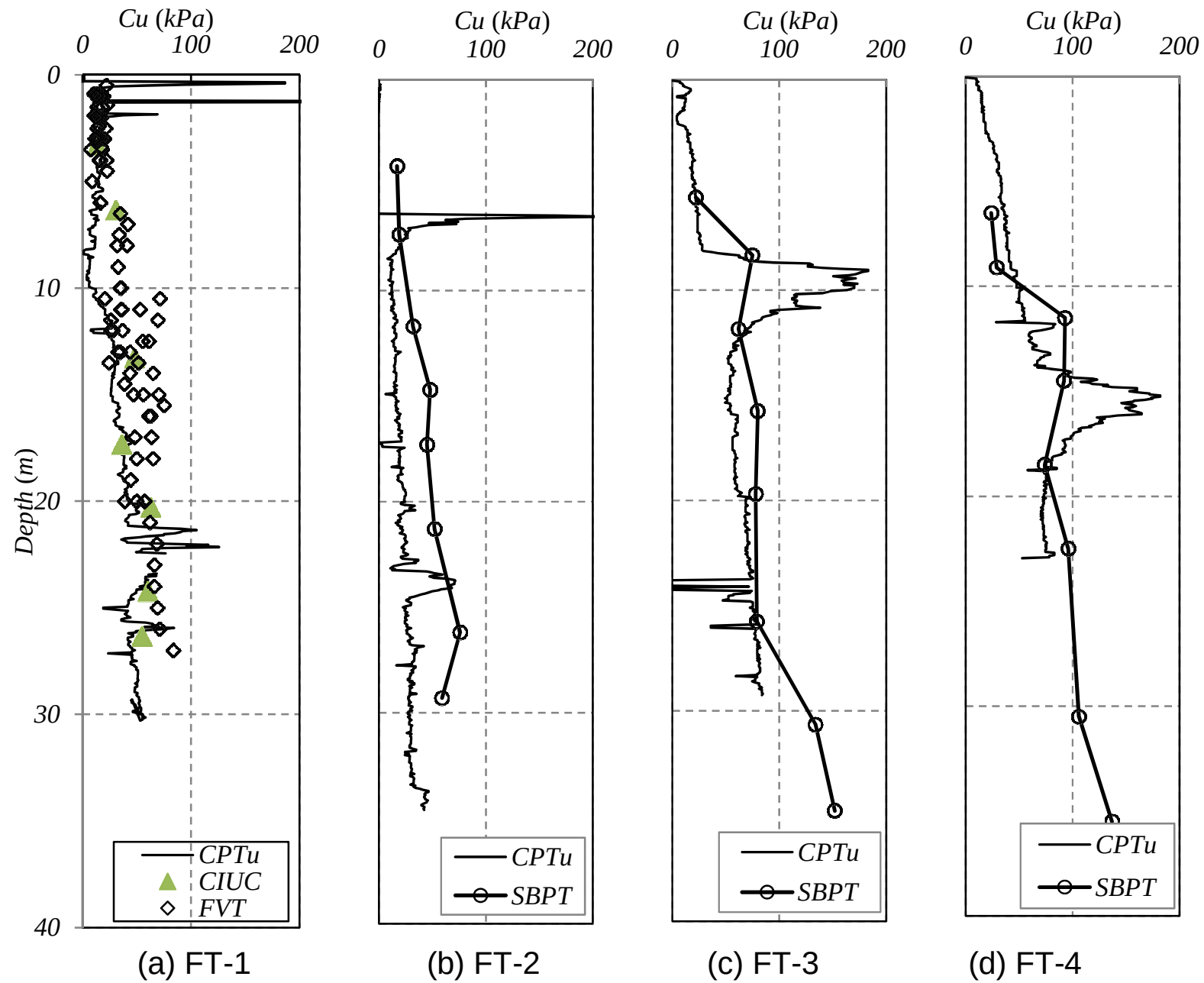


Undrained Shear Strength Determination

$$p_m = \sigma_l + c_u \ln(\Delta V/V)$$

Where p_m is the pressure applied by the membrane, σ_l is the limit pressure, $\Delta V/V$ is the volume change to the current volume of the membrane ratio.





Comparison of c_u profiles measured by SBPT and CPTU at different location

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- Part 3. Use of pressuremeter tests in sandfill

SBPT to determine shear modulus for sandfill

- SBPT is particularly suitable for sandfill as it does not need to pre-bore a borehole.
- Conventionally, an unloading-reloading shear modulus G_{ur} is determined from the unloading-reloading loop based on linear elastic theory.
- Cao et al. (1998, 2002) proposed a hyperbolic model to fit the unloading-reloading curve in the SBPT in sand based on cavity expansion theory.

Sand Modulus Determination

Cylindrical cavity
pressure σ_a

$$\sigma_a = \sigma_{ho} + \frac{2(1-\nu)\tau_r}{(1-2\nu)} \left\{ 1 - \left[1 + \frac{G_i}{(1-\nu)\tau_r} \left(\frac{a-a_o}{a} \right) \right]^{-(1-2\nu)} \right\}$$

Assuming $\tau = \frac{\gamma}{1/G_i + \gamma/\tau_r}$

G_i = initial shear modulus and τ_r = reference shear stress at infinite strain.

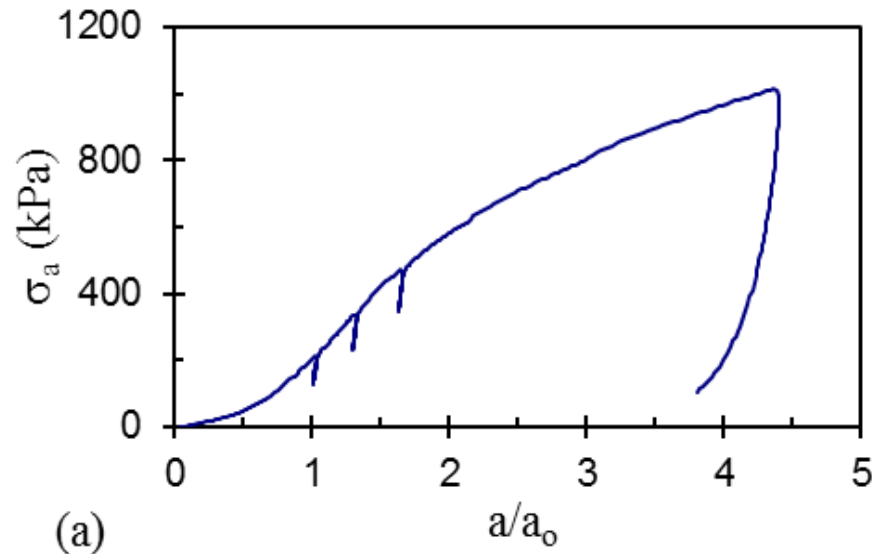
Mean stress p at the cavity wall prior to soil yielding

$$p = \frac{\sigma_{vo} - 2\nu\sigma_{ho}}{3} + \frac{2(1+\nu)(\sigma_a - \tau)}{3} \quad \tau = \tau_r \left\{ 1 - \left[1 + \frac{G_i}{(1-\nu)\tau_r} \left(\frac{a-a_o}{a} \right) \right]^{-2\nu} \right\}$$

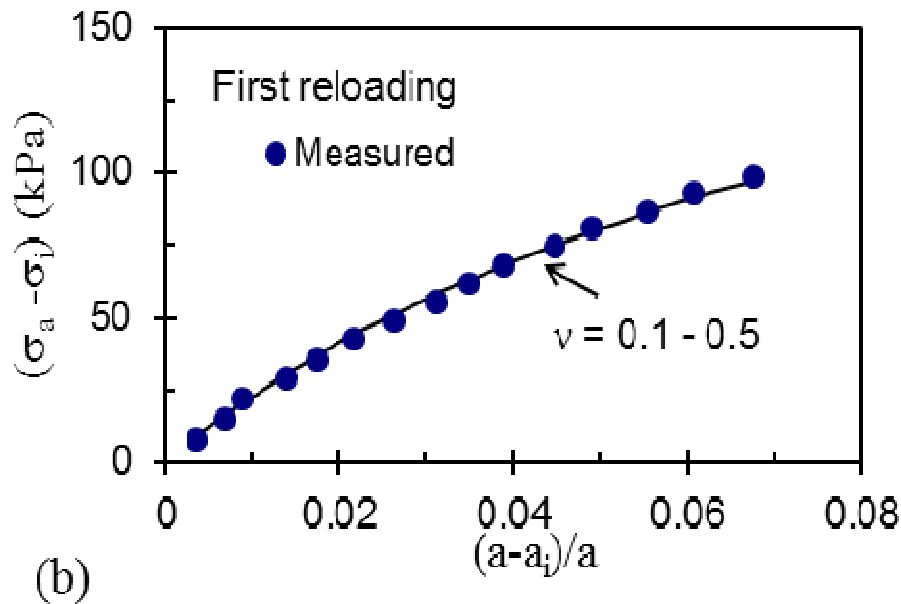
Mean stress at the cavity wall during unloading

$$p = \frac{\sigma_{vo} - 2\nu\sigma_{ho}}{3} + \frac{2(1+\nu)[\sigma_a - \sigma_{ai} \sin \phi' / (1 + \sin \phi') + \tau]}{3}$$

SBPMT in sand with 3 unloading/reloading loops



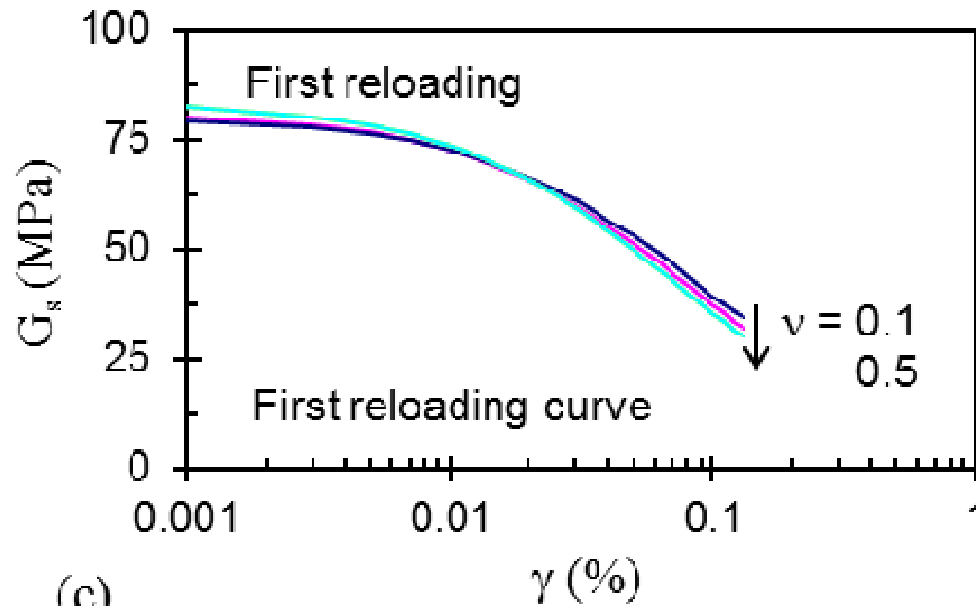
$$\sigma_a = \sigma_{ho} + \frac{2(1-\nu)\tau_r}{(1-2\nu)} \left\{ 1 - \left[1 + \frac{G_i}{(1-\nu)\tau_r} \left(\frac{a-a_o}{a} \right) \right]^{-(1-2\nu)} \right\}$$



Curve fitting of first reloading curve to obtain **G_i** and **τ_r**

Coefficient of deformation
 $r^2 = 0.996$

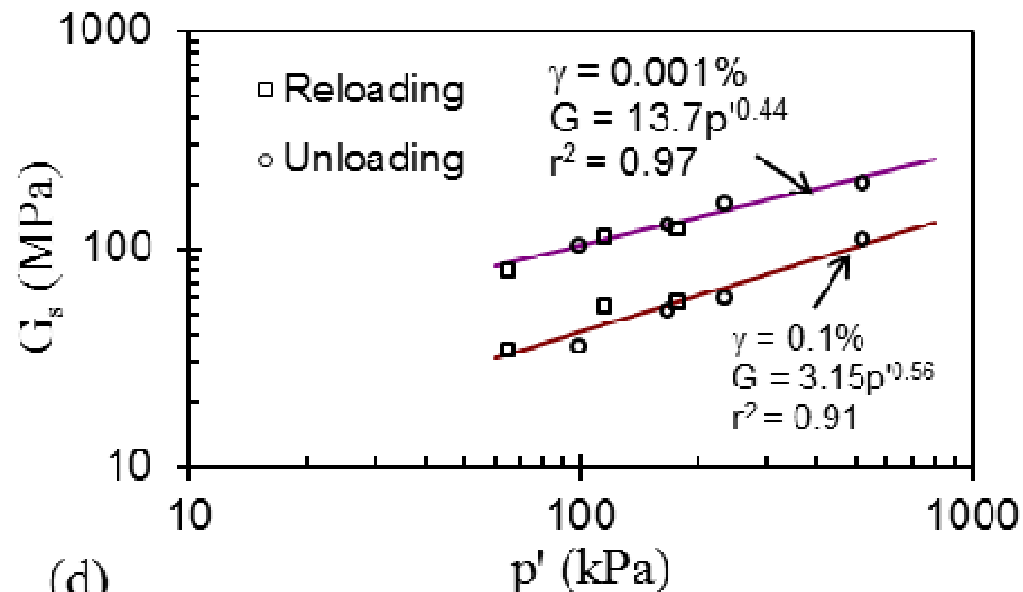
Poisson's ratio $\nu = 0.1 - 0.5$



(c)

$$\tau = \frac{\gamma}{1/G_i + \gamma/\tau_r}$$

Based on **G_i** and **τ_r**
from curve fitting



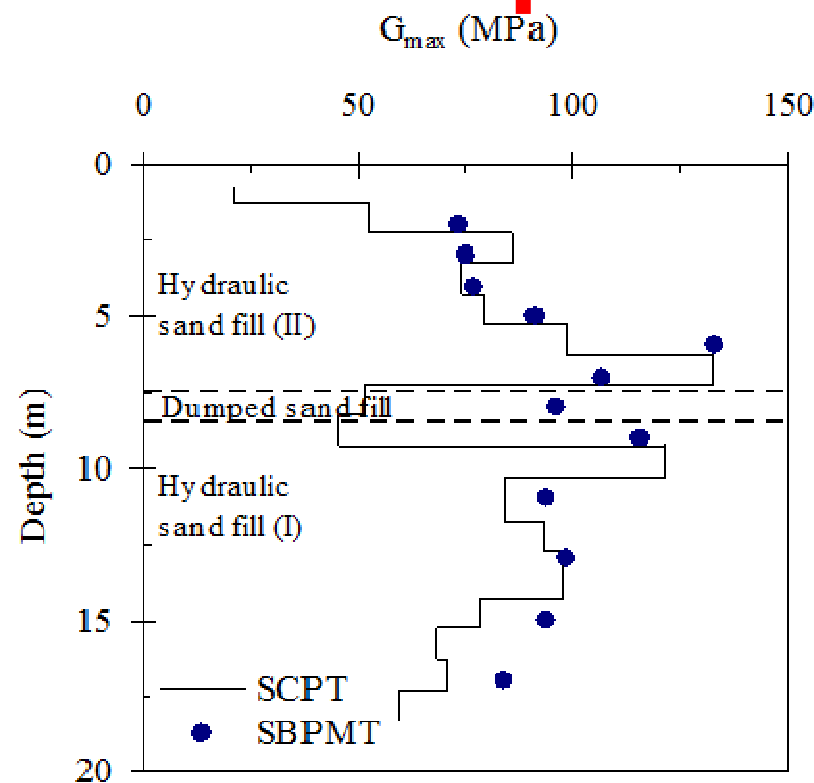
(d)

Logarithmic plots of **secant shear modulus G_s** against the **p'** for **γ** of **0.001% and 0.1%**

For unloading, p' is the mean effective stress at the start point of unloading.

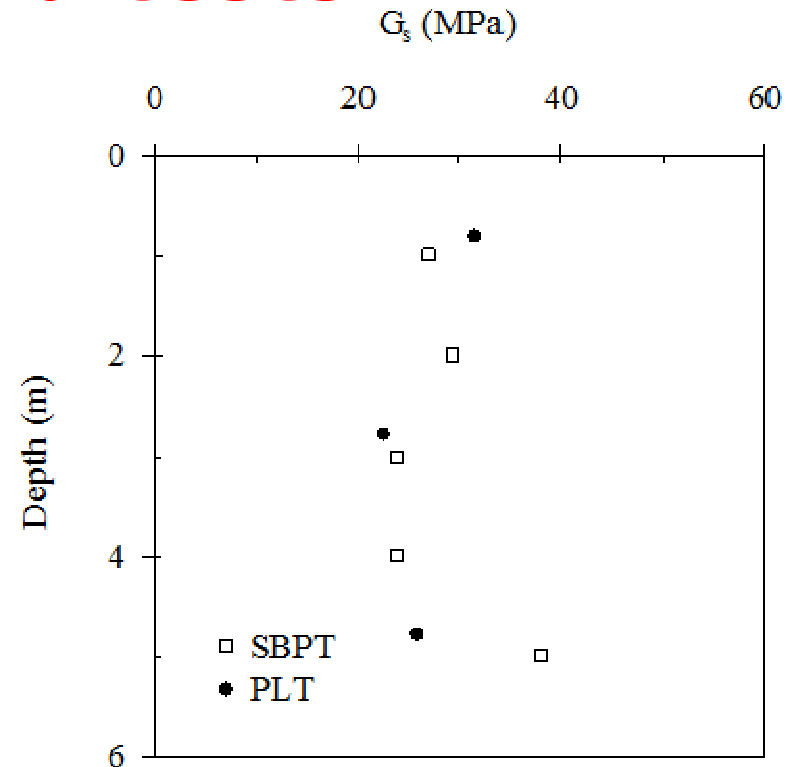
For reloading, p' is the mean effective stress at the start point of reloading

Comparison of G_s from SBPM, CPTU and plate load tests



G_{max} profiles interpreted from
SCPT and SBPT

Strain level of 0.001%



G_s profiles interpreted from
PLT and SBPT

Strain level of 0.2%

Conclusions

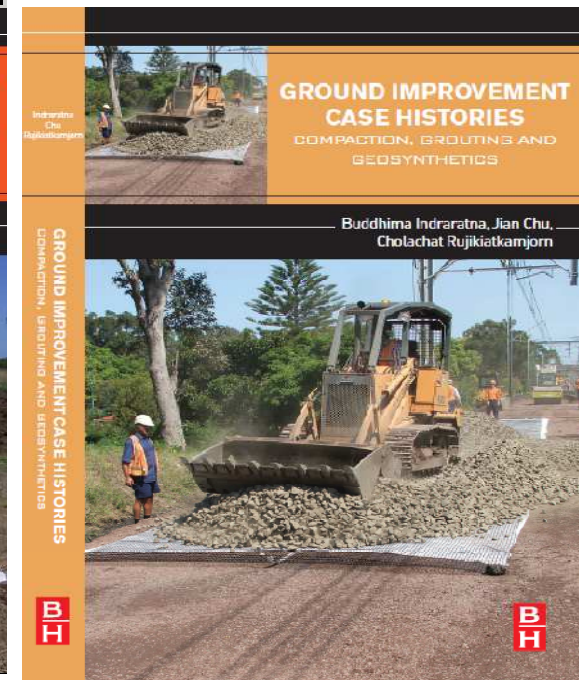
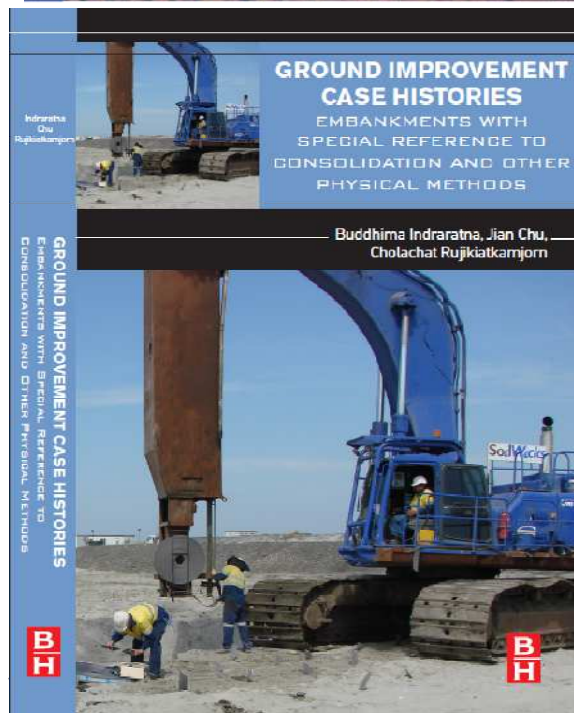
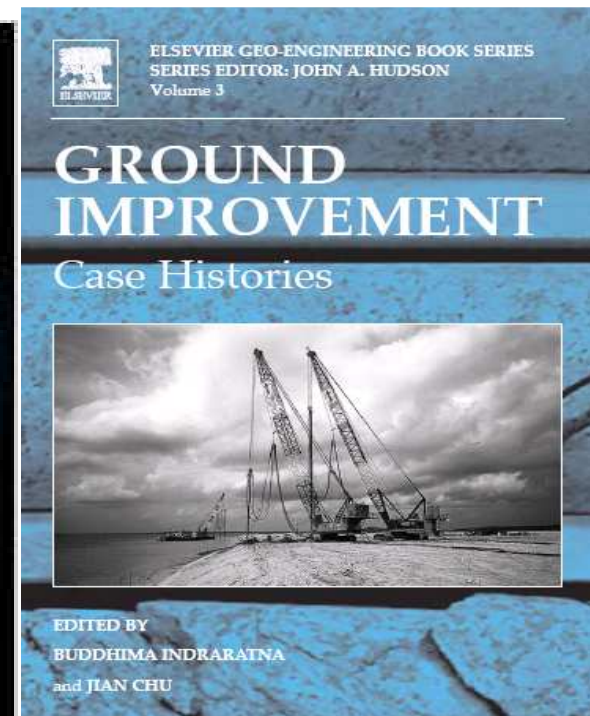
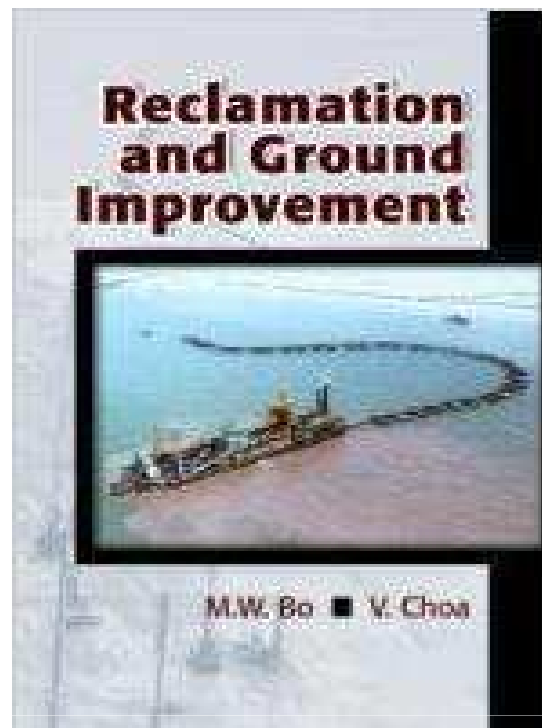
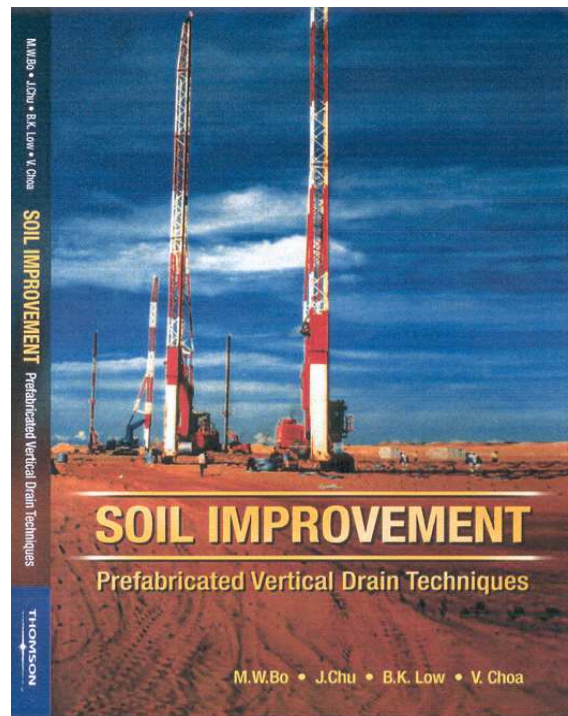
- 1) The coefficient of consolidation c_v or c_h is an important soil parameter for soil improvement works using vertical drains. The c_h value of the Singapore marine clay at the NC state is in the range of 2.0 to 5.0 m²/yr as determined by Rowe cell or CPTU dissipation tests. The value of c_h generally increases with depth and is typically 2 to 3 times higher than that of c_v .
- 2) For SBPT holding tests, the c_h values estimated from the pore pressure reading and the total pressure reading are comparable. In general, the c_h or k_h determined from SBPT holding tests is greater than that by CPTU dissipation tests. The difference is mainly due to the smear effect on CPTU and the interpretation method in which the rigidity index has been taken into consideration in CPTU, but not in SBPM.

Conclusions (Cont'd)

- 3) The undrained shear strength values c_u determined by SBPT agree well with those by CPTu although the c_u value by the SBPT tends to be greater.
- 4) The non-linear stiffness parameters of sand can be obtained from the SBPT based on the proposed interpretation method. The interpreted secant shear modulus at 0.2% shear strain level is similar to the secant shear modulus calculated from the unloading-reloading curve in the plate load test. The interpreted maximum shear modulus is comparable with that calculated from the shear wave velocity measured from the SCPT.

Acknowledgements

- The contributions of many team members to the research and development works associated with the Changi East Land Reclamation Projects, in particular, Professor V. Choa, Drs M.W. Bo, A. Arulrajah, M.F. Chang, and C.I. Teh are gratefully acknowledged.



List of references

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**17TH International Conference on
Soil Mechanics & Geotechnical Engineering**

State of the Art Report

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Dredging International n.v., DEME, Belgium

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Thank you!
Merci!
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