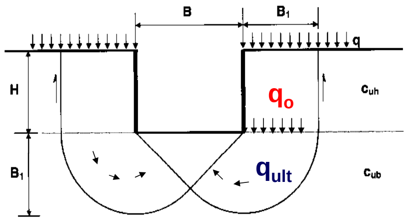
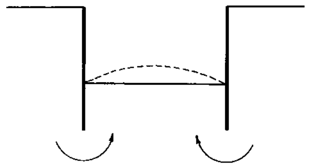
Basal Heave Stability

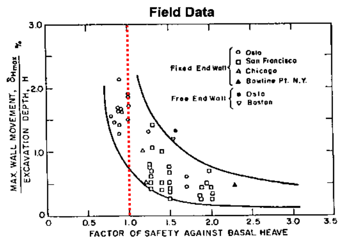


How do we check basal heave stability?

Which method should we use?

1





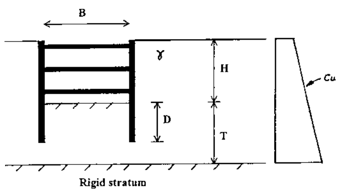
Which method should we use?

- Terzaghi
- Bjerrum & Eide
- Eide et al.
- Tschebotarioff
- Goh
- Chang
- Wong and Goh
- O'Rourke
- Su et al.
- Ukritchon et al.
- Plaxis

Does FOS≤1 mean failure?

2

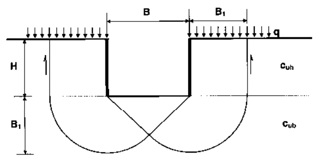
Methods of Analysis



- Terzaghi (1943)
- Bjerrum & Eide (1956)
- Eide et al. (1972)
- Goh (1994)

3

Terzaghi's Method
(Terzaghi, 1943)



Range of Applications

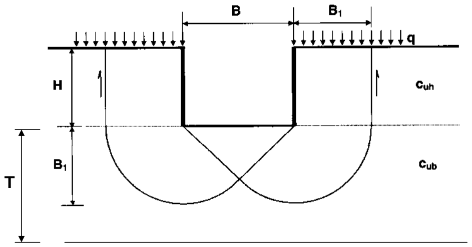
- For wide excavation
- For excavation with length much greater than width
- For sheetpile walls regardless of penetration depth
- For diaphragm walls with short penetration depth

Limitations

- May not be applicable to narrow excavation
- Does not consider effect of shape of excavation area
- Does not consider contribution from adhesion
- Does not consider contribution from wall penetration
- Does not consider the effect of wall stiffness

4

Terzaghi's Method



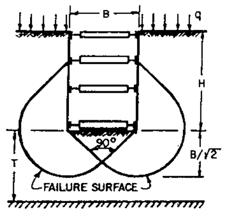
$$FS = \frac{5.7\, c_{ub}\, B_1}{\gamma\, H\, B_1 \;-\; c_{uh} H}$$

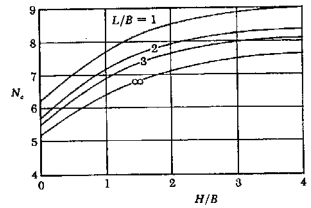
If $T \geq 0.7B$, $B_1 = 0.7B$

If $T \geq 0.7B$, $B1 = T$

5

Bjerrum and Eide's method (1956)





$$FS = \frac{c_u\, N_c}{\gamma\, H + q}$$

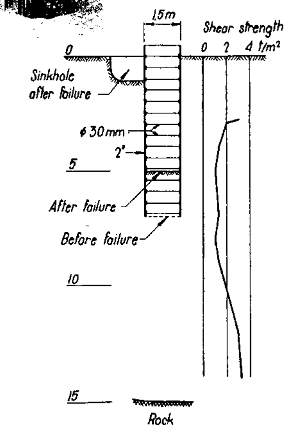
Range of Applications & Limitations:

- For narrow excavations
- Ignored effect of wall penetration
- Ignored effect of clay thickness
- Ignored effect of wall stiffness

6

Basal Heave Stability

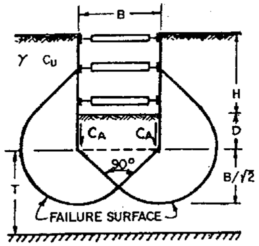
(Bjerrum and Eide, 1956)



7

Eide et al.'s Method (1972)

$$FS = \frac{c_u\, N_c + 2\, c_a\, D\, (1 + B/L)\, /\, B}{\gamma\, H + q}$$



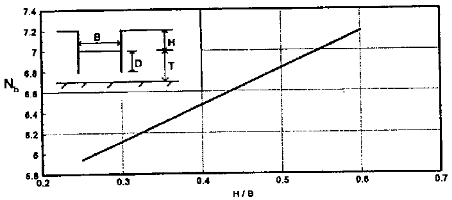
Range of Applications & Limitations:

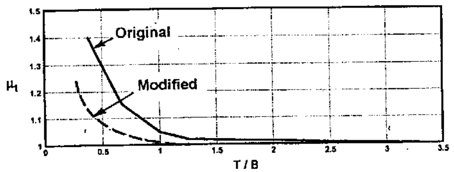
- For narrow excavations
- Ignored effect of clay thickness
- Ignored effect of wall stiffness

8

Goh's Method (1994)

$$FS = \frac{c_u N_h}{\gamma H + q} \mu_t \mu_d \mu_w$$

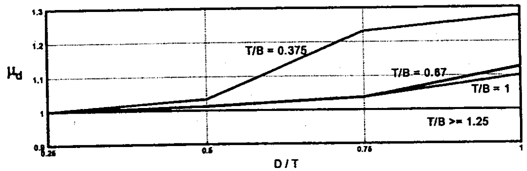


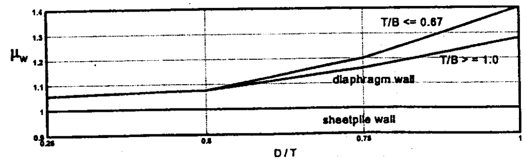


9

Goh's Method (1994)

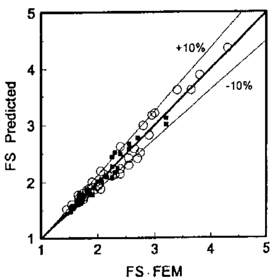
$$FS = \frac{c_u N_h}{\gamma H + q} \mu_t \mu_d \mu_w$$





10

Goh's Method (1994)



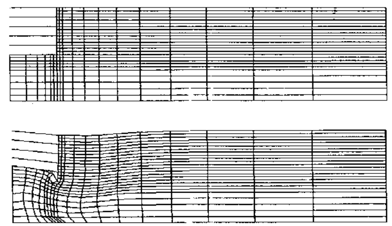
Sheetpile wall ■ Diaphragm wall ○

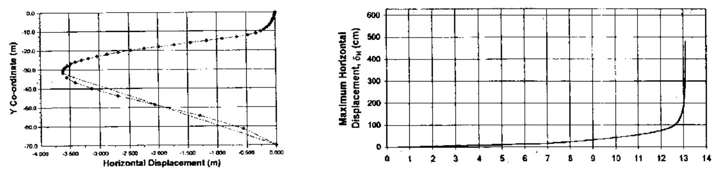
Advantages & Disadvantages:

- Applicable only to long excavations (L>>B)
- Applicable only to wide excavations (B/H>1)
- Applicable only to constant c_u
- Not certain what c_u to use if c_u increases with depth
- Considered effect of wall penetration (D)
- Considered effect of clay thickness (T)
- Considered effect of wall stiffness (EI)
- Does not consider effect of excavation shape (L/B)
- Reliability of full penetration case (D/T=1) is uncertain
- Does not consider slippage along inner wall

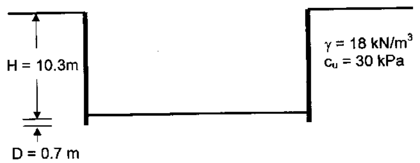
11

Critical Height based on SAGE CRISP Analysis





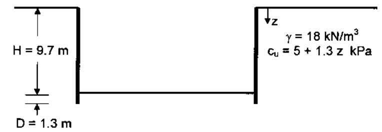
Comparison of Methods – Case 1 – Sheetpile Wall



FEM (Sage Crisp)	=	1.00	
Terzaghi (1943)	=	1.00	(1.00)
Bjerrum & Eide (1956)	=	0.89	
Eide et al. (1972)	=	0.90	
Goh (1994)	=	1.02	

13

Comparison of Methods – Case 2 – Sheetpile Wall



FEM (Sage Crisp)	=	1.00	
Terzaghi (1943)	=	1.05	(1.04)
Bjerrum & Eide (1956)	=	0.55	(c_u at H)
	=	0.98	($c_{u,AVG}$ within 0.7B below H)
Eide et al. (1972)	=	0.61	(c_u at H)
	=	1.05	($c_{u,AVG}$ within 0.7B below tip)
Goh (1994)	=	---	(0.99) Use $c_{u,AVG}$ within 0.5B below H

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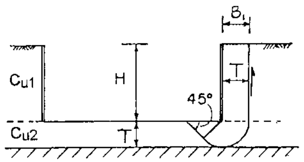
Modification to Terzaghi's Method



Terzaghi (1943)

$$FS = \frac{5.7\, c_{u2}\, B_1}{\gamma H B_1 - c_{u1} H}$$

Modified Terzaghi

$$FS = \frac{5.7\, c_{u2}\, B_1 + c_{u1} H}{\gamma H B_1}$$

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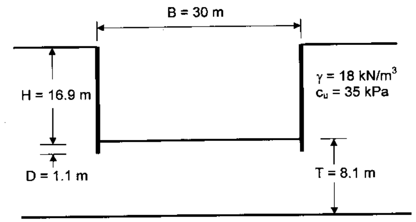
Comparison of Methods – Case 3 – Sheetpile Wall



FEM (Sage Crisp)	=	1.00	
Terzaghi (1943)	=	0.86	(0.90)
Bjerrum & Eide (1956)	=	0.67	
Eide et al. (1972)	=	0.69	
Goh (1994)	=	1.20	(1.00)

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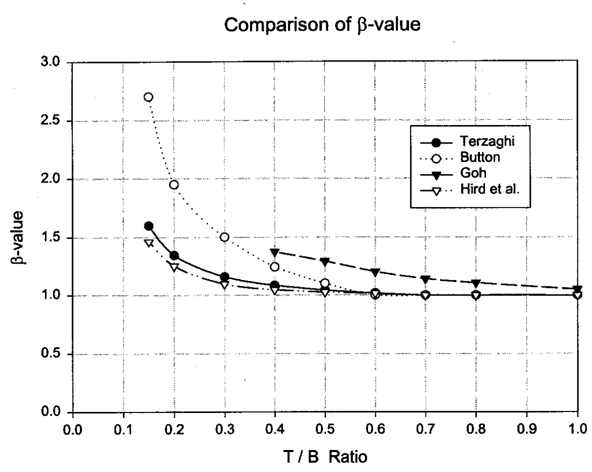

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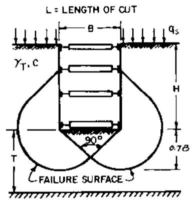
Effect of Depth to Hard Stratum (T)



When T ≥ 0.7B, failure surface can be developed freely.

When T < 0.7B, the development of failure surface is restrained. It is no longer the plane of lowest resistance. Therefore, there will be an increase in factor of safety. The correction factor β accounts for the effect of depth to hard stratum, T.

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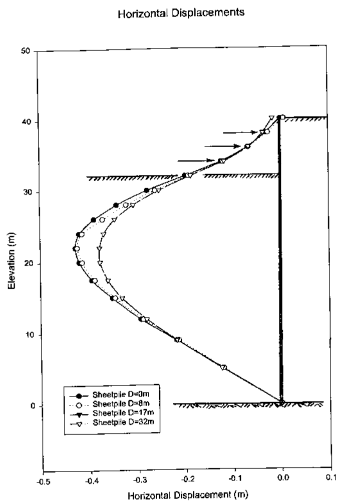

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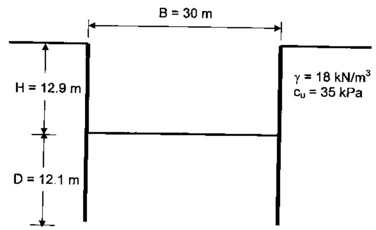
Comparison of Methods – Case 4 – Sheetpile Wall



FEM (Sage Crisp)	=	1.00	
Terzaghi (1943)	=	0.95	(0.95)
Bjerrum & Eide (1956)	=	0.84	
Eide et al. (1972)	=	**0.97**	
Goh (1994)	=	1.00	(1.00)

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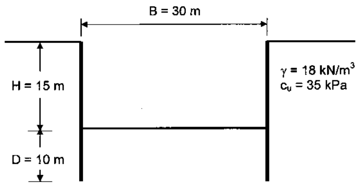
Comparison of Methods – Case 5 – Diaphragm Wall



FEM (Sage Crisp)	=	1.00	
Terzaghi (1943)	=	0.81	(0.83)
Bjerrum & Eide (1956)	=	0.75	
Eide et al. (1972)	=	0.89	
Goh (1994)	=	0.93	(0.93)

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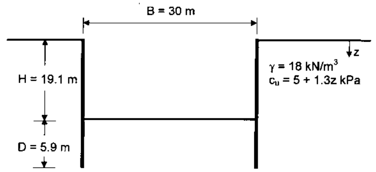
Comparison of Methods – Case 6 – Diaphragm Wall

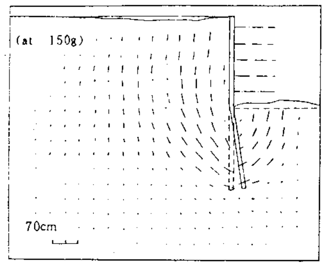


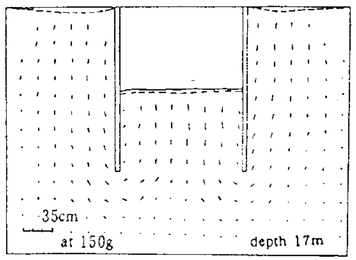
FEM (Sage Crisp)	=	1.00	
Terzaghi (1943)	=	0.76	(0.77)
Bjerrum & Eide (1956)	=	0.52	(c_u at H)
	=	0.75	($c_{u,AVG}$ within 0.7B below H)
Eide et al. (1972)	=	0.83	(c_u at H)
	=	0.98	($c_{u,AVG}$ within 0.7B below tip)
Goh (1994)	=	---	(0.99)

22

Effect of Wall Penetration

(Zhang and Zhang, 1994)





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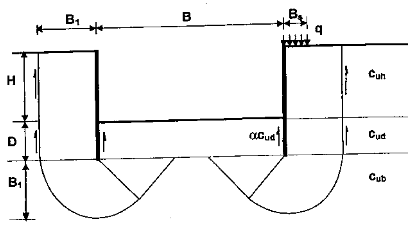
Modified Terzaghi's Method for Diaphragm Wall

(Wong and Goh, 2001)



Note: B_1 = 0.7B or (T-D) whichever is smaller and $B_s \leq B_1$

Method 1:

$$F_{s1} = \frac{5.7\, c_{ub} B_1}{\gamma H B_1 - c_{uh} H - (1+\alpha) c_{ud} D + q B_s}$$

Method 2:

$$F_{s2} = \frac{5.7\, c_{ub} B_1 + c_{uh} H + (1+\alpha) c_{ud} D}{\gamma H B_1 + q B_s}$$

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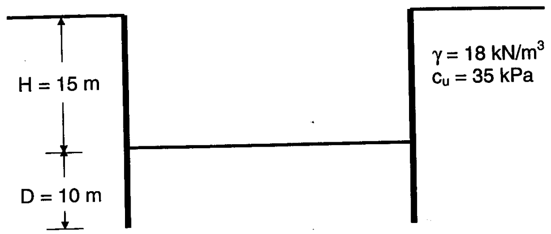
Modified Terzaghi's Method for Diaphragm Wall

(Wong and Goh, 2001)

Case 5



Terzaghi (1943) :	F_s = 0.81
Modified Terzaghi :	F_{s1} = 0.94
	F_{s2} = 0.96

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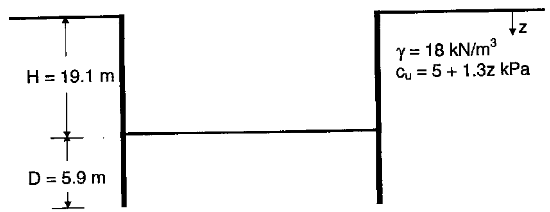
Modified Terzaghi's Method for Diaphragm Wall (Wong and Goh, 2001)

Case 6



Terzaghi (1943) :	F_s = 0.76
Modified Terzaghi :	F_{s1} = 0.94
	F_{s2} = 0.95

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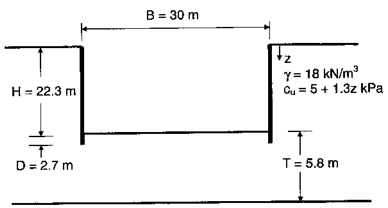
Comparison of Methods – Case 20

Diaphragm Wall



Terzaghi (1943):	Fs = 0.82	
Modified Terzaghi:	Fs = 1.13	(Method 1)
	Fs = 1.06	(Method 2)

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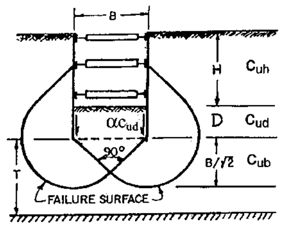
Narrow Excavation for all Wall Types

Modified Eide et al.'s Method



$$F_s = \frac{c_{ub} N_c \beta + 2\alpha c_{ud} D\,(1 + B/L) / B}{\gamma H + q}$$

For (H+D)/B < 2.5: $N_c \sim 5\,(1+0.2B/L)\,[1+ 0.2(H+D)/B]$

For (H+D)/B ≥ 2.5: $N_c \sim 7.5\,(1+0.2B/L)$

T / B	0.15	0.2	0.3	0.4	0.5	0.6	≥ 0.7
β	1.60	1.34	1.16	1.08	1.04	1.02	1.00

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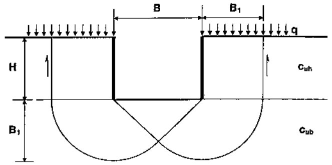
Wide Excavation with Sheetpile Wall



Modified Terzaghi

$$F_s = \frac{5.7\, c_{ub} B_1 + c_{uh} H}{\gamma H B_1 + q B_s}$$

Goh (1994)

$$F_s = \frac{c_u N_h}{\gamma H + q} \mu_t \mu_d \mu_w$$

Note: B_1 = 0.7B or T whichever is smaller and $B_s < B_1$

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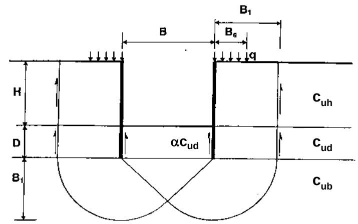
Wide Excavation with Diaphragm Wall



Modified Terzaghi

$$F_s = \frac{5.7\, c_{ub} B_1 + c_{uh} H + (1 + \alpha)\, c_{ud} D}{\gamma H B_1 + q B_s}$$

Modified Goh

$$F_s = \frac{c_u N_h}{\gamma H + q} \mu_t \mu_d \mu_w$$

Note: B_1 = 0.7B or (T-D) whichever is smaller and $B_s \leqslant B_1$

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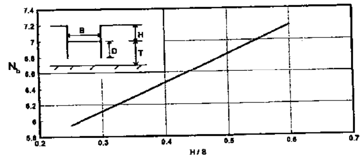
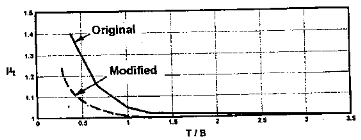
Modified Goh's Method

$$FS = \frac{c_u N_h}{\gamma H + q} \mu_t \mu_d \mu_w$$

Use average c_u within 0.5B below the formation level.





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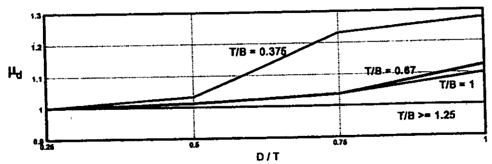
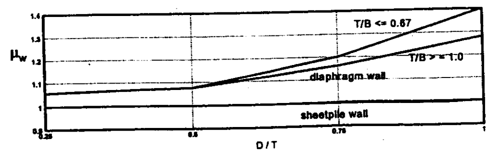
Modified Goh's Method

$$FS = \frac{c_u N_h}{\gamma H + q} \mu_t \mu_d \mu_w$$





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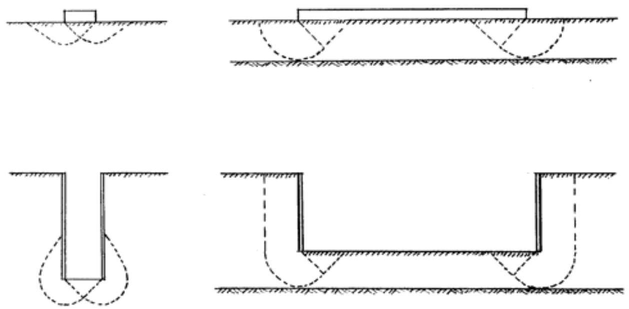
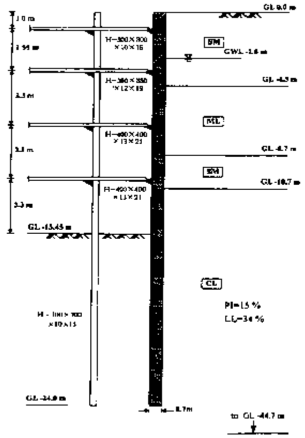
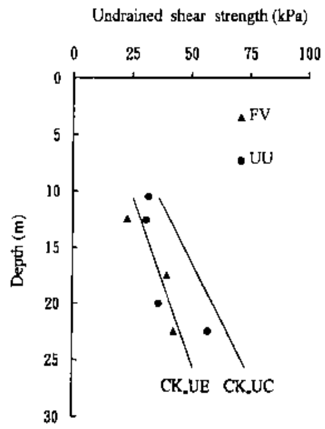
How important is the shape factor?

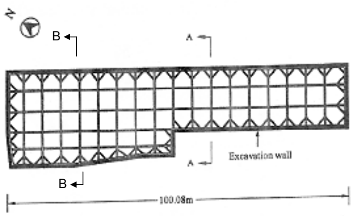


Basal Heave Failure in Taipei (1998)



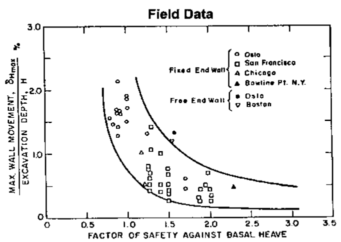


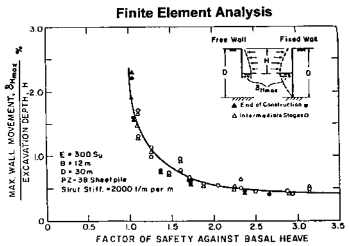
Basal Heave Failure in Taipei (1998)



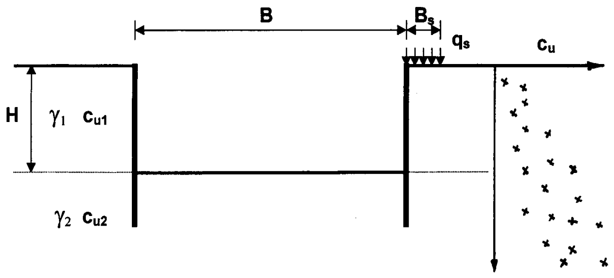
	Factor of Safety	
Method	A-A	B-B
Terzaghi	0.67	0.66
Bjerrum & Eide	0.58/0.69	0.61/0.69
Wong & Goh	0.94	0.99

What factor of safety should we use?





How reliable is the computed F.S.?



$$FS = \frac{5.7\, c_{u2}\, B_1 + c_{u1} H}{\gamma H B_1 + q_s B_s}$$

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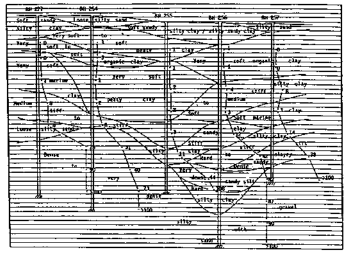
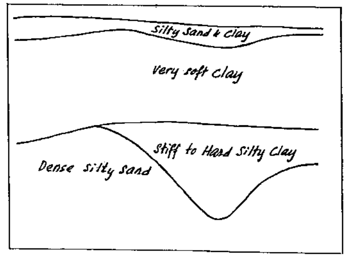
Subsoil Conditions & Idealized Soil Profile





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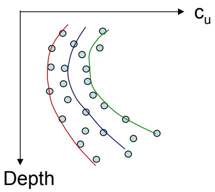
What type of test should we conduct to determine c_u?

- Field tests: FVT, SPT, CPT, PMT, DMT, BST
- Lab Tests: UU, UC, ICU, Ck_oTC, Ck_oTE, Ck_oDSS
- Others: Fall cone, Torvane, Pocket Penetrometer

Which strength envelope should we use ?

1. **Most conservative:** "worst scenario"
2. **Best Estimate:** "most probable scenario"
3. **Most optimistic:** "most favourable scenario"



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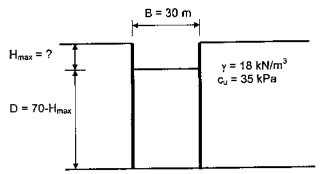
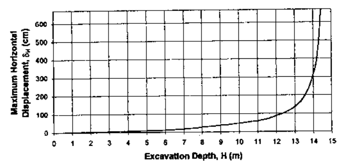
Basal Heave of Wall with Full Penetration to Hard Stratum



Case 7 - Sheetpile Wall



FEM (Sage Crisp)	=	13.4 m
Terzaghi (1943)	=	12.5 m
Bjerrum & Eide (1956)	=	10.8 m
Eide et al. (1972)	=	70 m
Goh (1994)	=	12.8 m

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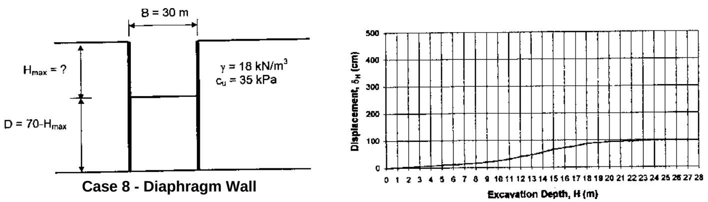
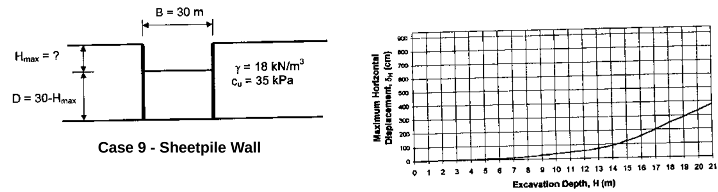
Basal Heave of Wall with Full Penetration to Hard Stratum



FEM (Sage Crisp)	=	70 m
Terzaghi (1943)	=	12.5 m
Bjerrum & Eide (1956)	=	10.8 m
Eide et al. (1972)	=	70 m
Goh (1994)	=	18 m

Basal Heave of Wall with Full Penetration to Hard Stratum



FEM (Sage Crisp)	=	30 m
Terzaghi (1943)	=	12.5 m
Bjerrum & Eide (1956)	=	10.8 m
Eide et al. (1972)	=	30 m
Goh (1994)	=	12.8 m

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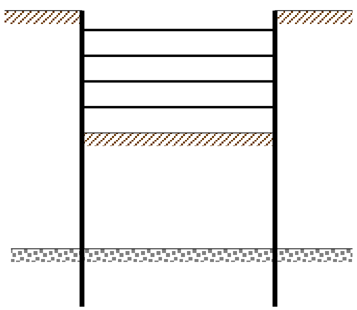
Excavation with Full Penetration of Wall into Hard Stratum



Basal heave stability is not an issue for this case.

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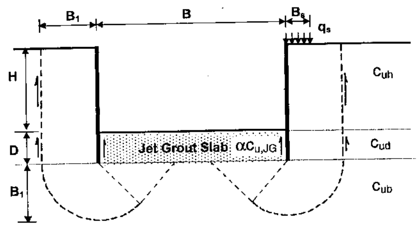
Basal Heave Stability with Jet Grout Slab

Block Failure



$$F_s = \frac{5.7\, c_{ub} B_1 + c_{uh} H + c_{ud} D + \alpha\, c_{u,JG} D}{\gamma H B_1 + q B_s}$$

Note: $B_1 = 0.7B$ or (T-D) whichever is smaller and $B_s \leq B_1$

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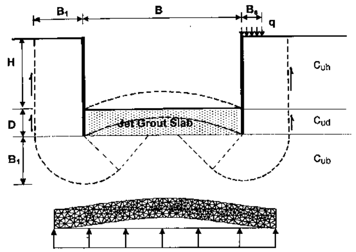
Basal Heave Stability with Jet Grout Slab

Bending Failure



$q_{JG} = 12\, M_{max} / B^2 = 4\, c_{u,JG}\, D^2 / B^2$

$$F_S = \frac{5.7\, c_{ub} B_1 + c_{uh} H + c_{ud} D + q_{JG} B_1}{\gamma H B_1 + q\, B_s}$$

Note: $B_1 = 0.7B$ or (T-D) whichever is smaller and $B_s \leqslant B_1$

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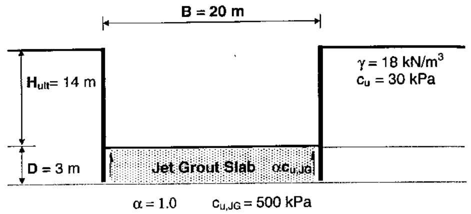
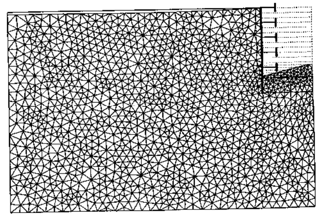
Basal Heave Stability with Jet Grout Slab





PLAXIS:	$F_s = 1.00$
Bending Failure:	$F_s = 1.00$
Block Failure:	$F_s = 1.25$

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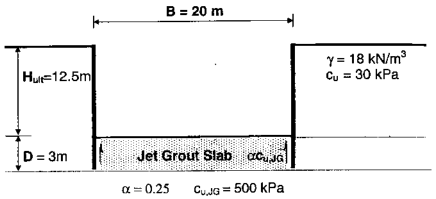
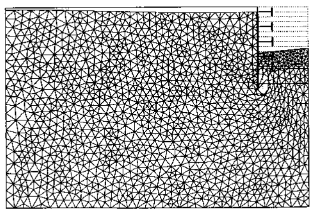
Basal Heave Stability with Jet Grout Slab





PLAXIS:	$F_s = 1.00$
Bending Failure:	$F_s = 1.11$
Block Failure:	$F_s = 1.03$

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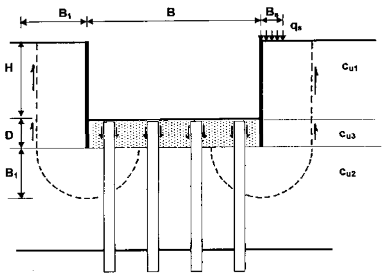
Basal Heave Stability with Jet Grout Slab



$$FS = \frac{5.7\, c_{u2} B_1 + c_{u1} H + c_{u3} D + Q_{JG}}{\gamma H B_1 + q_s B_s}$$

Note: $B_1 = 0.7B$ or T whichever is smaller and $B_s \leqslant B_1$

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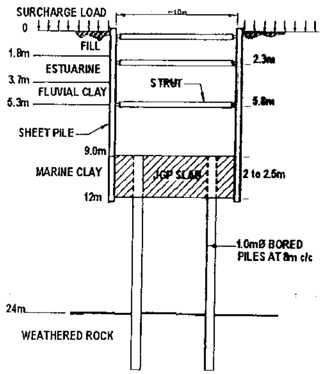
Basal Heave Stability at Clarke Quay

(Shirlaw et al. 2000)



Factor of Safety without JGP = 0.45 to 0.6

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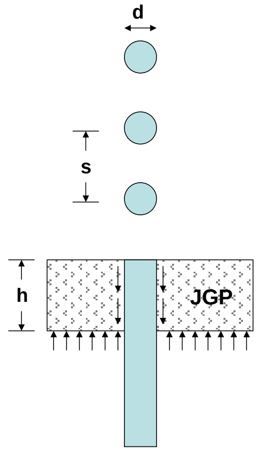
Evaluation of Adhesion on Piles with JGP in FEA



Q_s on piles in field = (π d h / s) c_a

Q_s on piles in FEA = 2 h $c_{a,FEA}$

$c_{a,FEA} = (\pi\ d\ c_a) / (2\ s)$

Pile Spacing	$c_{a,FEA}$
2.5 d	0.63 c_a
3.0 d	0.52 c_a
3.5 d	0.45 c_a
4.0 d	0.39 c_a

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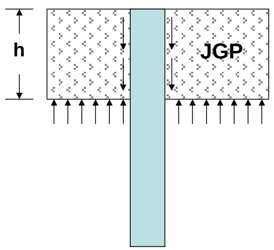
How can we determine c_a between JGP and pile?



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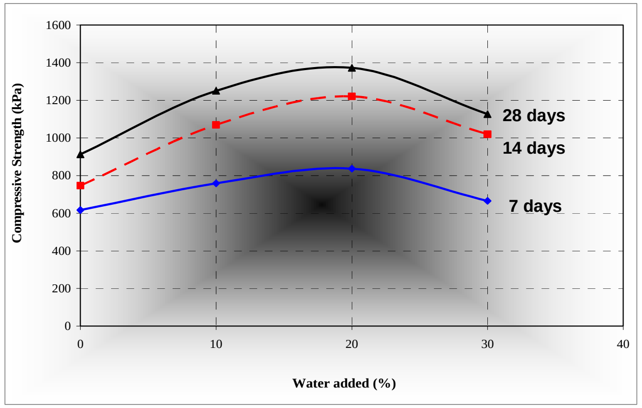
Mixing of clay & cement

Roughen the surface

Completed specimens

Specimen and moulds

Compressive strength of specimen at different curing time (Goh, 2005)



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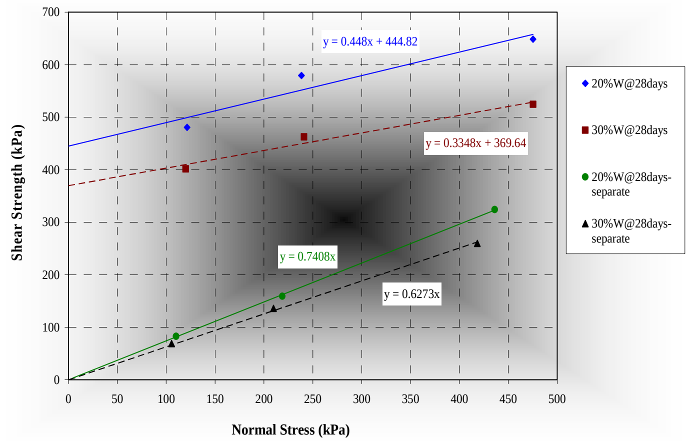
Adhesion between concrete with clay-cement mixture (Goh, 2005)



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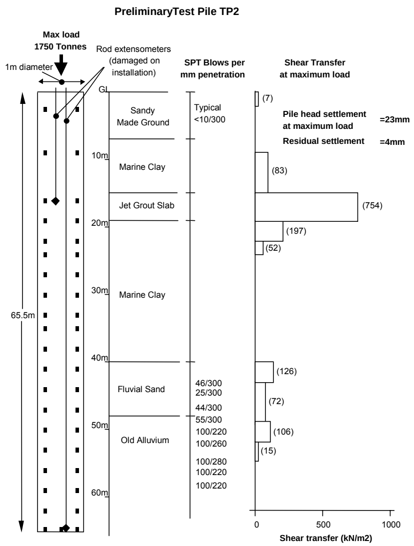
Pile Load Test at KPE

(Shirlaw et al., 2005)



Measured adhesion = 754 kPa

Adhesion at failure >>754 kPa

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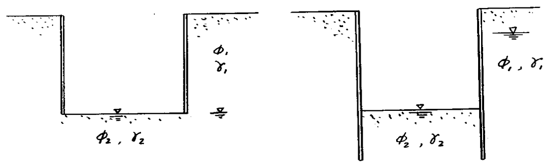
Bottom Heave in Sand



Use γ_1' = total unit wt.
γ_2' = submerged unit wt.

Use γ_1' = weighed average of total & submerged
$\gamma_2' = \gamma_{b2}' - i\gamma_w$

$$F.S. = 2 N_{\gamma 2} \left(\frac{\gamma_2'}{\gamma_1'}\right) K_A \tan\phi_1$$

$$K_A = \frac{1 - \sin\phi_1'}{1 + \sin\phi_1'}$$

$$N_{\gamma 2} = 1.80 \tan\phi_2' \left[e^{\pi \tan\phi_2'} \cdot \tan^2\left(45 + \frac{\phi_2'}{2}\right) - 1 \right]$$

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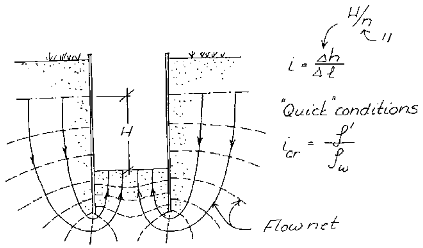
Piping in Sand



Piping is a phenomenon of water rushing up through pipe-shaped channels due to upward seepage under high gradient. It can lead to total collapse of the system. Sufficient penetration of sheetpile must be used to lengthen the seepage path and to reduce the hydraulic gradient.

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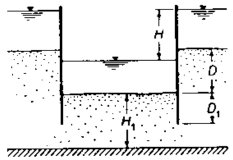
Penetration Depth against Piping

(Teng, 1962)



Fs = 1.5

Site conditions	*Width of excavation*					
	8D	*4D*	*2D*	*D*	*½D*	*¼D*
1. Homogeneous with infinite depth						
Loose sand	0.7*D*	0.8*D*	0.9*D*	1.0*D*	1.2*D*	1.4*D*
Dense sand	0.4*D*	0.5*D*	0.6*D*	0.8*D*	1.0*D*	1.3*D*
2. Homogeneous, impervious layer below (dense)						
$H_1/D = 1$		0.4*D*	0.4*D*	0.6*D*	0.8*D*	0.9*D*
$H_1/D = 2$		0.4*D*	0.5*D*	0.8*D*	1.1*D*	1.3*D*