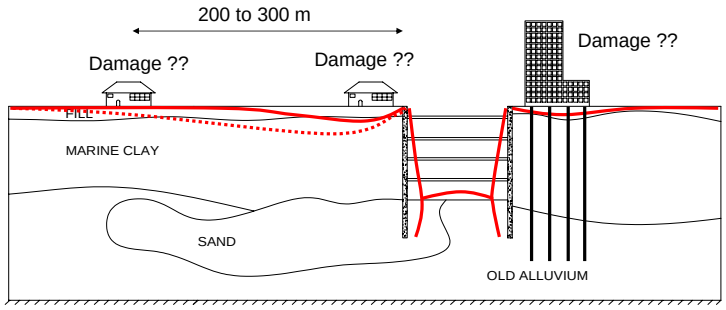
## Wall Deflections and Ground Settlement

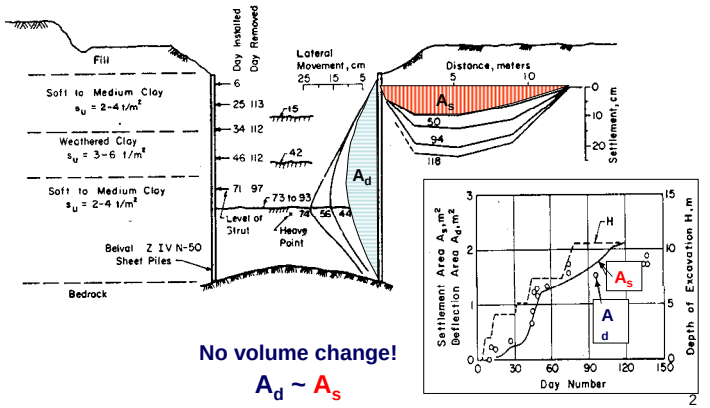



1

Main Cause of Wall Deflection

## Undrained Shear Distortion in Clay

Vaterland 1, Oslo (NGI, 1962)



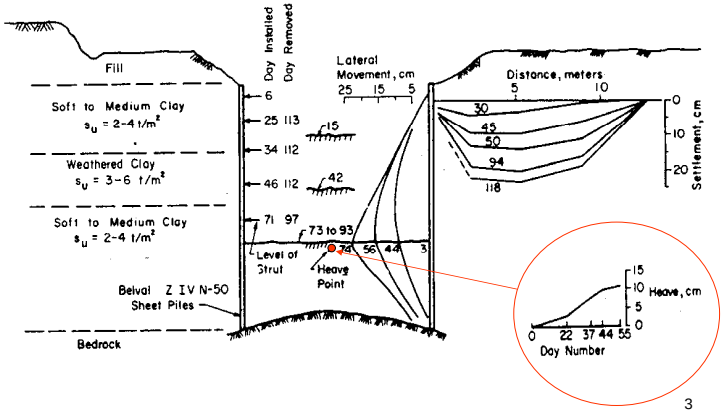

**No volume change!**

**$A_d \sim A_s$**

2

## Wall Deflection and Ground settlement

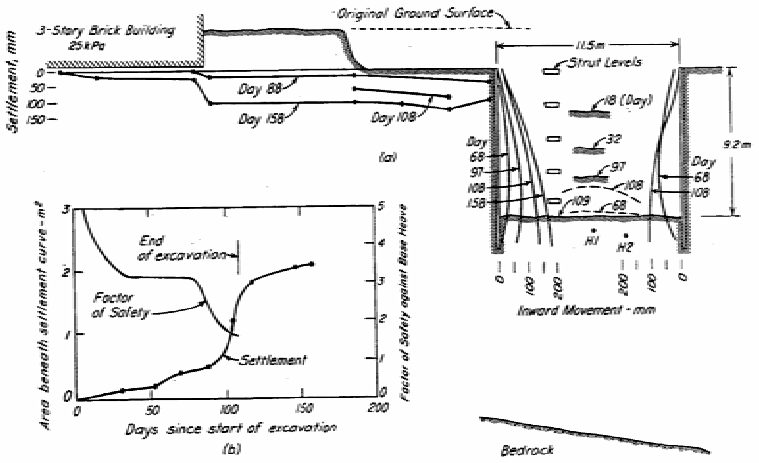
Vaterland 1, Oslo (NGI, 1962)



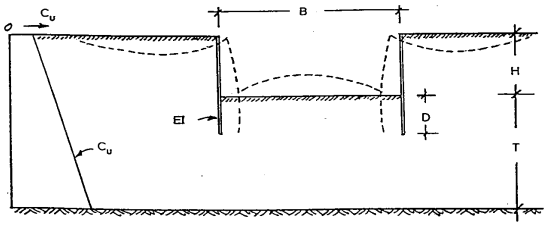

3

## Wall & Soil Movements of an Excavation in Oslo

(NGI, 1962)

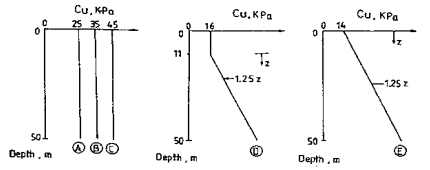


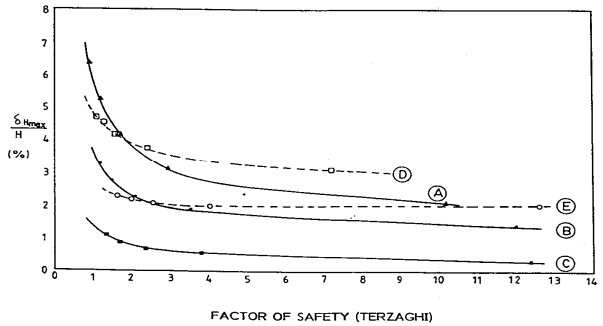
## Major Factors Affecting Soil and Wall Movements in Deep Excavations



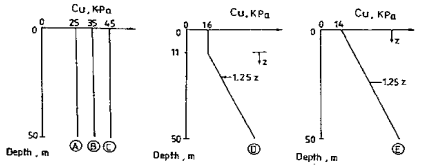

- Undrained shear strength, $c_u$
- Depth of excavation, H
- Width of excavation, B
- Depth to hard stratum, T
- Depth of penetration, D
- Wall stiffness, EI
- Vertical strut spacing
- Construction workmanship

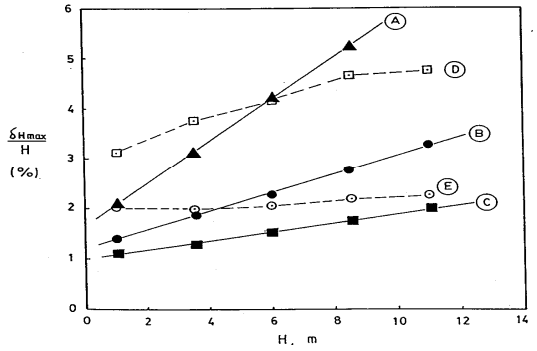
## Effect of Shear Strength on Wall Deflection



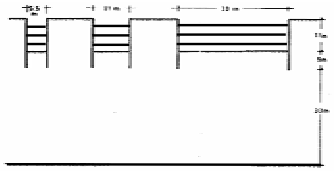



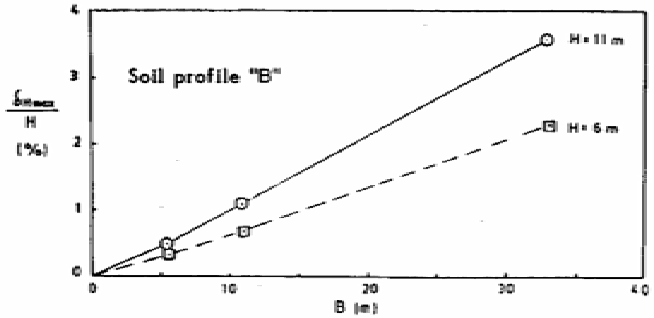

## Effect of Shear Strength on Wall Deflection



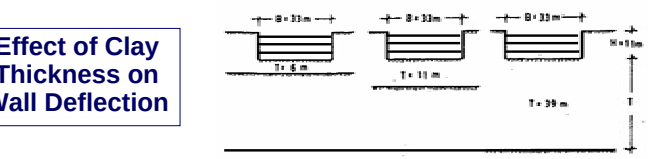



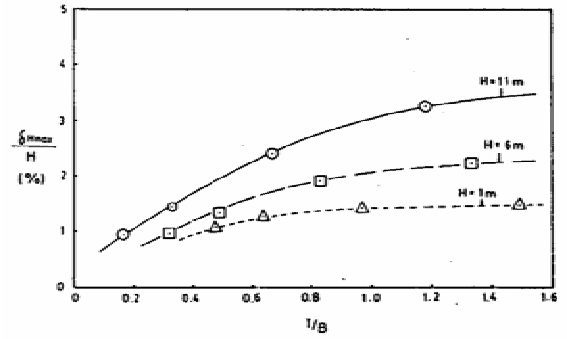

## Effect of Excavation Width on Wall Deflection



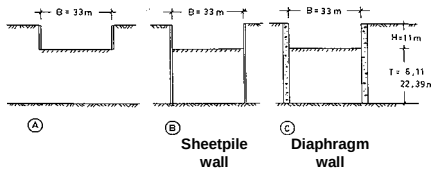


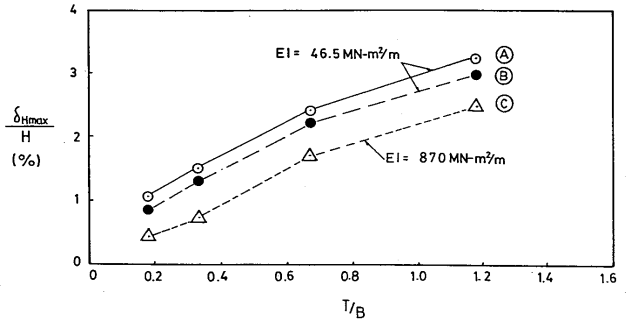
## Effect of Clay Thickness on Wall Deflection



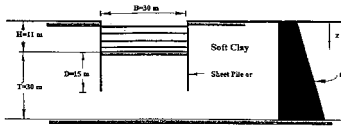


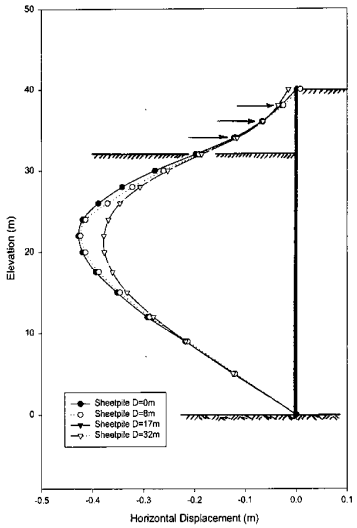

## Effect of Wall Stiffness on Wall Deflection



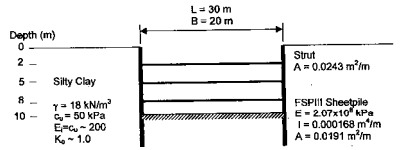



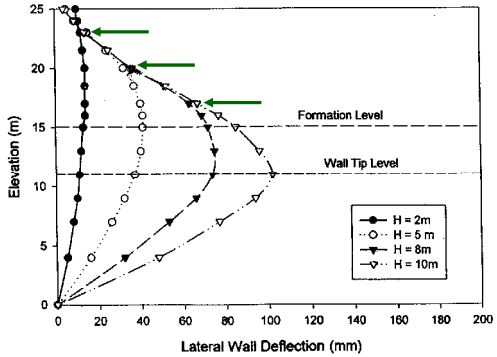

## Effect of Wall Penetration Depth of Sheetpile Wall on Wall Deflection



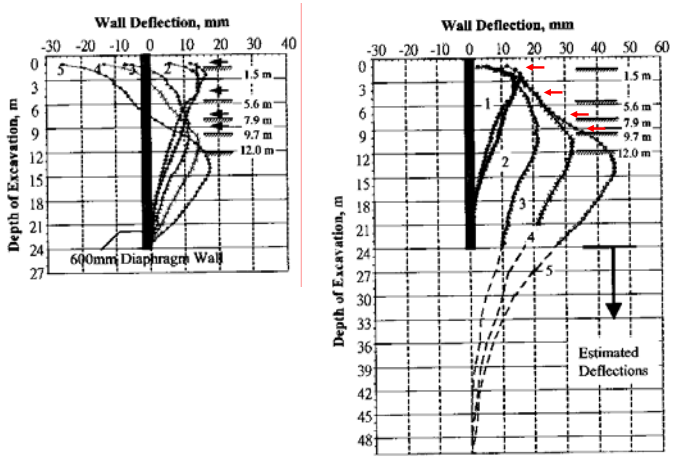




## Wall Deflections at Different Stages of Excavation



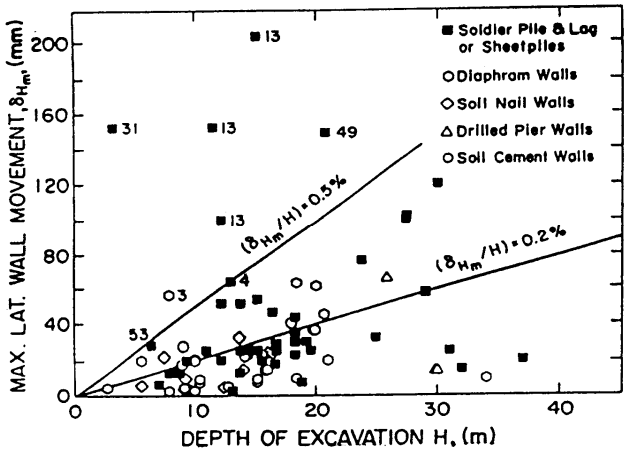



## Questionable Wall Deflection Profiles




## Observed Max. Wall Deflections in Stiff Clays, Residual Soils & Sands

(Clough & O'Rourke, 1990)

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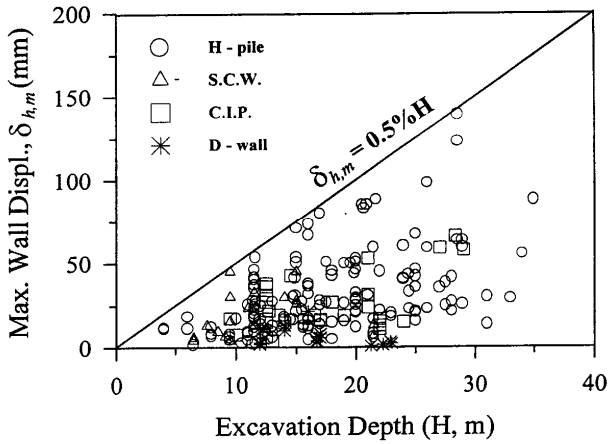
## Maximum Wall Deflections – Korean Experience

(Yoo & Kim, 1999)

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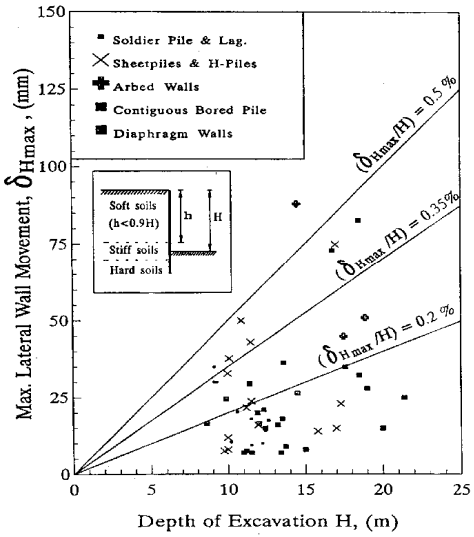
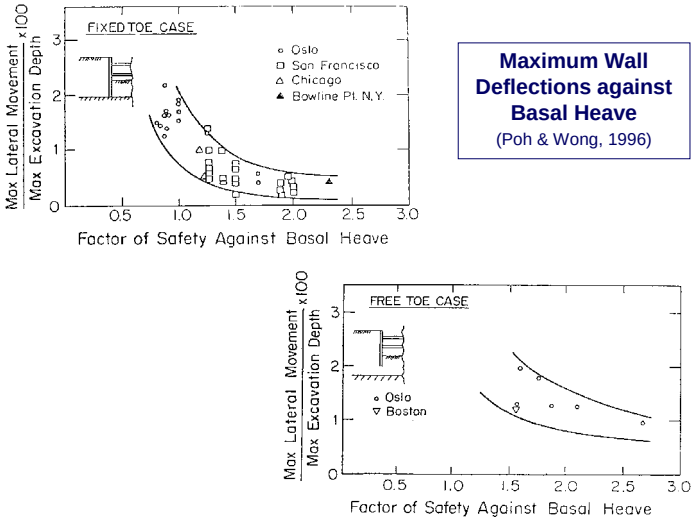
## Maximum Wall Deflections – Singapore Experience

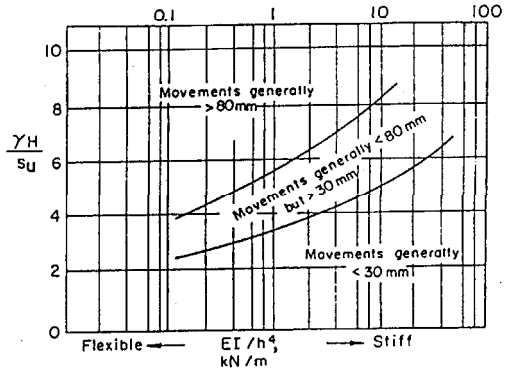
(Poh & Wong, 1996)



**Maximum Wall Deflections against Basal Heave**
(Poh & Wong, 1996)




**Wall Deflections Against Wall Stiffness**
(Mana & Clough, 1977)

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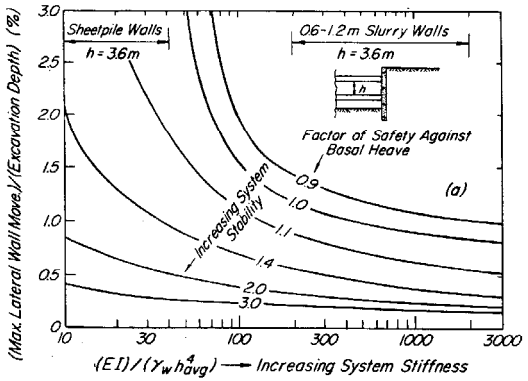
**Design Curves to Estimate Wall Deflections**
(Clough & O'Rourke, 1990)

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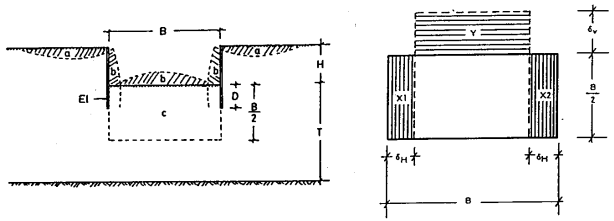
**Estimation of Maximum Wall Deflection**
(Wong & Broms, 1989)



This method postulates that the behaviour of the soil within zone "C" governs the lateral wall movement.

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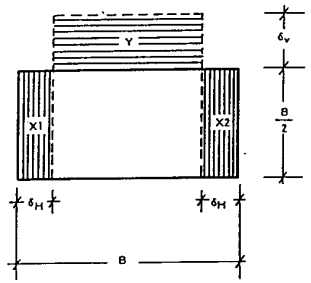
## Estimation of Maximum Wall Deflection
(Wong & Broms, 1989)




Since there is no volume change,

Area X1 + Area X2 = Area Y1

$2\,\delta_H\,(B/2) = \delta_V\,(B - 2\,\delta_H)$

$\delta_H = \delta_V - 2\,\delta_V\,\delta_H / B$

Since $2\,\delta_V\,\delta_H / B$ is small compared to $\delta_V$ and $\delta_H$,

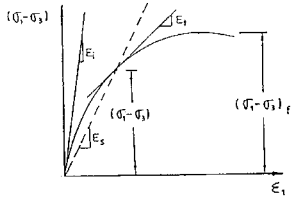
$\delta_H \sim \delta_V$

$\Delta\varepsilon_V = \delta_V / (B/2)$

$\Delta\varepsilon_V = \Delta\sigma_V / E_s = \gamma H / E_s$

$\delta_H = 0.5\,\gamma\,H\,B / E_s$

## Evaluation of Soil Modulus $E_s$



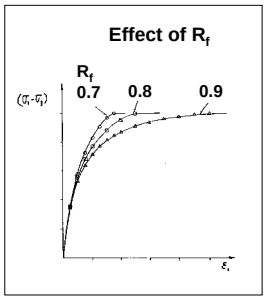

Based on the hyperbolic model by Duncan & Chang (1970), the secant modulus can be determined as follows:

$$E_s = E_i\,(1 - S_L\,R_f)$$

where $E_i$ = Initial tangent modulus

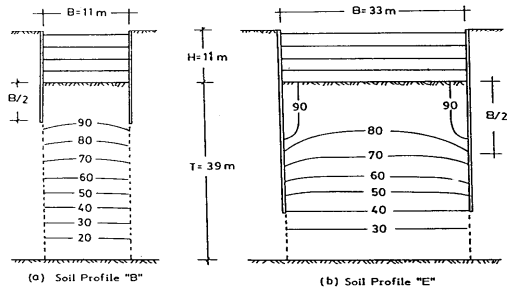
$S_L$ = Stress level within zone "C"

$R_f$ = Failure ratio




## Evaluation of Stress Level $S_L$

$$S_L = \frac{1}{\text{Factor of Safety}} = \frac{(\gamma H + q)}{c_u\,N_c\,\beta}$$

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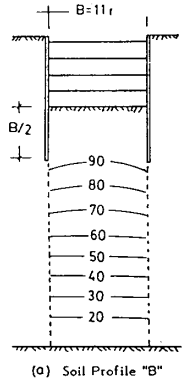
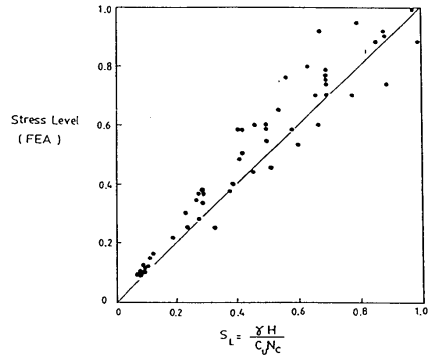
## Evaluation of Stress Level $S_L$

$$S_L = \frac{1}{\text{Factor of Safety}} = \frac{(\gamma H + q)}{c_u\,N_c\,\beta}$$

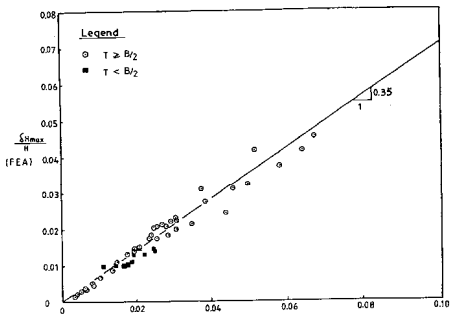


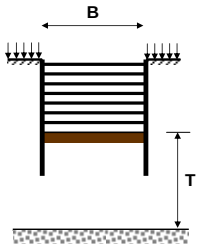



## Calibration against FEA Results to obtain $\delta_{H,max}$

$\delta_{H,max} = 0.35 \gamma H d / E_s$

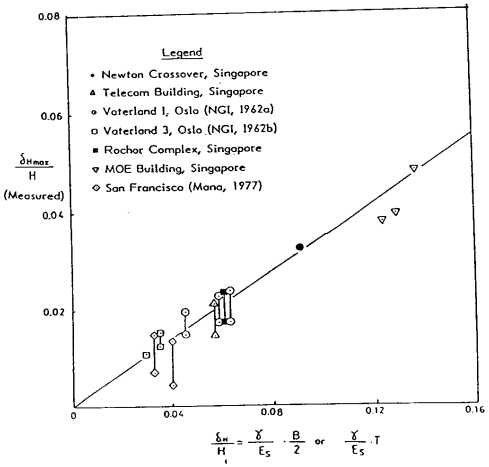
where d = B/2 or T whichever is smaller




$$\frac{\delta_{Have}}{H} = \frac{\gamma}{E_s}\left(\frac{B}{2}\right) \text{ or } \frac{\gamma}{E_s} \cdot T$$

## Comparison of Results with Field Records




$$\frac{\delta_H}{H} = \frac{\gamma}{E_s} \cdot \frac{B}{2} \text{ or } \frac{\gamma}{E_s} \cdot T$$

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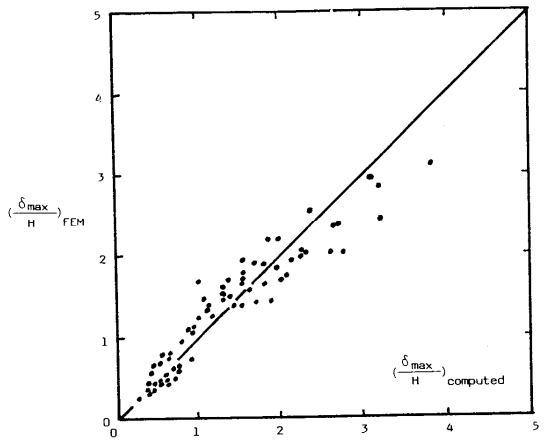
## Comparison of Results with FEA

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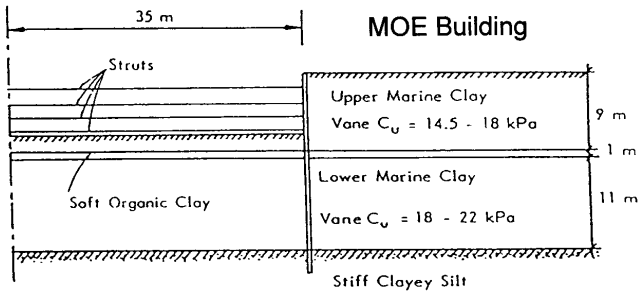
## Comparison of Results with Field Records

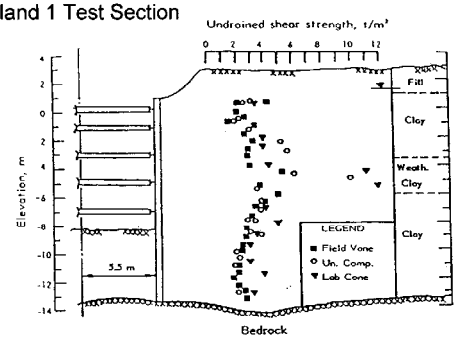



| Depth (m). (1) | Measured deflections (mm) (2) | Computed deflections (mm) (3) |
|---|---|---|
| 3.7 | 140 | 160 |
| 5.1 | 200 | 235 |
| 6.8 | 330 | 326 |

3

## Comparison of Results with Field Records

Vaterland 1 Test Section




| Depth (m) (1) | Measured deflections (mm) (2) | Computed deflections (mm) (3) |
|---|---|---|
| 4 | 59–78 | 64 |
| 6 | 103–137 | 122 |
| 8 | 137–190 | 178 |

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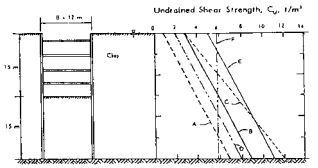
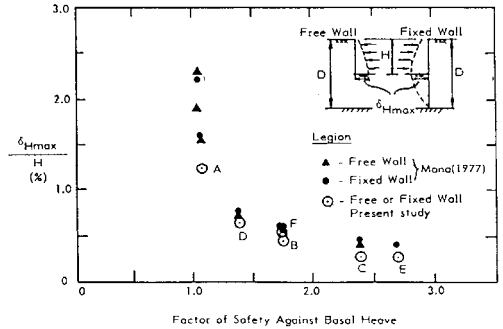
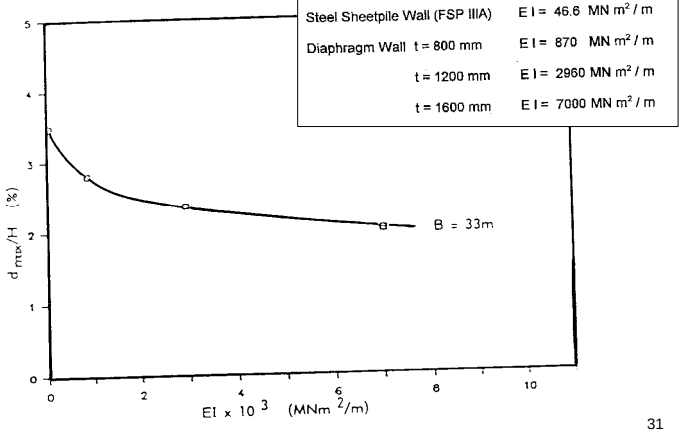
## Comparison of Results with FEA by Mana

(Mana, 1976)




## Effect of Wall Stiffness on Wall Deflection

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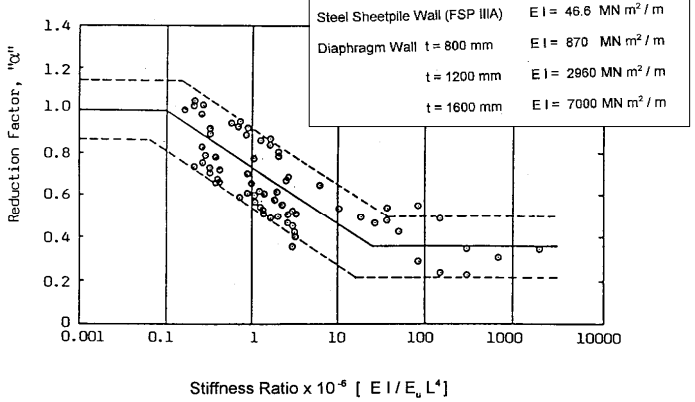
## Effect of Wall Stiffness on Wall Deflection

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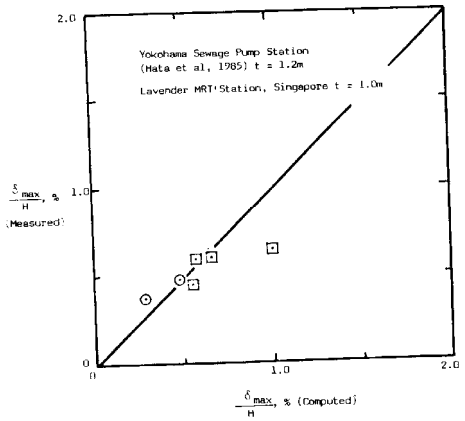
**Comparison of Results with Field Records**

(Wong, Broms & Goh, 1990)

$$\delta_{max} = \frac{0.35\gamma H}{E_s}(d)\alpha$$




## Causes of Ground Settlement

1. Undrained shear distortion
2. Lowering of ground water table
3. Under-drainage
4. Seepage through wall without lowering of ground water table
5. Leakage through base slab

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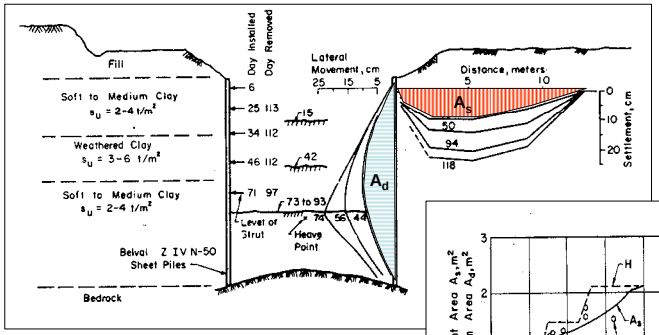
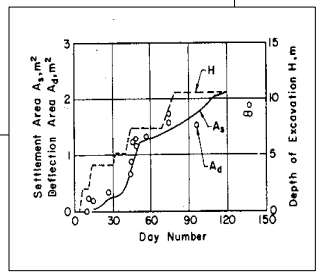
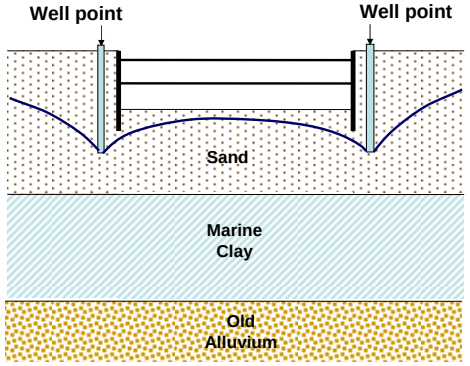
## Undrained Shear Distortion




**There is no volume change.**

## Lowering of Ground Water Table




Causes:
- Pumping
- Wall leakage

Lowering of ground water table will increase the effective stress in soft clay and result in consolidation settlement. 36

## Effect of Lowering of Groundwater Table

FROM A SPACIOUS BUNGALOW TO A WRECK IN 2½ YEARS

OVER 2½ years, this is what has become of a bungalow, which is back-to-back to the site of Balmoral Plaza.

Because of soil subsidence, the spacious garden has acquired a gentle bowl shape.

A pillar was in danger of collapsing until the plaza developer put up wooden supports.

A front gate cannot open or shut any more because of the uneven ground.

Inside the house, a visitor senses the living room slipping away. The wall bears an ugly patch where the plaza developer has cemented extensive cracks.

The bungalow is occupied by businessman Poh Hock Keat, 48, and his family, but is owned by his father, who is living in Indonesia.

Mr Poh said he has engaged a lawyer to take up the matter. With whatever compensation he gets, he said, he is considering tearing down the property and rebuilding it.

Under normal circumstances, the bungalow is worth $1 million, he added.

Developer: It's a private dispute

THIS is a private dispute and is best settled in private, said the developer of Balmoral Plaza.

When contacted by The Straits Times, Mr Lee Seng Eng, the property manager of Balmoral Plaza Pte Ltd, would only say: "This is a private dispute and is best settled in private. We are in communication with the parties involved."

The plaza, which will have shopping, residential and office units, is expected to be ready by the end of next year, he said.

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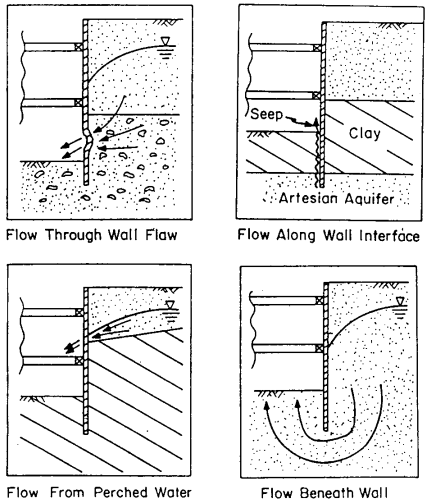
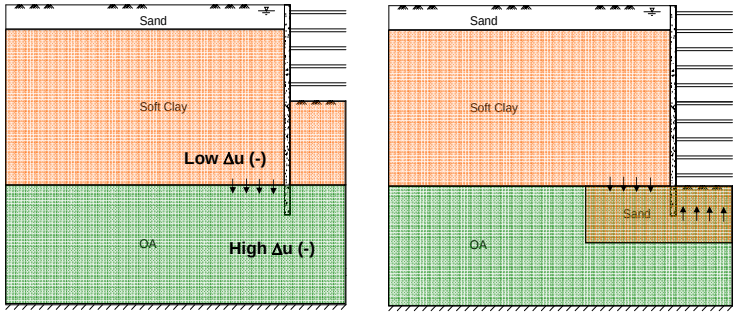
**Ground settlement due to piping and loss of fines.**

**Pot holes can develop at the ground surface.**




## Two Causes of Ground Settlement due to Under-Drainage




**1. Under-drainage due to negative excess pore pressure in OA**

**2. Under-drainage due to water flow into sand layer**

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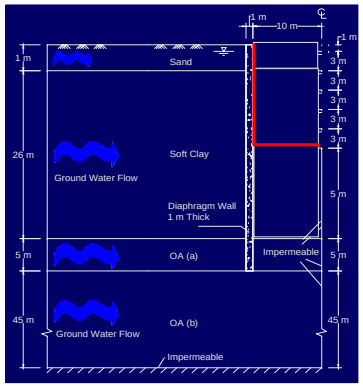
## Hypothetical Model

Excavation Sequence:

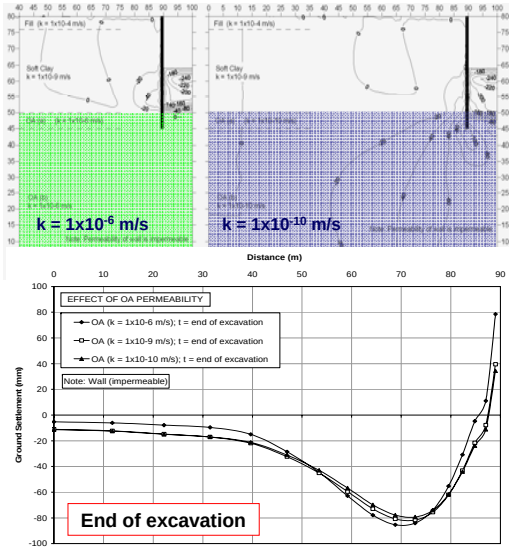
1. Excavate 2 m for 15 days.
2. Install strut & excavate 3 m for 15 days in each layer
3. Construct base slab for 4 months
4. Consolidate for 5 years
5. Change diaphragm wall permeability
6. Consolidate for 45 years




40

**Excess Pore Pressure Contours at end of Excavation**

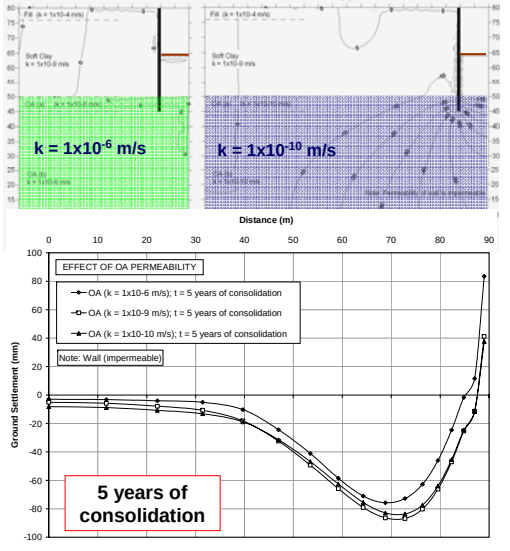
**Under-Drainage due to Negative Excessive Pore Pressure in OA**




**Ground Settlement Profiles at end of Excavation**

**Excess Pore Pressure Contours at end of 5 years**

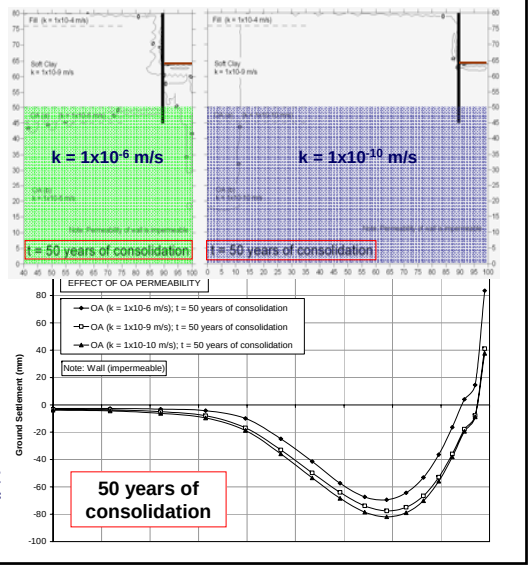
**Under-Drainage due to Negative Excessive Pore Pressure in OA**




**Ground Settlement Profiles at end of 5 years**

**Excess Pore Pressure Contours at end of 50 years**

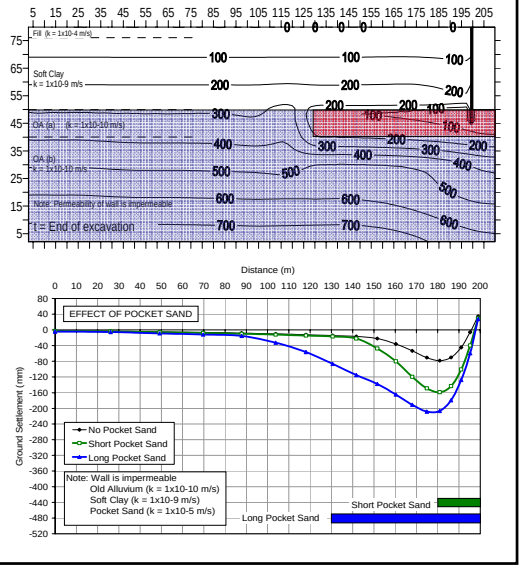
**Under-Drainage due to Negative Excessive Pore Pressure in OA**




**Ground Settlement Profiles at end of 50 years**

**Total Pore Pressure Contours at end of Excavation**

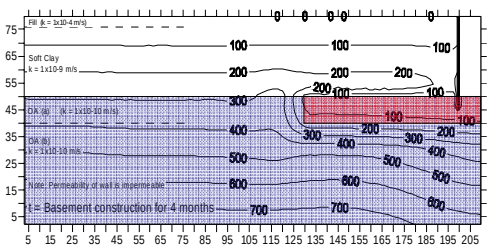
**Under-Drainage due to Water Flow into Sand Layer**

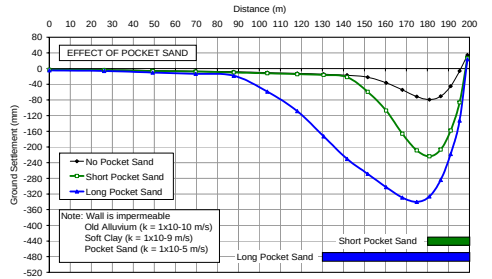



**Ground Settlement Profiles at end of Excavation**

**Total Pore Pressure Contours at end of 4 months**

**Under-Drainage due to Water Flow into Sand Layer**

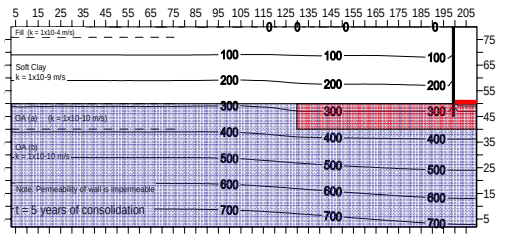


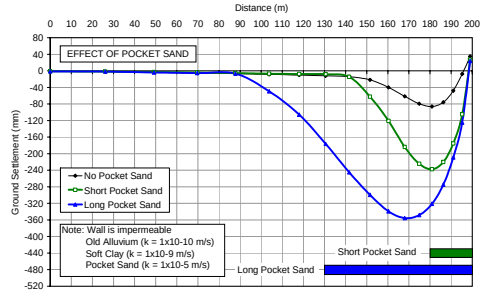




**Ground Settlement Profiles at end of 4 months**

**Total Pore Pressure Contours at end of 5 years**

**Under-Drainage due to Water Flow into Sand Layer**

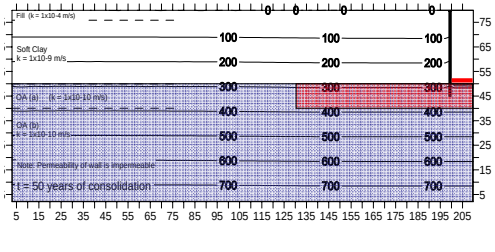


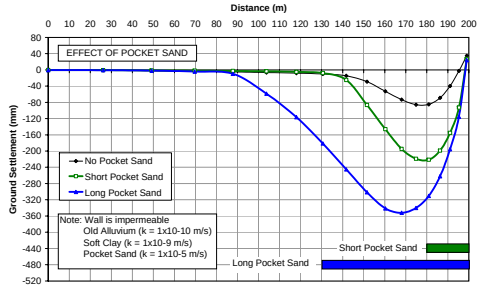




**Ground Settlement Profiles at end of 5 years**

**Total Pore Pressure Contours at end of 50 years**

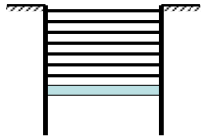
**Under-Drainage due to Water Flow into Sand Layer**

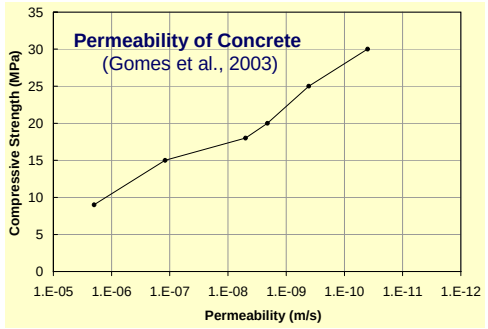


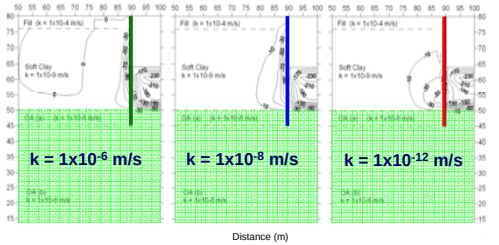

**Ground Settlement Profiles at end of 50 years**

**Settlement due to Steady State Seepage through Wall and Base Slab**



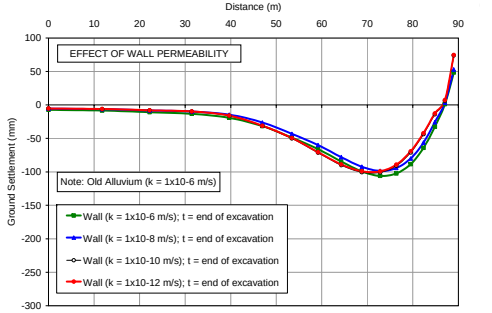


**Total Pore Pressure Contours at end of Excavation**

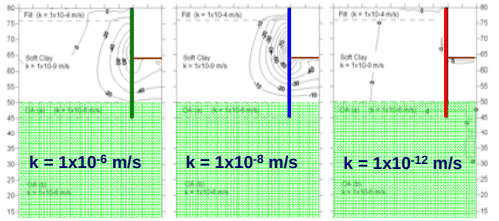



**Effect of Wall Leakage on Post-Excavation Settlement**

**Ground Settlement Profiles at end of Excavation**

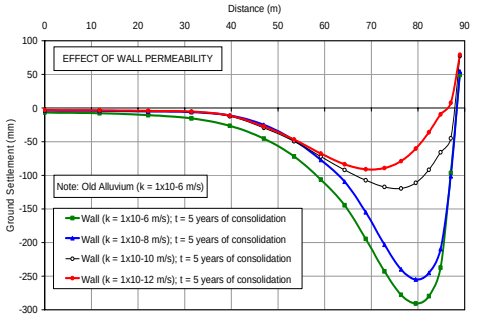



**Total Pore Pressure Contours at end of 5 years**

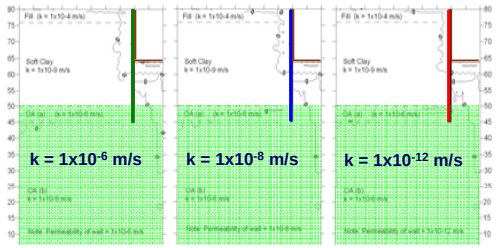



**Effect of Wall Leakage on Post-Excavation Settlement**

**Ground Settlement Profiles at end of 5 years**

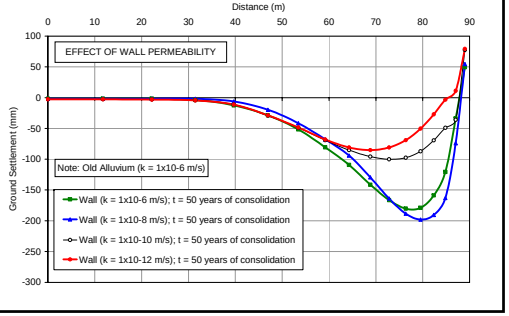



**Total Pore Pressure Contours at end of 50 years**

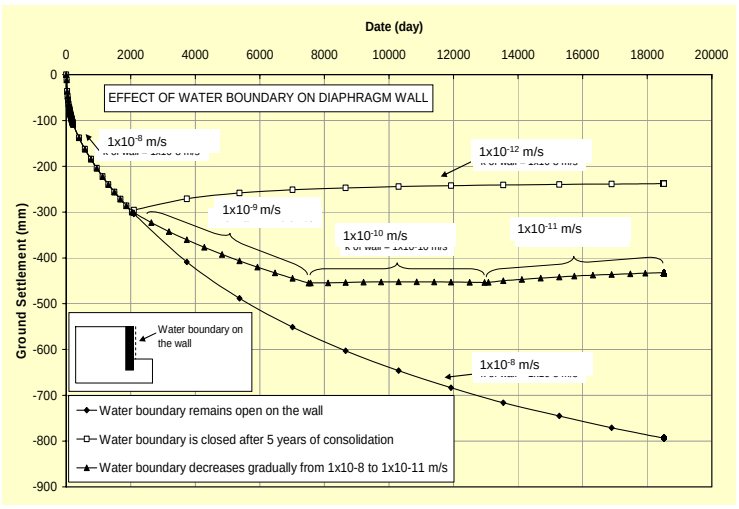



**Effect of Wall Leakage on Post-Excavation Settlement**

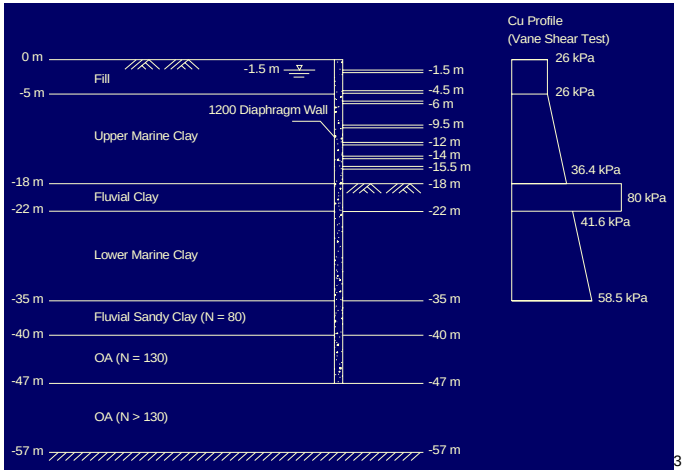
**Ground Settlement Profiles at end of 50 years**




## Effect of Wall Leakage on Post-Excavation Settlement

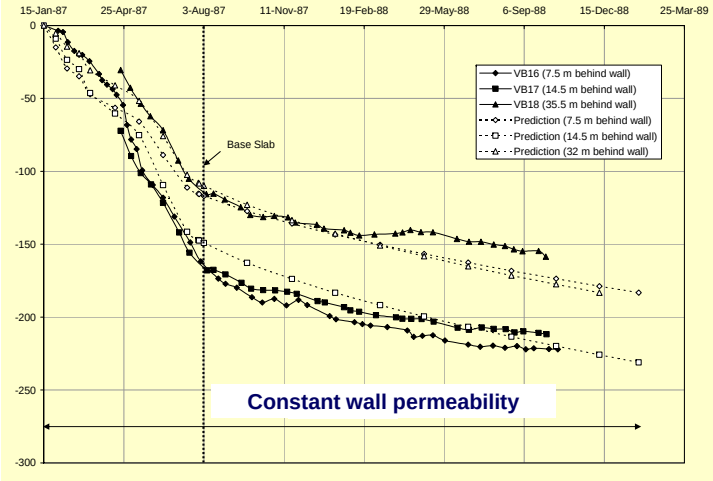


## Case Study: Bugis MRT Station



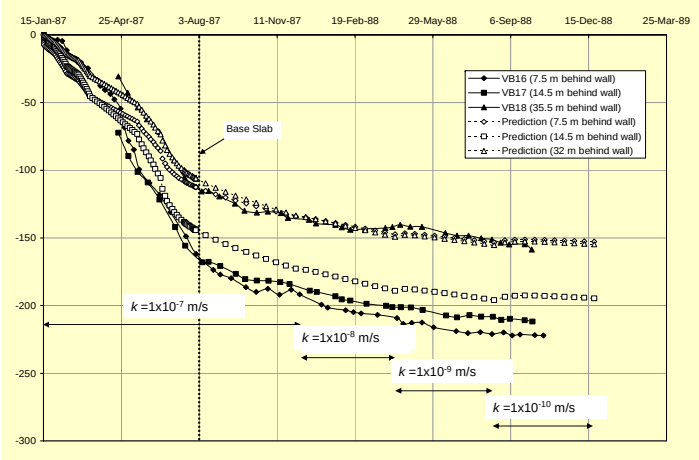

3

## Case Study: Bugis MRT Station




## Case Study: Bugis MRT Station

**Wall permeability decreases from $1x10^{-7}$ to $1x10^{-10}$ m/s**




## Conclusions on Ground Settlement

- Most ground settlement comes from immediate settlement due to undrained shear distortion.
- Effect of under-drainage on ground settlement due to negative excess pore pressure in Old Alluvium is not significant.
- Effect of under-drainage due to water flow into sand layer is significant.
- Effect of wall leakage on ground settlement is also significant.
- It is important to arrest all observable leakages in the wall and base slab as soon as possible.

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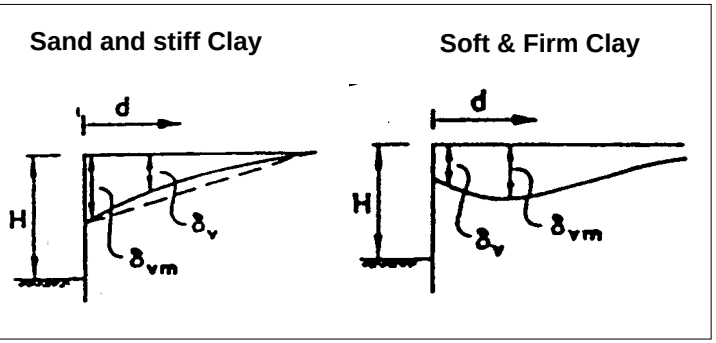
## Typical Ground Settlement Profile

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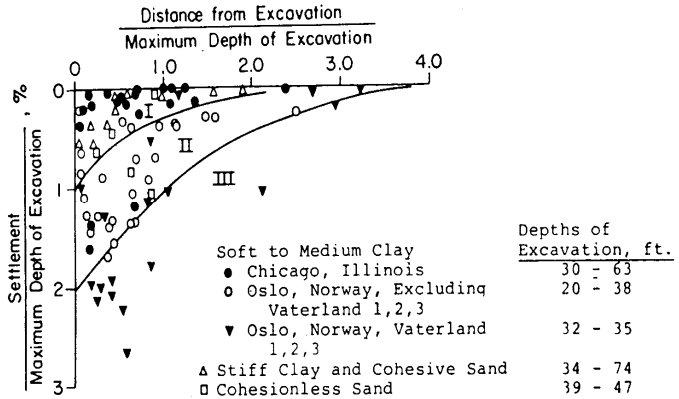
## Ground Settlement beyond Excavation Area
(Peck, 1969)

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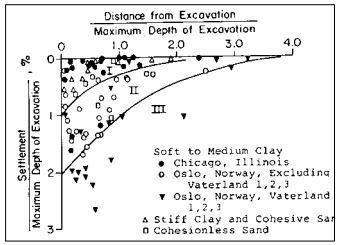
## Ground Settlement beyond Excavation Area
(Peck, 1969)



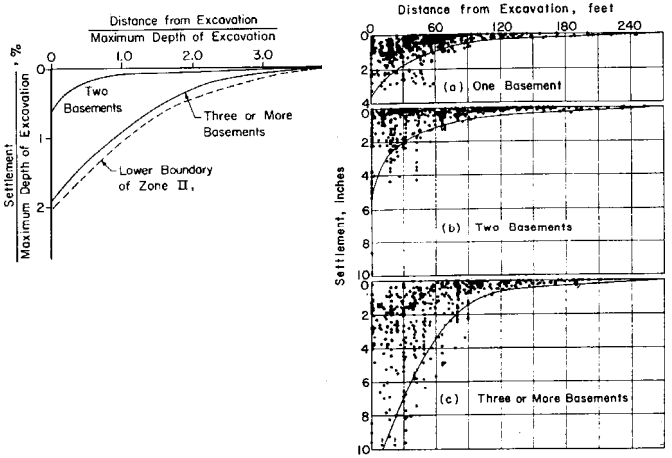

Zone I
Sand and Soft to Hard Clay
Average Workmanship

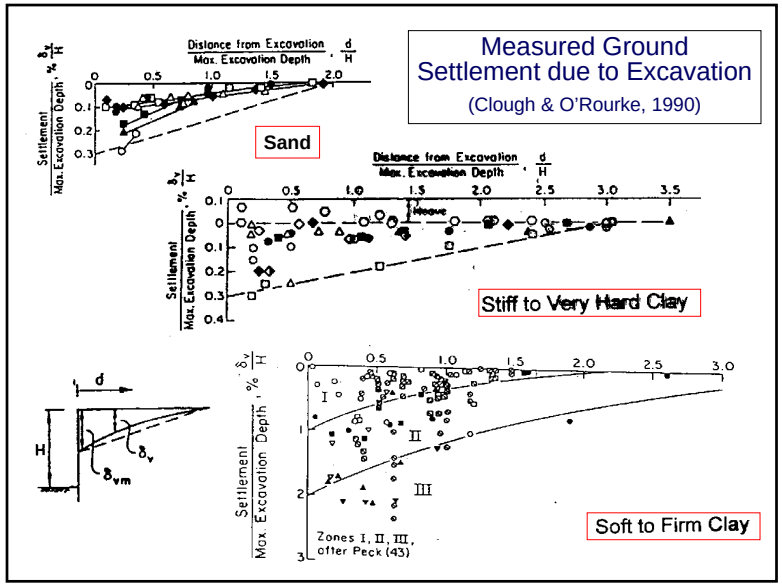
Zone II
a) Very Soft to Soft Clay
1) Limited depth of clay below bottom of excavation
2) Significant depth of clay below bottom of excavation but $N_b < N_{cb}$ (See Chapter 8)
b) Settlements affected by construction difficulties

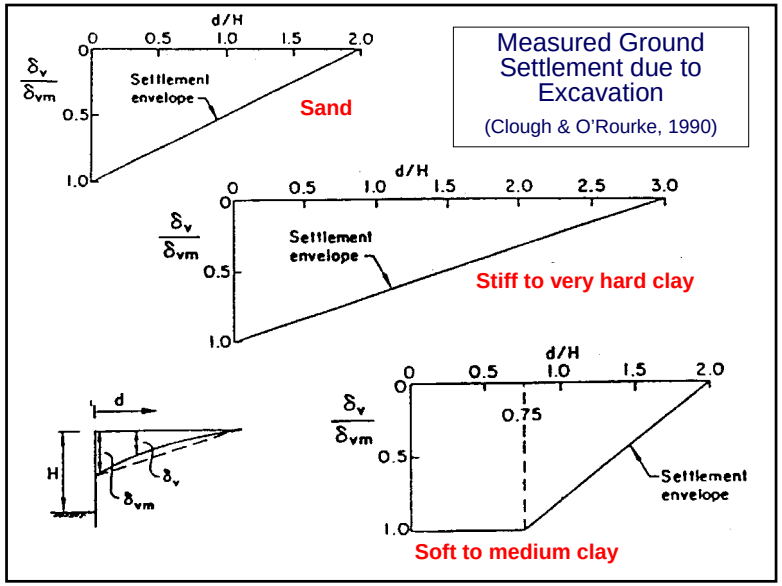
Zone III
Very Soft to Soft Clay to a significant depth below bottom of excavation and with $N_b \leq N_{cb}$

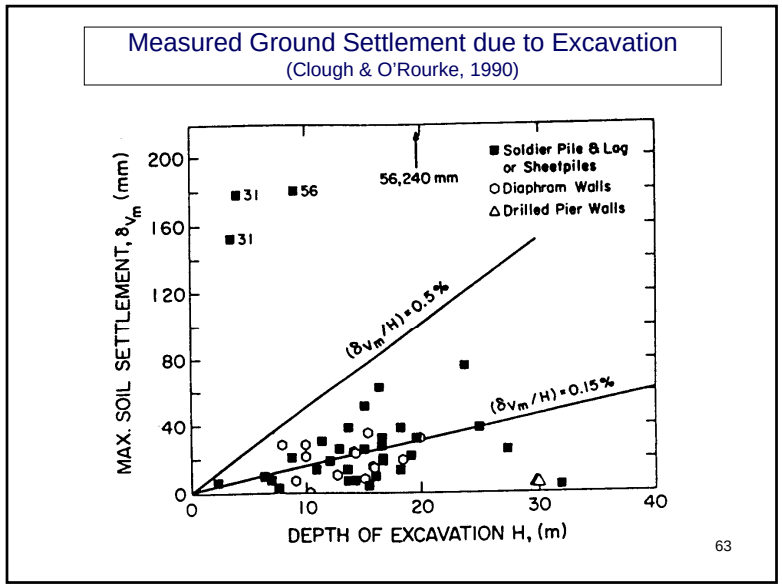
Note:
All data shown are for excavations using standard soldier piles or sheet piles braced with cross-bracing or tiebacks.

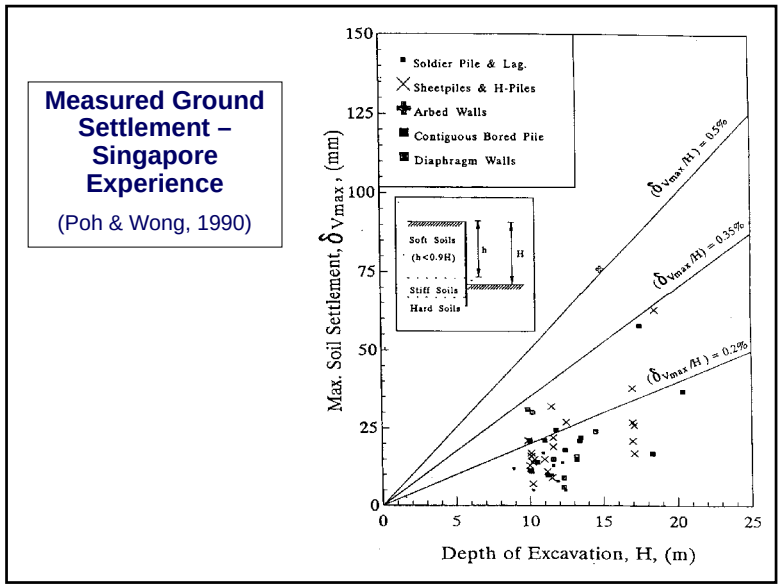
## Ground Settlement due to Excavation in Chicago
(Peck, 1969)



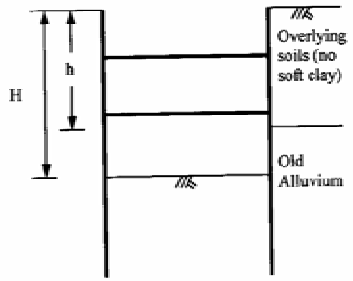

Measured Ground Settlement due to Excavation
(Clough & O'Rourke, 1990)
Sand
Stiff to Very Hard Clay
Soft to Firm Clay
Zones I, II, III, after Peck (43)


Measured Ground Settlement due to Excavation
(Clough & O'Rourke, 1990)
Sand
Settlement envelope
Stiff to very hard clay
Soft to medium clay


Measured Ground Settlement due to Excavation
(Clough & O'Rourke, 1990)
Soldier Pile & Lag or Sheetpiles
Diaphram Walls
Drilled Pier Walls
56,240 mm
(δVm/H)=0.5%
(δVm/H)=0.15%
MAX. SOIL SETTLEMENT, δVm (mm)
DEPTH OF EXCAVATION H, (m)
63


Measured Ground Settlement – Singapore Experience
(Poh & Wong, 1990)
Soldier Pile & Lag
Sheetpiles & H-Piles
Arbed Walls
Contiguous Bored Pile
Diaphragm Walls
Soft Soils (h<0.9H)
Stiff Soils
Hard Soils
Max. Soil Settlement, δVmax, (mm)
Depth of Excavation, H, (m)

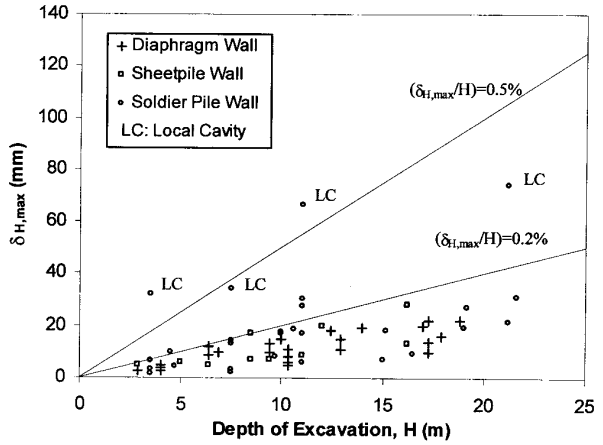
## Excavations in Stiff Soil Conditions in Old Alluvium
(Li & Wong, 2001)




1. h < 0.7 H
2. No soft clay is present.
3. Overlying soils include fill, fluvial sand and fluvial clay.

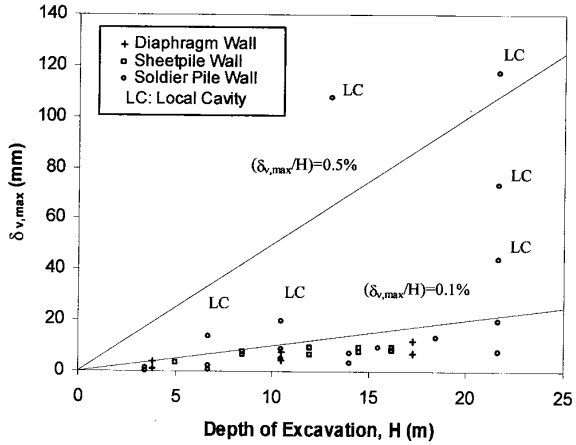
65

## Maximum Wall Deflections in Stiff Soil Condition
(Li & Wong, 2001)



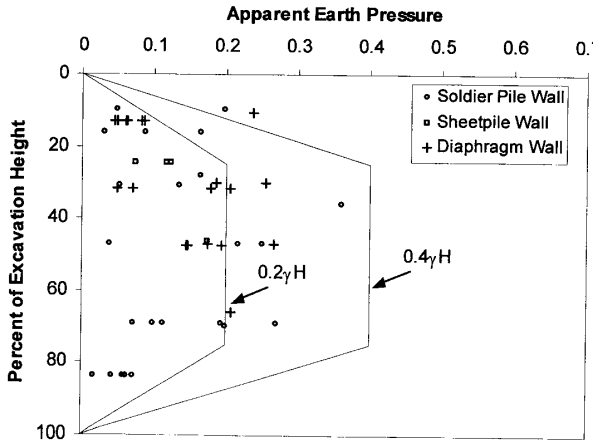

66

## Maximum Ground Settlement in Stiff Soil Condition
(Li & Wong, 2001)




67

## Maximum Strut Forces in Stiff Soil Condition
(Li & Wong, 2001)

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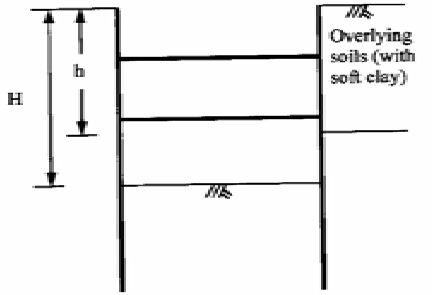
## Excavations in Medium Soil Conditions in Old Alluvium
(Li & Wong, 2001)




1. h < 0.7 H
2. Soft clay is present.
3. Overlying soils include fill, fluvial sand and clay, organic clay and peaty clay.

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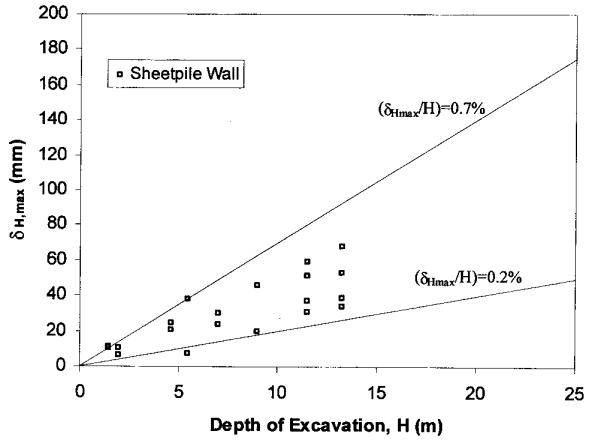
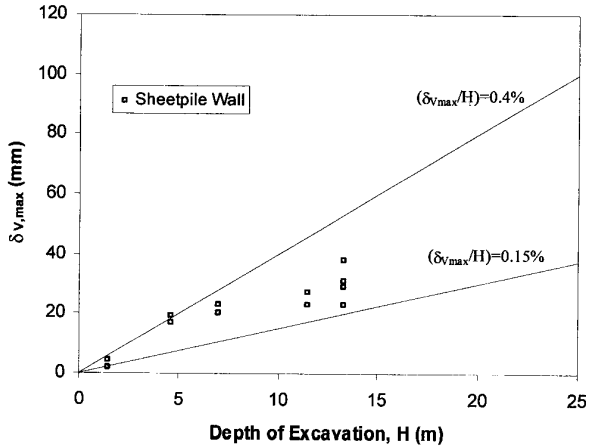
## Maximum Wall Deflections in Medium Soil Condition
(Li & Wong, 2001)



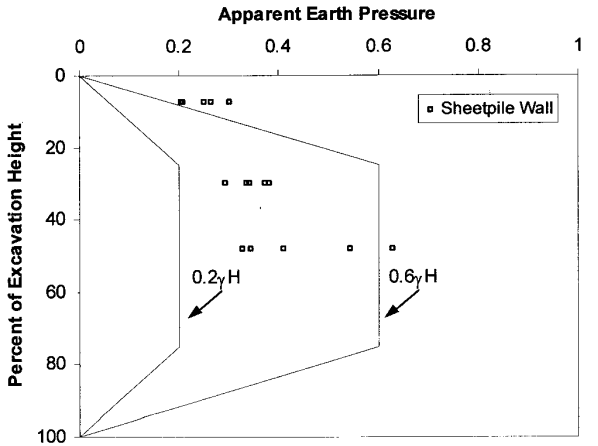

70

## Maximum Ground Settlement in Medium Soil Condition
(Li & Wong, 2001)




71

## Maximum Strut Forces in Medium Soil Condition
(Li & Wong, 2001)

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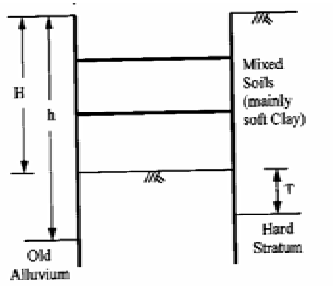
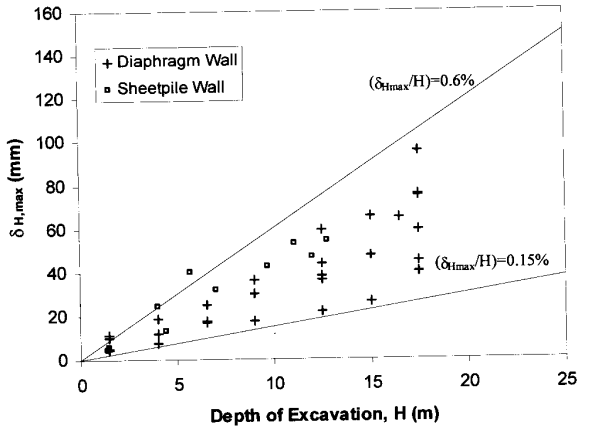
## Excavations in Soft Soil Conditions in Old Alluvium
(Li & Wong, 2001)




1. **h > H**
2. **Soft clay is present and T<0.7B.**
3. **Overlying soils include fill, fluvial sand and clay, peaty clay and marine clay.**

73

## Maximum Wall Deflections in Soft Soil Condition
(Li & Wong, 2001)

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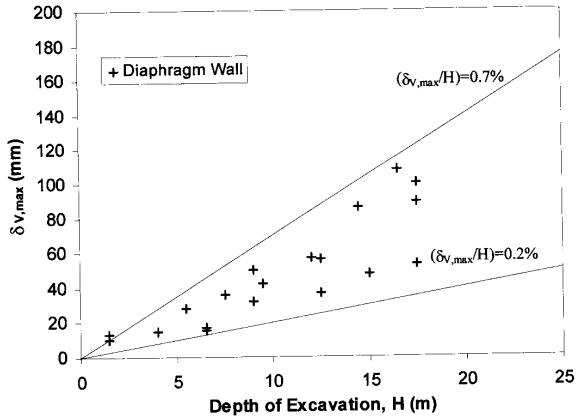
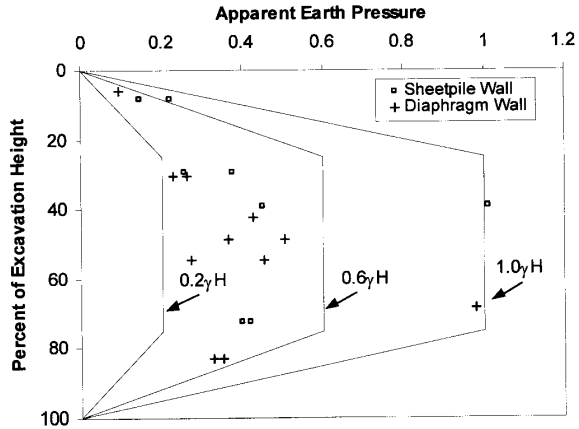
## Maximum Ground Settlement in Soft Soil Condition
(Li & Wong, 2001)




75

## Maximum Strut Forces in Soft Soil Condition
(Li & Wong, 2001)

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