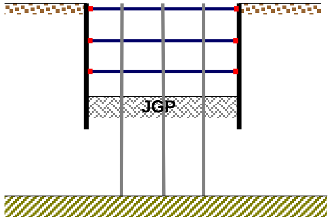
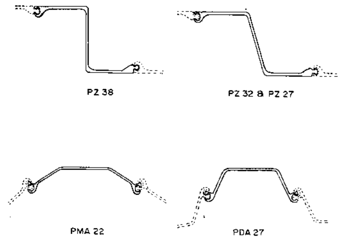
Issues in Deep Excavation Analysis

1. Modelling of sheetpile wall
2. Modelling of soldier pile wall
3. Modelling of diaphragm wall
4. Modelling of piles within excavation
5. Modelling of Jet Grout Slab
6. Sensitivity Study
7. Back-Analysis



Modelling of Sheetpile Wall



"Z" Sections

- Use full section modulus

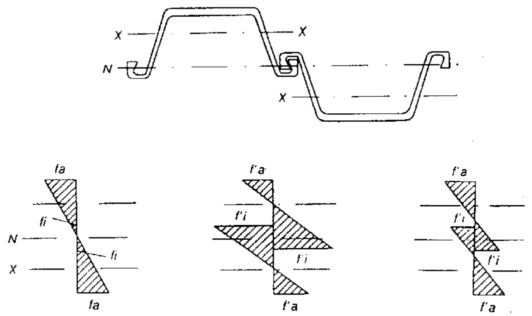
"U" Sections

- US practice: assumed no transfer of shear across neutral plane
- European practice: assumed full shear transfer
- Research results: partial shear transfer

What "EI" should we use?

2

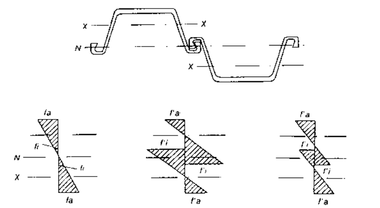
Effect of Clutch Slippage on "EI"



Full Shear Transfer	No Shear Transfer	Partial Shear Transfer
$(EI)_{Double}$	$2x(EI)_{Single}$	EI = ?

3

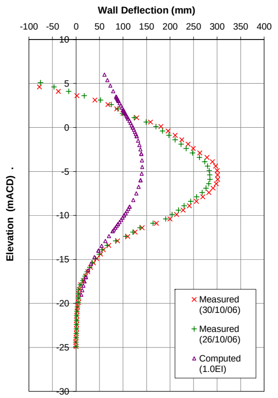
Effective Stiffness of U-Section



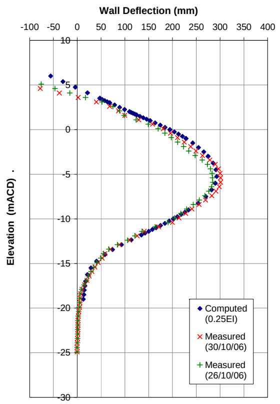
Investigators	Pile	Effective Pile Stiffness
Thompson & Matich, 1961	Algoma	0.4 – 1.0
Matich et al., 1964	Larssen	0.4 – 1.0
Baumann, 1934	Larssen	0.4 – 0.89
Bromborough Lock (1987)	Larssen	0.32 – 0.41
Williams & Little, 1992	Larssen	0.28 – 0.43

4

Effect of Wall Stiffness due to Clutch Slippage



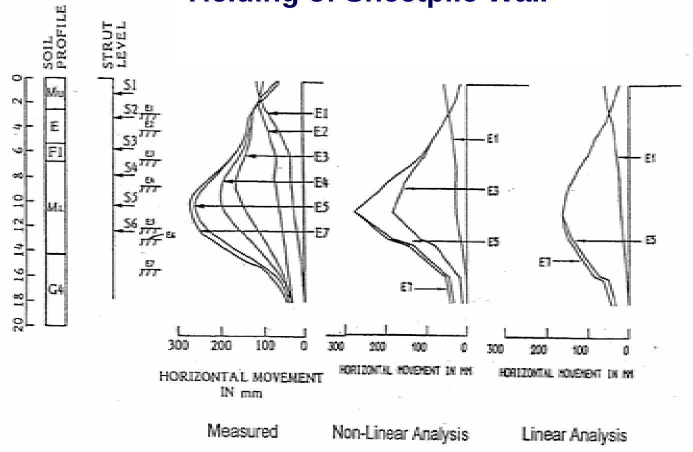
No Slippage -- 1.0EI



Partial Slippage -- 0.25EI

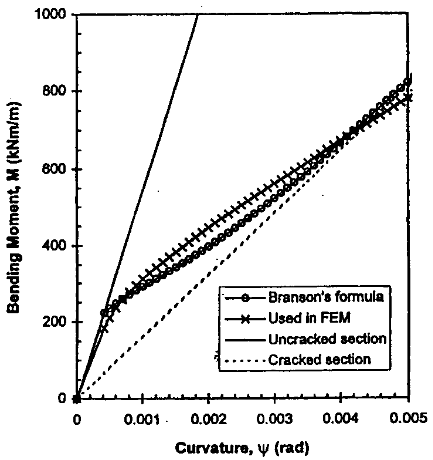
5

Yielding of Sheetpile Wall



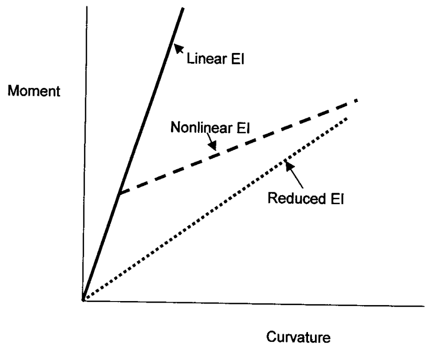
6

Effect of Cracking in Diaphragm Wall



7

Modelling of Diaphragm Wall Stiffness in FEA



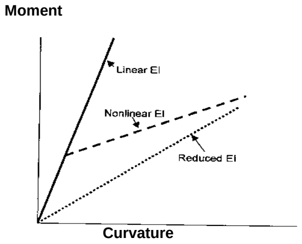
Choice of Wall Stiffness

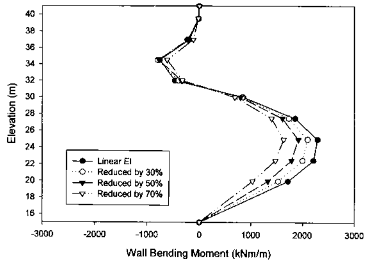
- **Linear EI**
- **Reduced EI**
- **Nonlinear EI**

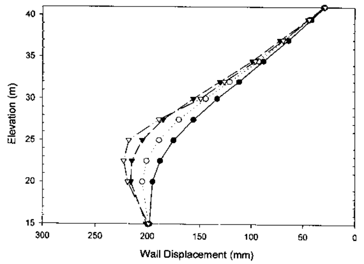
8

Effect of Using Reduced Diaphragm Wall Stiffness

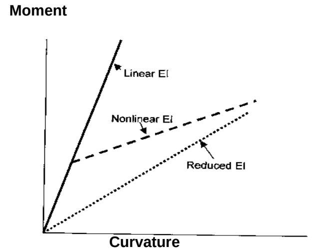
0.3, 0.5, 0.7 & 1.0EI

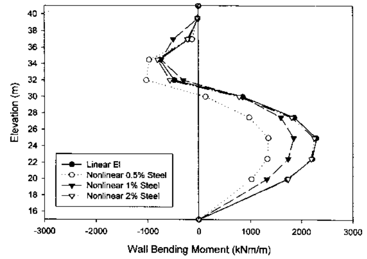


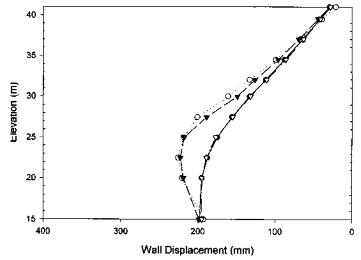




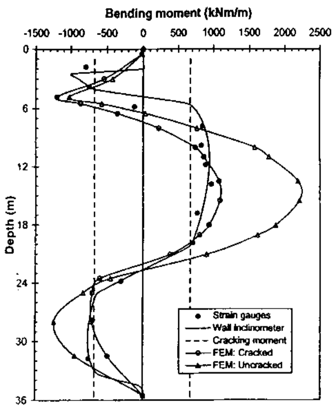
Effect of Using Nonlinear Diaphragm Wall Stiffness

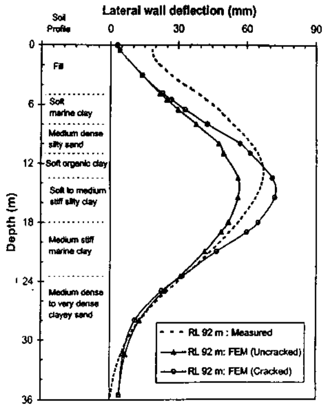






Effect of Cracking in Diaphragm Wall





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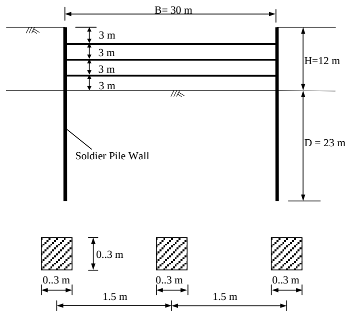
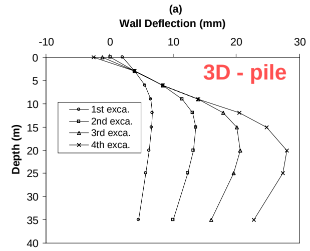
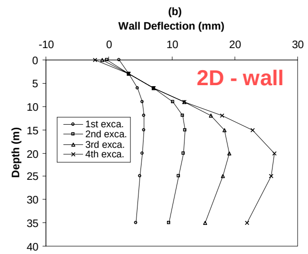
Modelling of Soldier Piles in 2-D



$I_{wall} = I_{pile} / s$

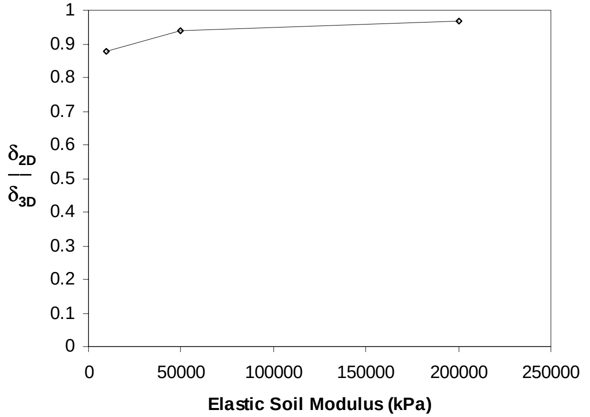
$A_{wall} = A_{pile} / s$





Modelling of Soldier Piles in 2-D

Effect of Soil Modulus on Wall Deflection



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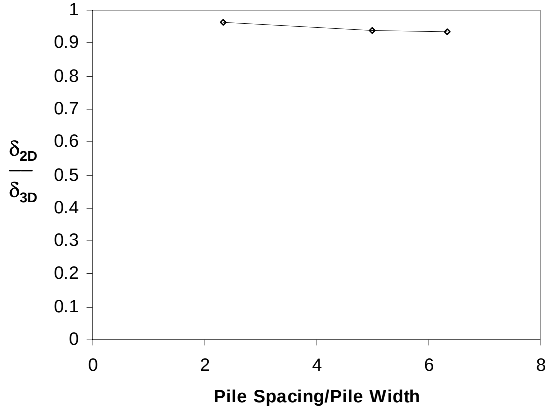
Modelling of Soldier Piles in 2-D

Effect of Pile Spacing on Wall Deflection



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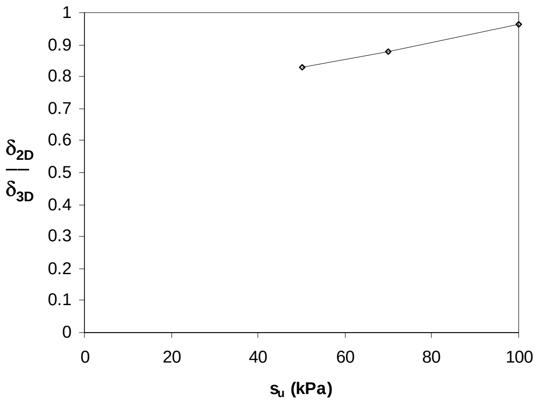
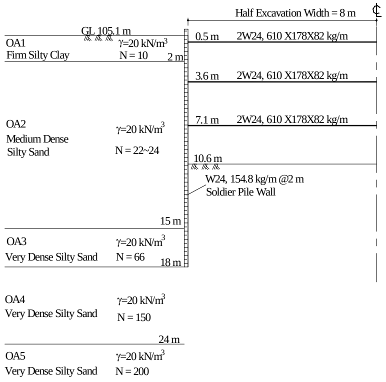
Modelling of Soldier Piles in 2-D

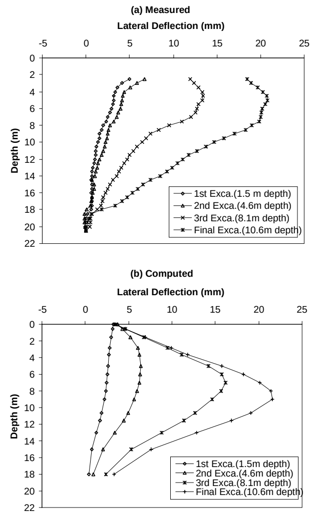
Effect of Soil Strength on Wall Deflection



15

Punggol-Sengkang cut-n-cover tunnel at CH43+780.

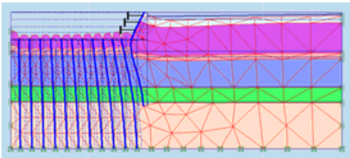


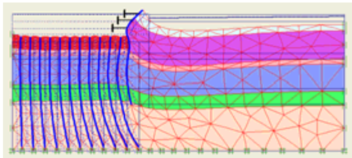


Modelling of Piles in Excavation with and without JGP Slab

By

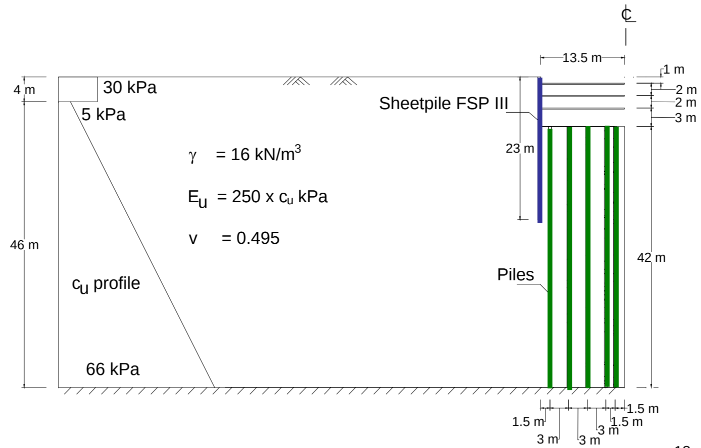
Wong Kai Sin





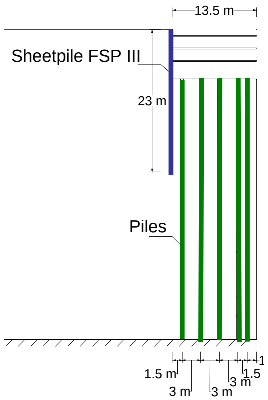
17

Should we include piles in the analysis?



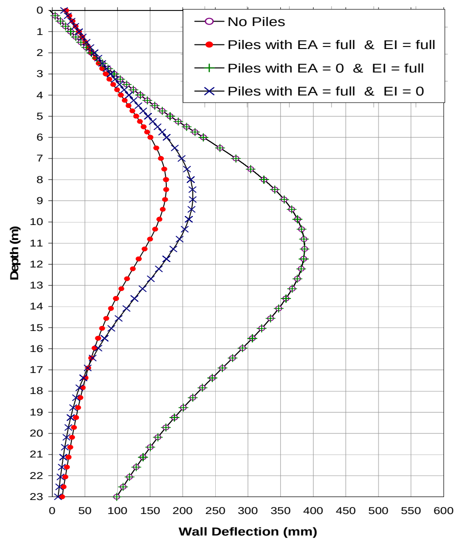
18

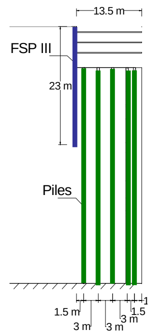
What are the options?



Method	Axial Stiffness	Flexural Stiffness
1	0	0
2	Full	Full
3	Full	0
4	0	Full

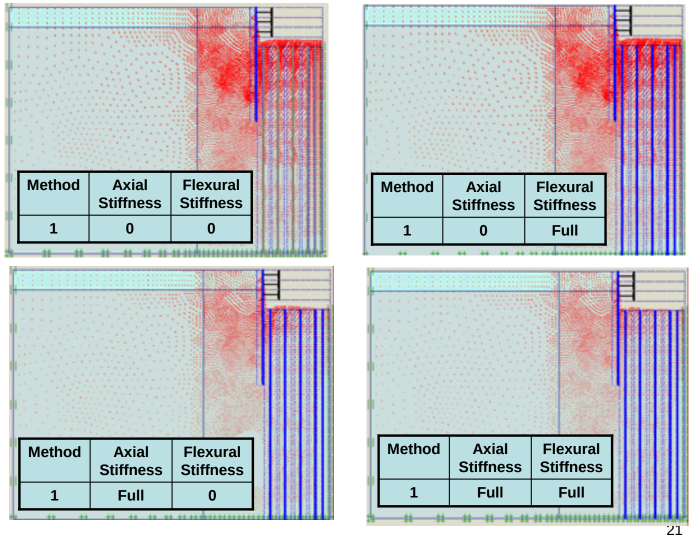
19





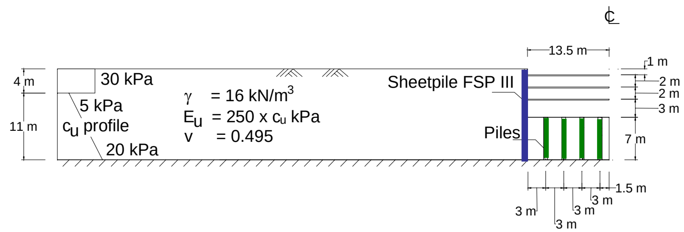
Which method is correct?

20



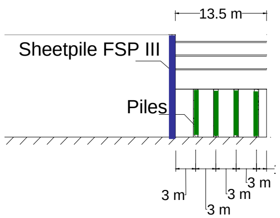
21

Is it necessary to model the piles?



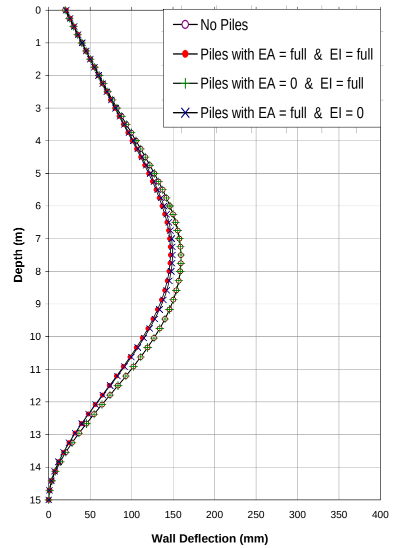
22

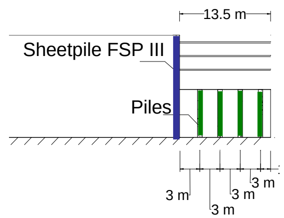
How should we model the piles?



Method	Axial Stiffness	Flexural Stiffness
1	0	0
2	Full	Full
3	Full	0
4	0	Full

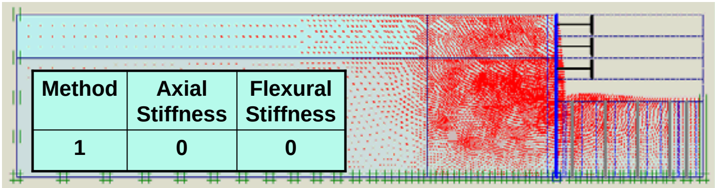
23



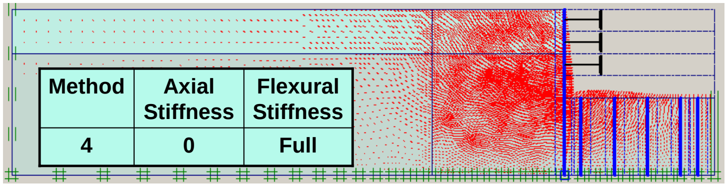


Which method is correct?

24

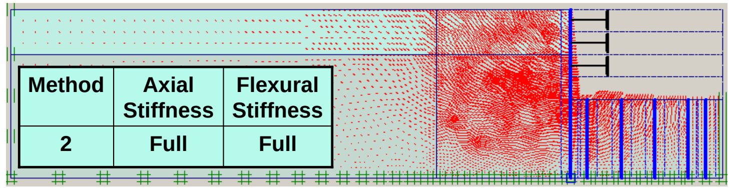


Method	Axial Stiffness	Flexural Stiffness
1	0	0

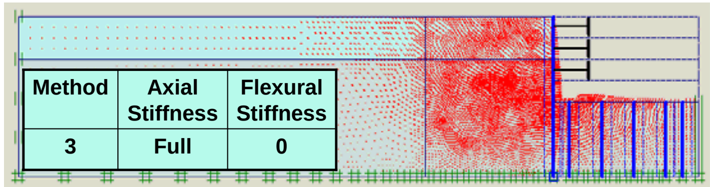


Method	Axial Stiffness	Flexural Stiffness
4	0	Full

25



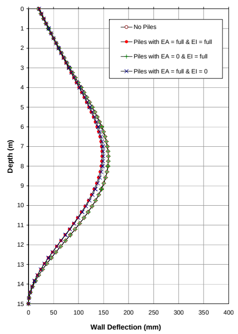
Method	Axial Stiffness	Flexural Stiffness
2	Full	Full

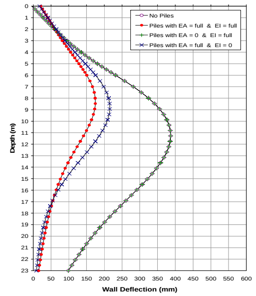


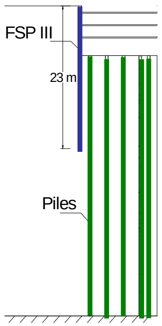
Method	Axial Stiffness	Flexural Stiffness
3	Full	0

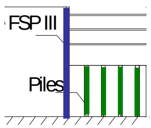
26

Should we model the piles?









What E_u/c_u should we use?

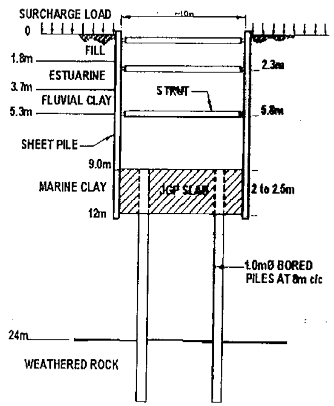
27

Factor of safety without JGP = 0.45 to 0.6

Clark Quay Station Entrance

(Shirlaw et al., 2005)

This is one occasion where modeling of piles is a must.



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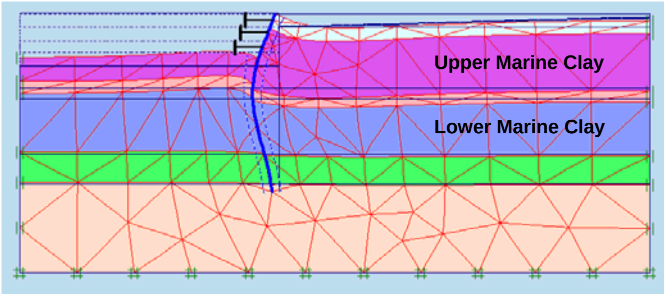
Another Example Illustrating Effect of Pile

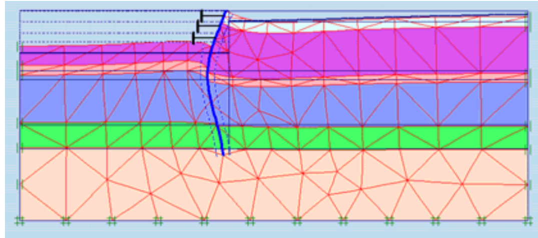
$\delta_{H,max}$ = 361 mm E_u/c_u = 100



This is from a case study. With E_u/c_u=100, the computed wall deflection profile without modeling the piles yielded very good agreement with measured values.

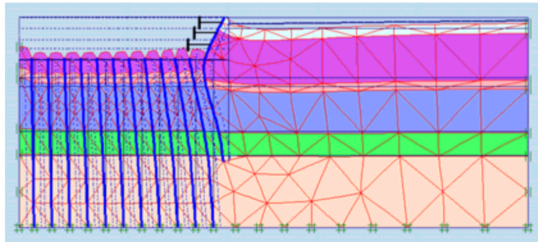
29

Effect of inclusion of piles -- E_u/c_u = 100 and EA = full



No Piles

$\delta_{H,max}$ = 361 mm



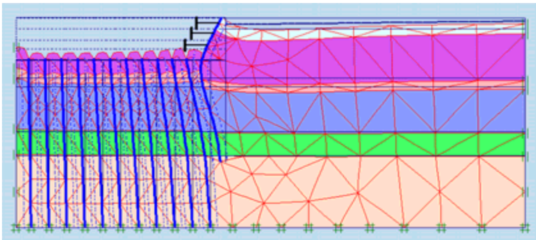
Piles at 3 m c/c

EI = full

$\delta_{H,max}$ = 230 mm

30

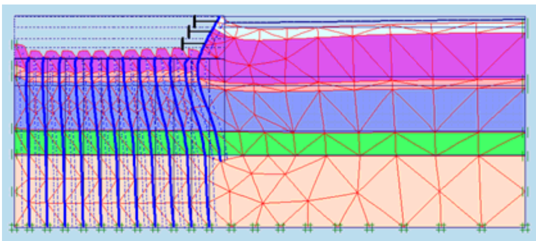
Effect of Pile Stiffness (EI) -- E_u/c_u = 100 and EA = full



Piles at 3 m c/c

EI = full

$\delta_{H,max}$ = 230 mm



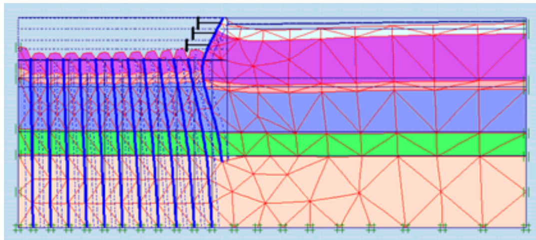
Piles at 3 m c/c

EI = 0

$\delta_{H,max}$ = 229 mm

31

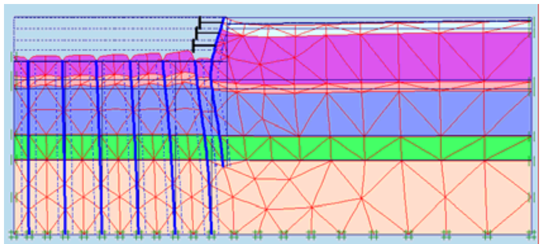
Effect of Pile Spacing -- E_u/c_u = 100 and EA = full



Piles at 3 m c/c

EI = full

$\delta_{H,max}$ = 230 mm



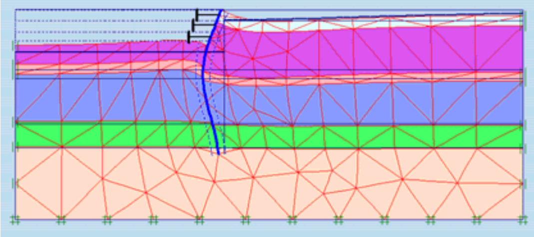
Piles at 6 m c/c

EI = full

$\delta_{H,max}$ = 311 mm

32

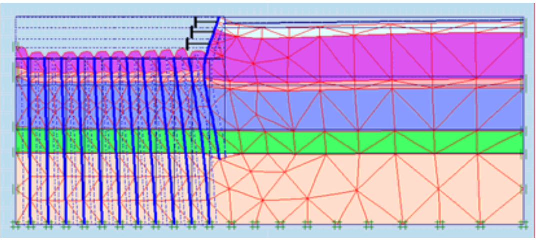
Modeling Inclusion of Piles -- What E_u/c_u should we use?



No Piles

$E_u/c_u = 100$

$\delta_{H,max} = 361$ mm



Piles at 3 m c/c

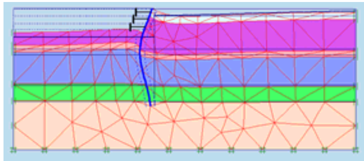
$E_u/c_u = 50$

$\delta_{H,max} = 342$ mm

33

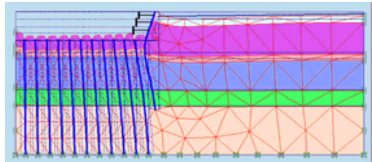
How should we model piles in an excavation?

1. Conduct an analysis without piles and determine δ_H profile and $\delta_{H,mas}$.
2. Conduct a second analysis with piles. Try different E_u/c_u ratios for marine clay until similar δ_H profile and $\delta_{H,max}$ are obtained.



No Piles -- $E_u/c_u = 100$

$\delta_{H,max} = 361$ mm

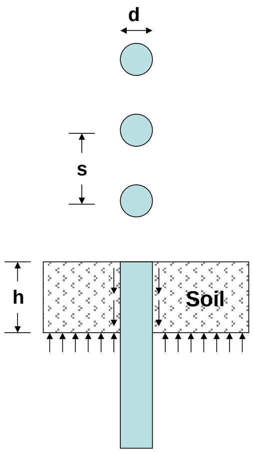


Piles at 3 m c/c -- $E_u/c_u = 50$

$\delta_{H,max} = 342$ mm

34

Evaluation of Adhesion on Piles in 2-D FEA



Q_s on piles in field = $(\pi\ d\ h\ /\ s)\ c_a$

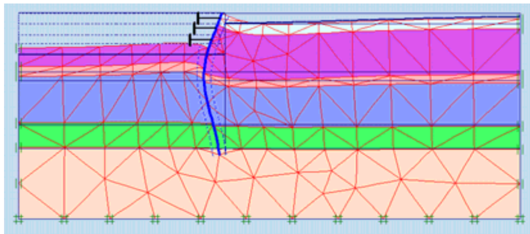
Q_s on piles in FEA = $2\ h\ c_{a,FEA}$

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

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

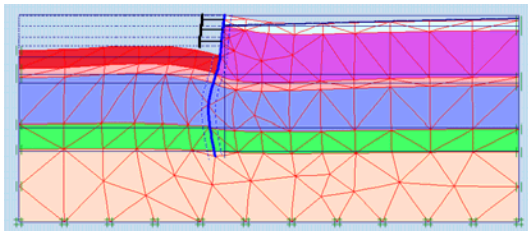
35

Effect of JGP Slab -- $E_u/c_u = 100$ and EA = full



No JGP

$\delta_{H,max} = 361$ mm

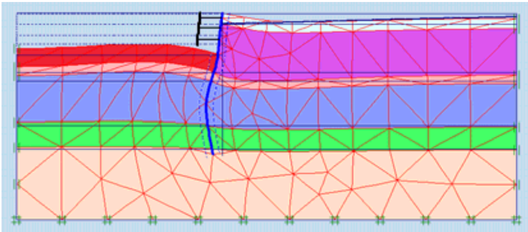


3m JGP

$\delta_{H,max} = 141$ mm

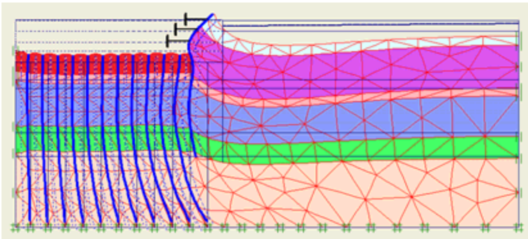
36

Effect of Inclusion of Piles -- E_u/c_u = 100 and EA = full



No Piles

$\delta_{H,max}$ = 141 mm



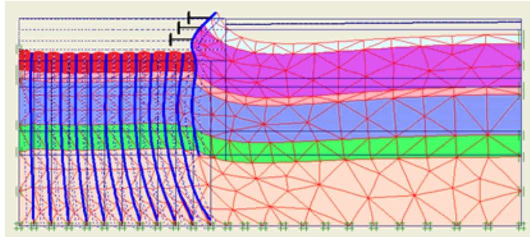
Piles at 3m c/c

EI = full

$\delta_{H,max}$ = 30 mm

37

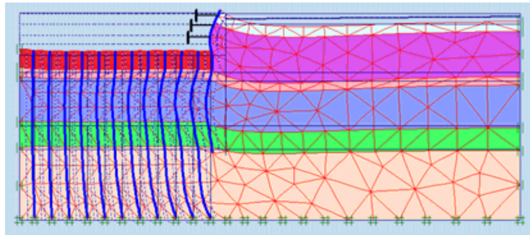
Effect of Flexural Stiffness of Piles -- E_u/c_u = 100 & EA = full



Piles at 3m c/c

EI = full

$\delta_{H,max}$ = 30 mm



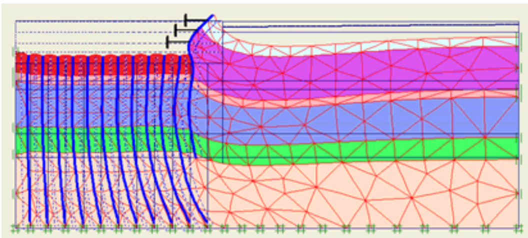
Piles at 3m c/c

EI = 0

$\delta_{H,max}$ = 34 mm

38

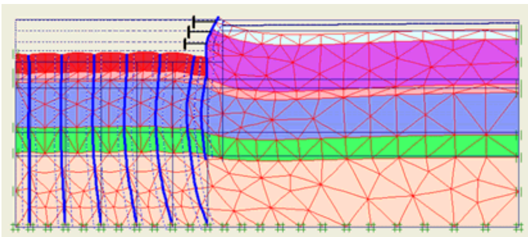
Effect of Pile Spacing -- E_u/c_u = 100 & EA = full



Piles at 3m c/c

EI = full

$\delta_{H,max}$ = 30 mm



Piles at 6m c/c

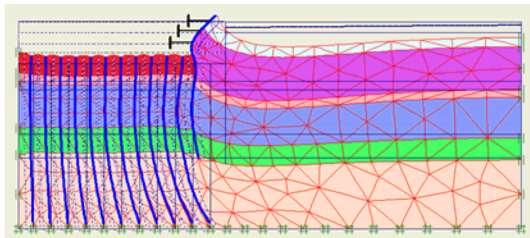
EI = full

$\delta_{H,max}$ = 37 mm

39

How should we model piles in an excavation with JGP?

Conduct the analysis with piles using full EI & EA .



Piles at 3m c/c

EI = full

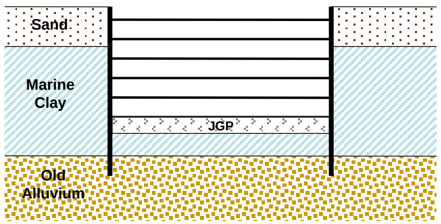
EA = full

$\delta_{H,max}$ = 30 mm

40

Four categories of analysis .....

1. Best estimate using moderately conservative parameters for construction control.
2. Sensitivity studies to finalise the design.
3. Back-analysis to calibrate soil & other parameters.
4. Re-analysis using calibrated parameters.



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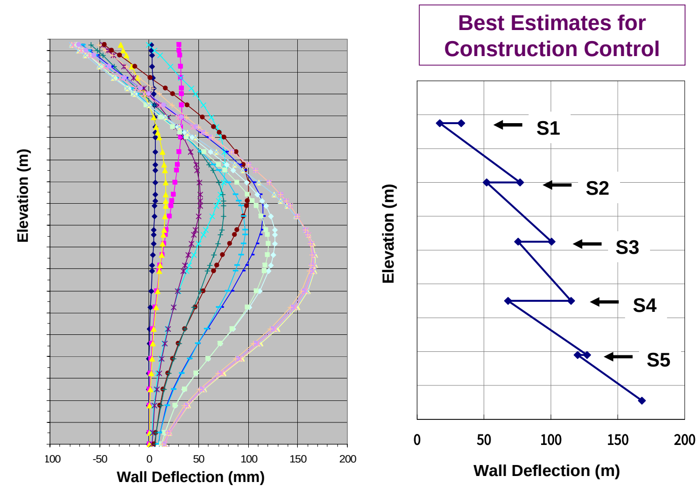
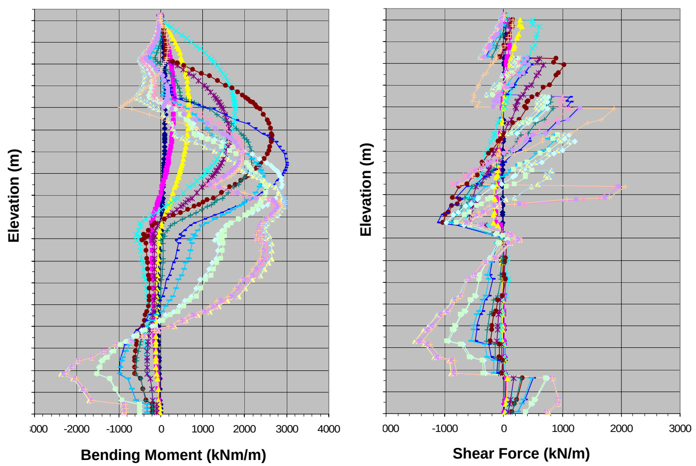
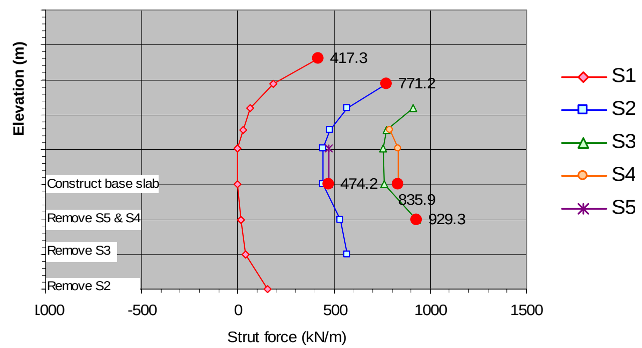
Wall Deflection Profile & Maximum Deflections at Various Stages



Bending Moment and Shear Forces at Various Stages



Strut Forces at Various Stages



Best Estimates for Construction Control

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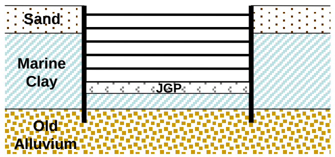
Sensitivity Study to Finalise Design



Surcharge	10 and 20 kPa
Soil Modulus (E_u/c_u)	300 and 200
Over-excavation	0.5 and 1 m
JGP Thickness	1.5 and 1.0 m
JGP modulus	150 and 100 MPa
Wall stiffness	1.0EI and 0.7EI
Modelling of bored piles	Included and excluded
Preload	100, 50 and 0%

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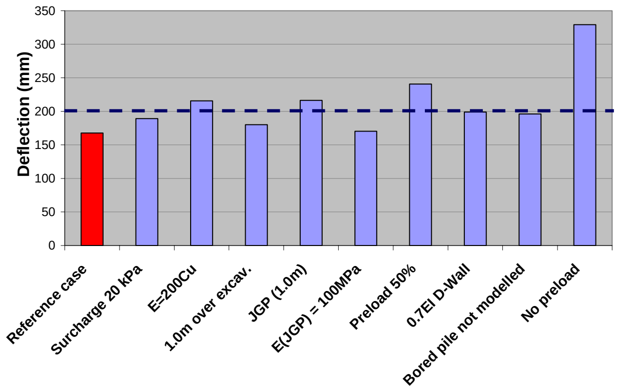
Sensitivity Study on Wall Deflection



Design $\delta_{H,max}$ = 200 mm

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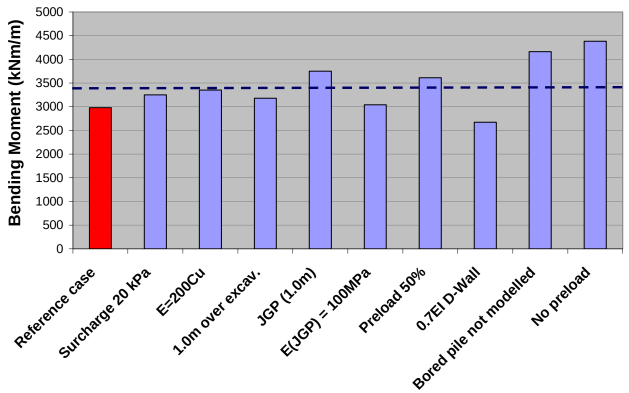
Sensitivity Study on Wall Bending Moment



Design M_{max} = 3400 kNm/m

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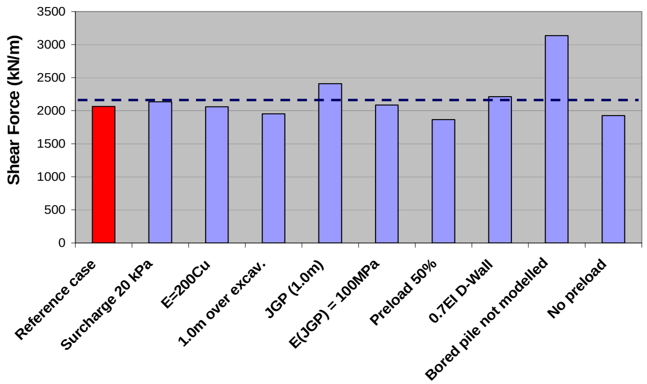
Sensitivity Study on Wall Shear Forces



Design V_{max} = 2200 kN/m

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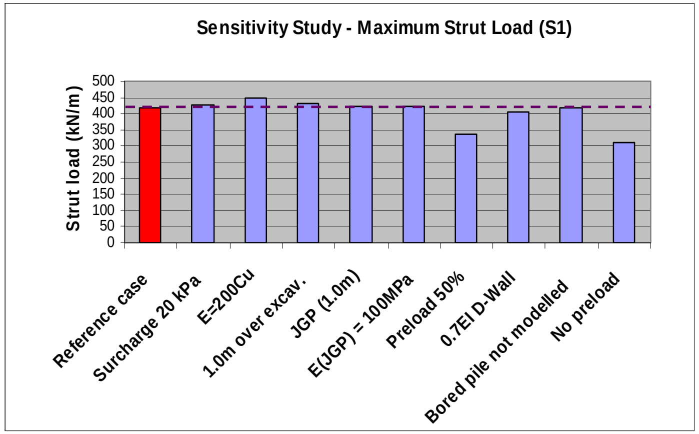
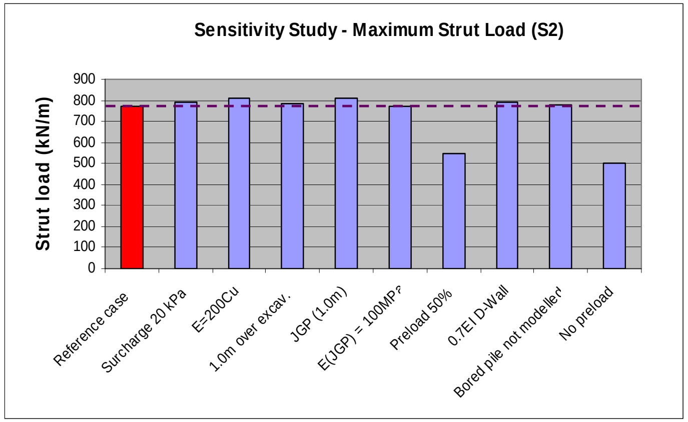


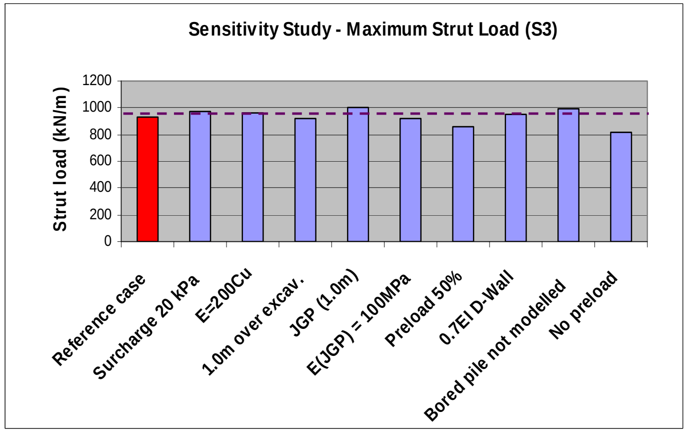
Design S1 = 420 kN/m

49



Design S2 = 780 kN/m

50



Design S3 = 960 kN/m

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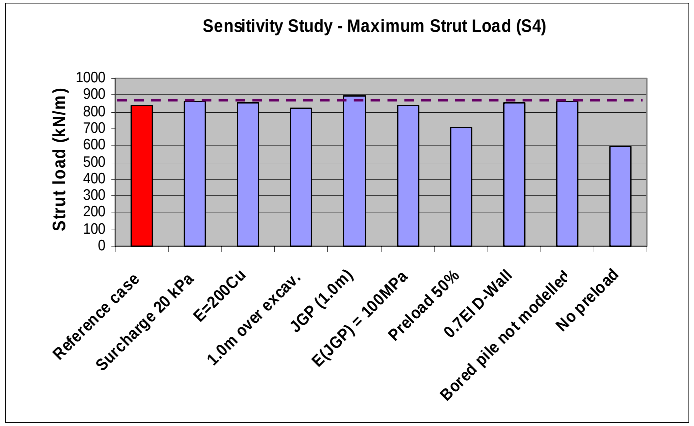

Design S4 = 880 kN/m

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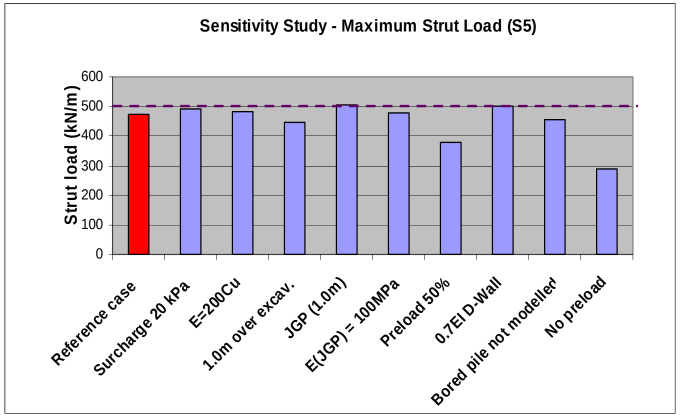

Design S5 = 500 kN/m

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Best Estimates and Design Values

			Best Estimates	Design Values based on Sensitivity Study
Diaphragm Wall	Deflection	mm	168	200
	Moment	kNm/m	2980	3400
	Shear	kN/m	2065	2200
Strut S1	Force	kN/m	417	420
Strut S2	Force	kN/m	771	780
Strut S3	Force	kN/m	929	960
Strut S4	Force	kN/m	836	880
Strut S5	Force	kN/m	474	550

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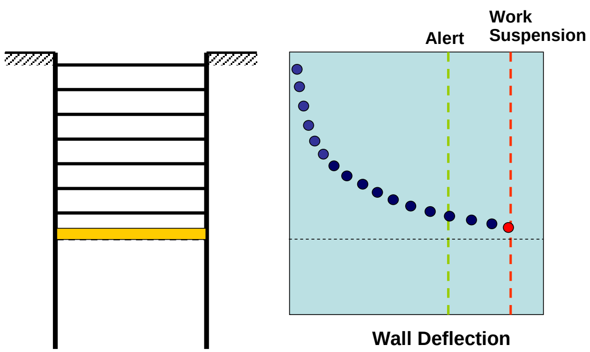
Back-Analysis

When should we conduct Back-Analysis?

Should we wait until the work suspension level is reached?

Or wait until we are told by the Authority?



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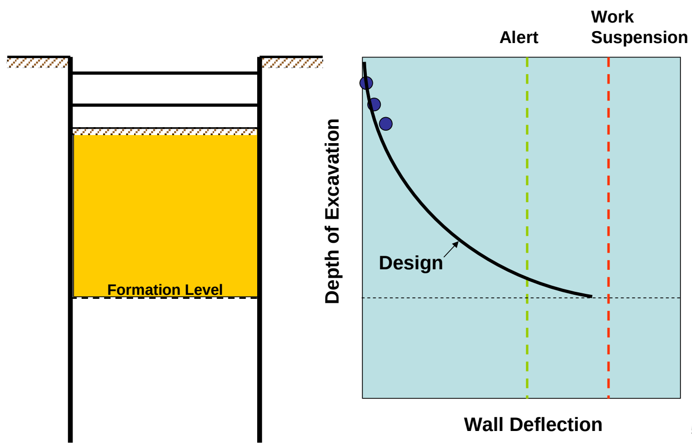
When should we conduct Back-Analysis?



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How should we conduct Back-Analysis?

Be sure to :

- Use relevant soil profile.
- Use as-built configuration.
- Follow as-built construction sequence.
- Vary parameters within reasonable limits.
- Understand limitations of the FEM.
- Use reliable instrumentation data.

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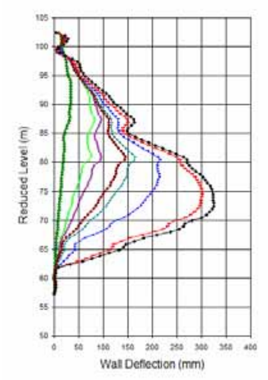
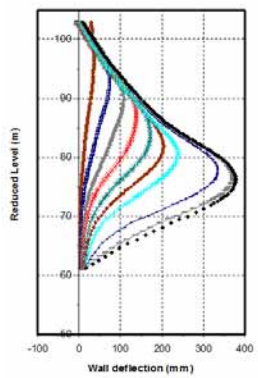
It is not necessary to have a perfect match!

Measured



Computed



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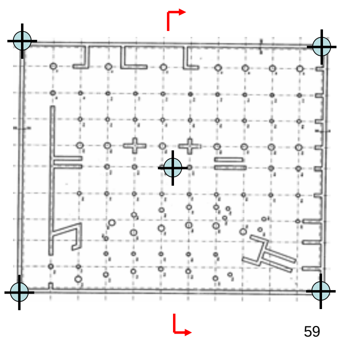
Information Needed for Back-Analysis

1. Understand soil condition at <u>instrumented section</u>

- In-situ soil condition
- Piling records
- Kingpost records
- Diaphragm wall records
- Diaphragm wall toe level
- Excavation records



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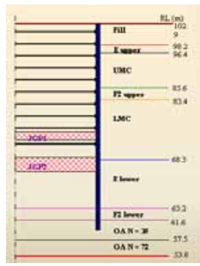
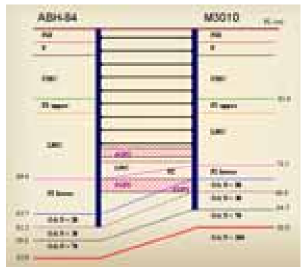
Is the design soil profile relevant to the instrumented section?



Design



Instrumented Section

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Calibration of Soil Parameters

Undrained Shear Strength of Marine Clay c_u

❖ Are the marine clays fully consolidated?

❖ Marine clays in many areas may not be fully consolidated even at 50 years after reclamation.

❖ c_u/σ'_v ~ 0.22 is a good choice where σ'_v is the current effective stress which may be lower than the effective overburden pressure.

❖ Using values below c_u/σ'_v = 0.20 needs justification.

❖ In many cases, it is not necessary to calibrate the shear strength.

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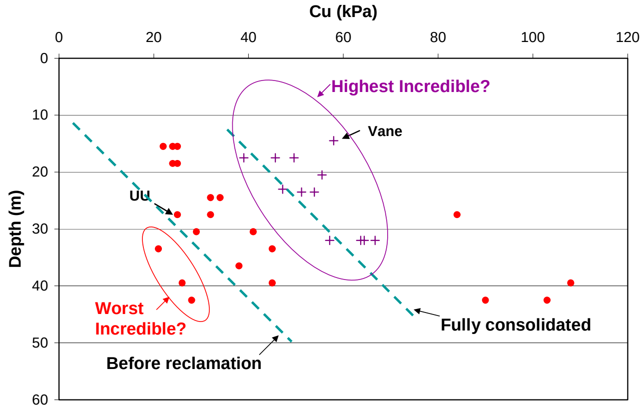
Calibration of Soil Parameters

Are you calibrating against "credible" data?



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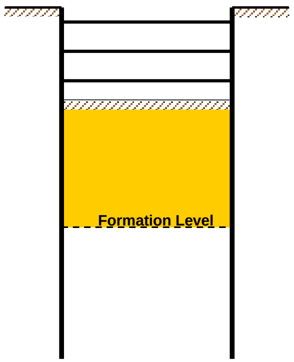
2. Know the Actual Construction Sequence

- As-built configuration
- Excavation records
- Strutting records
- Preloading records
- Surcharge
- Over-excavation
- Problems encountered



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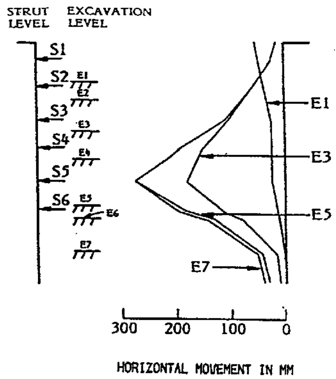
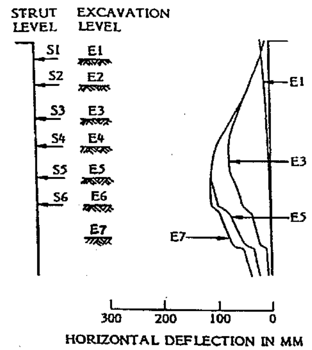
Follow As-Built Construction Sequence

As-Built



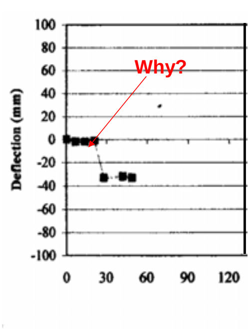
Design

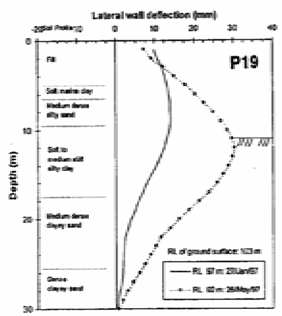


3. Check reliability of field measurements

What causes the sudden jump in readings?

Any possibility of toe movement at the inclinometer?





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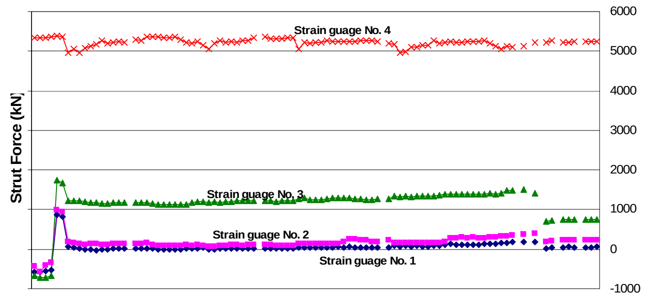
Are the measurements reliable?

- Are all the strain gauges working properly?
- Are the computations based on correct calibration factors?



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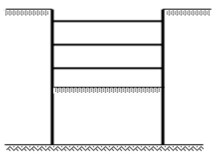
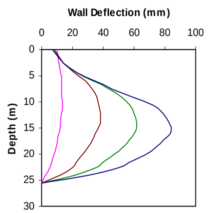
4. Understanding limitations of soil model used





Do you expect:

1. good agreement at all stages?

2. good agreement at early stages?

3. good agreement at the final stage?

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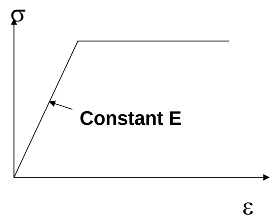

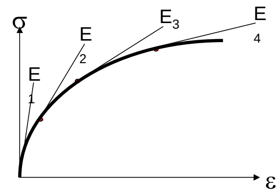

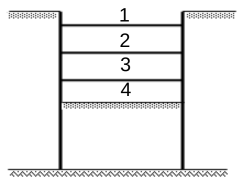

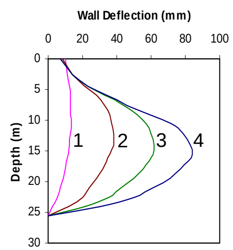

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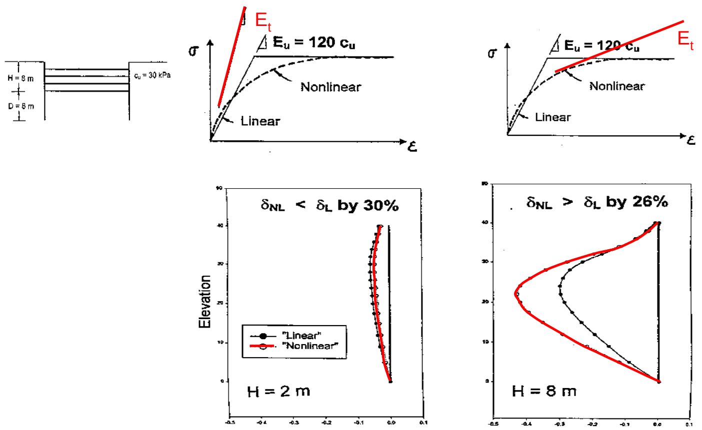
Constant E_u may not produce correct response at every stage



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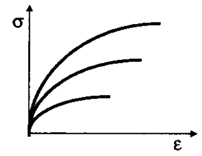
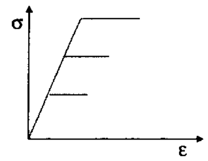
Modeling of Sand Behaviour with Mohr-Coulomb Model

Real Sand



If your site has a thick sand deposit, your analysis may not produce a reliable response.

Mohr-Coulomb Sand



Assess the results carefully!

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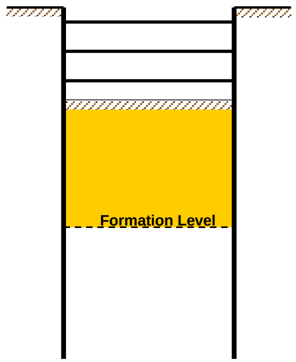
Calibration of Parameters

- **Soil profile**
- **Soil strength & modulus**
- **Unit weight & K_o**
- **Soil permeability**
- **Wall stiffness**
- **JGP strength & modulus**
- **JGP post-peak behaviour**
- **Preloads**



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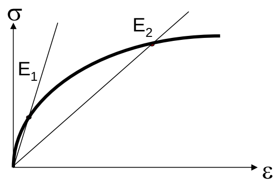
Important Parameters to be considered in Calibration

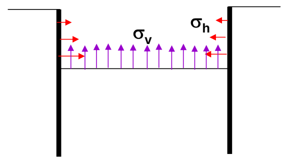
E_u/c_u

E_u/c_u varies with excavation depth.

γ & K_o

γ and **K_o** have significant impact on wall deflection and strut forces.





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