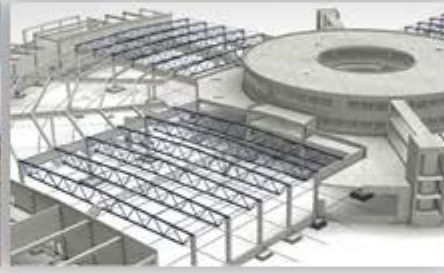


# Effective Deep Excavation Analysis and Design using

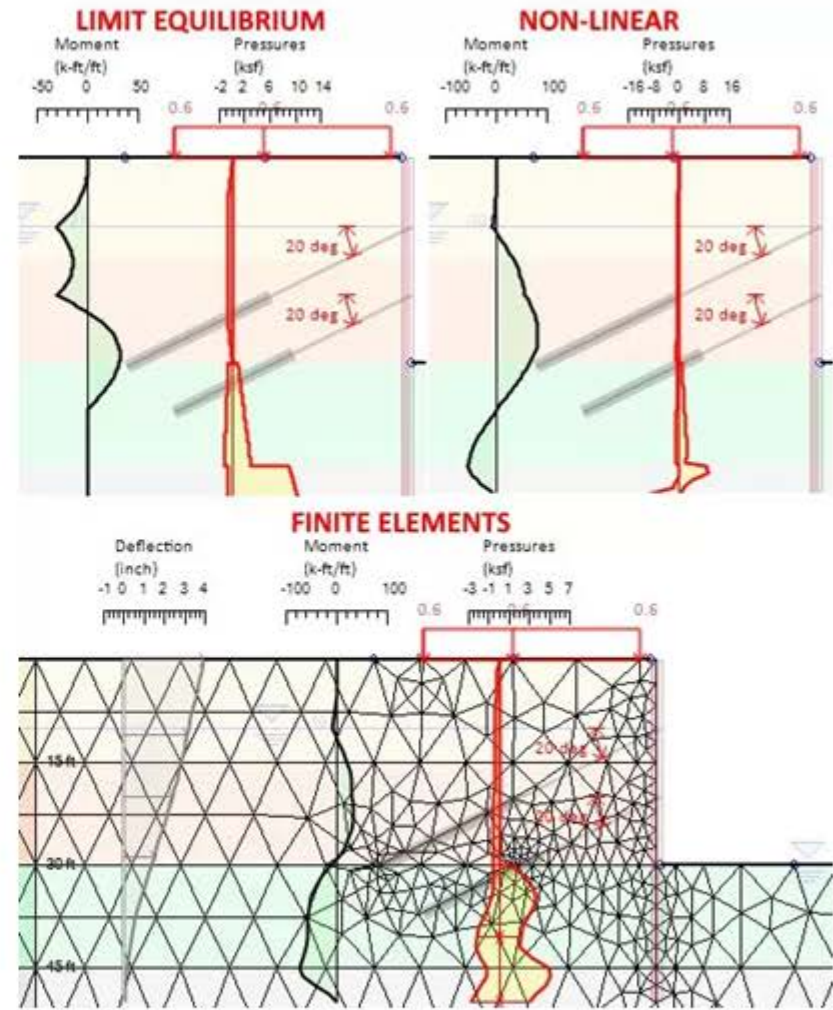


## GeoStruktur Sistem Solusindo

*Your Trusted Partner for Digital Transformation*

# Overview of DeepEX

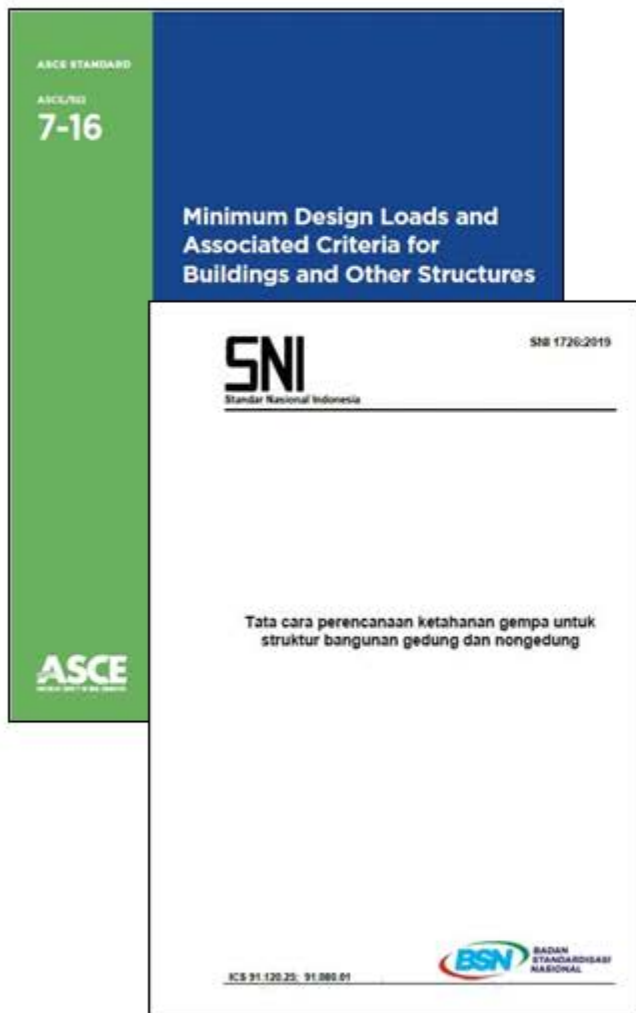
- DeepEX is the specialized software for deep excavation:
  - **Wall systems:** Soldier pile, tangent pile, secant pile, sheet pile, diaphragm wall, etc.
  - **Support systems:** Strut, raker, concrete slab, ground anchor, gravity wall\*, etc.
- It can use either Limit Equilibrium, Non-Linear, or Finite Element Method\* for the modeling problem.
- Unique features:
  - Soil **parameters correlation** from field tests.
  - **Strength calculation** of retaining and support system.
  - Design check with structural (e.g. ACI, AISC) and geotechnical design codes (e.g. AASHTO, Eurocode 7).
  - **Quick design comparison** of various retaining systems.
  - Customizable report (PDF or WORD format).
  - Export to DXF\*.



Analysis methods in DeepEX

\*Need optional module.

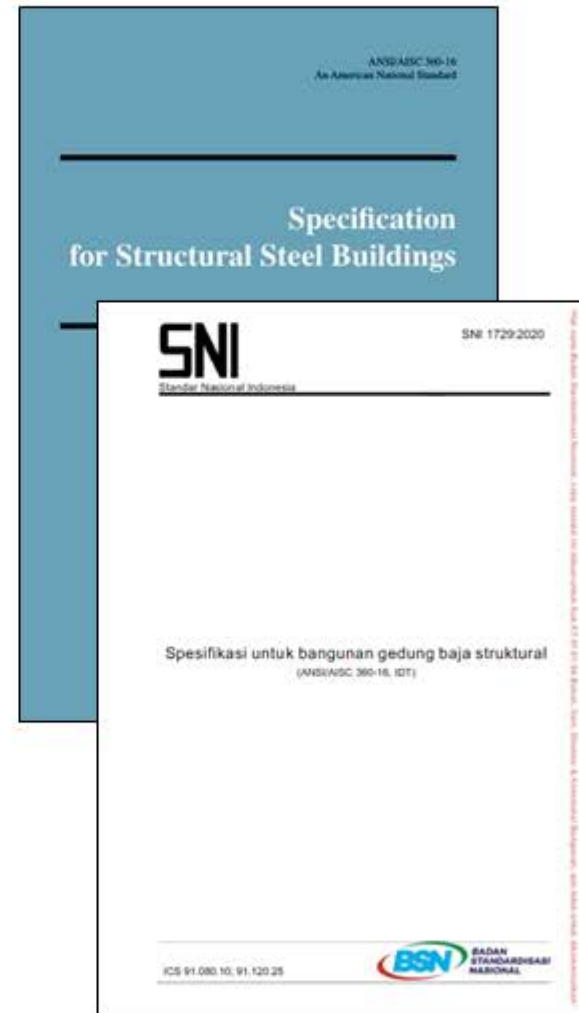
# Relevant Design Codes (in Indonesia)



**Earthquake-Resistant Design**  
SNI 1726-2019 (ASCE 7-16)



**Concrete Design**  
SNI 2847-2019 (ACI 318)



**Steel Design**  
SNI 1729-2020 (AISC 360)



**Geotechnical Design**  
SNI 8460-2017

# Design Sequences of Deep Excavation

Define soil parameters and stratigraphy

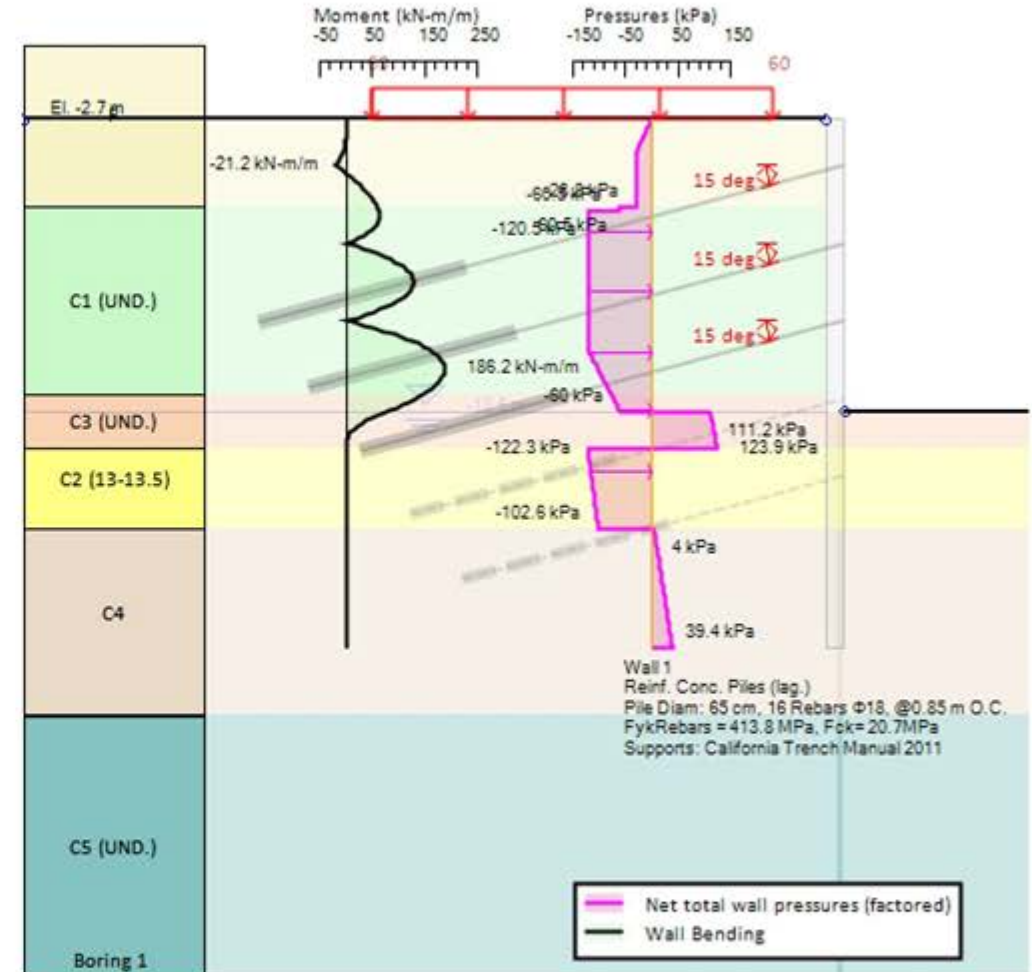
Determine wall and support system

Create construction stages

Select analysis method and design codes

Perform analysis and check safety ratio

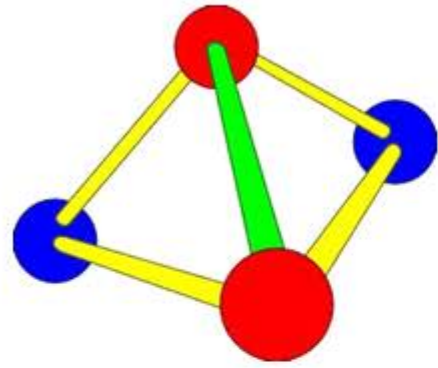
Generate report and drawing



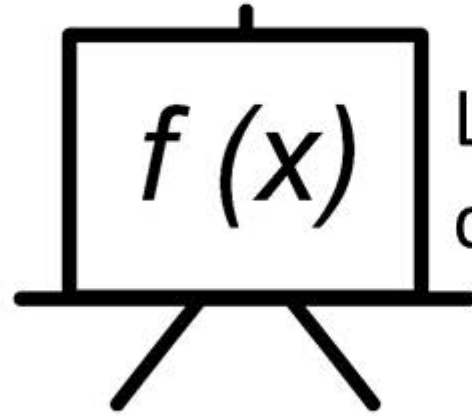
Analysis results in DeepEX  
(Cantilever wall with ground anchors)

# Outline

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Modeling challenges and workflow enhancements

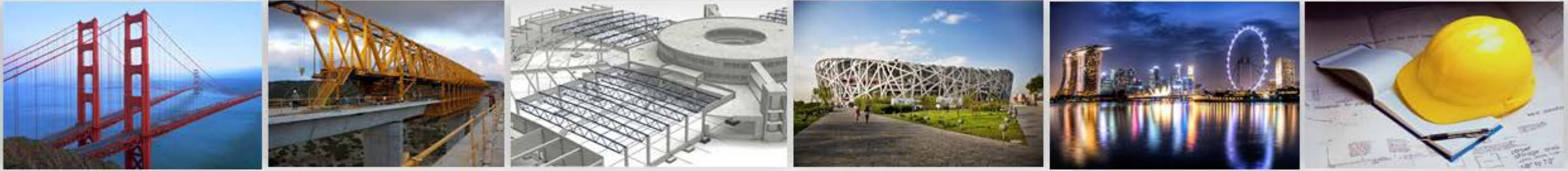


LEM approaches and design check



Essential design aspects & case study

# Effective Deep Excavation Analysis and Design



## Modeling Challenges and Workflow Enhancements



# Scopes in Deep Excavation Design

SAMPLE	DEPTH (m)	USCS SYMBOL	GRAPHIC LOG	ROCK / SOIL DESCRIPTION	DEPTH (m)	Penetration (mm/30 sec)	STANDARD
	0.00	CL		SILTY CLAY, brown ( 10YR 5/3 ), medium plasticity, medium dry strength, few gravel max dia of 12.00 cm, angular, stiff, ( Fill Material ).	1.00	1.00	
	1.00	CH		FAT CLAY, bluish gray ( GLEY2 5/1 ), high plasticity, high dry strength, soft to medium stiff.	1.45	1.00	1.15
	2.00				2.00	1.00	
	2.70				2.70	0.25	2.70
	3.00	MH		ELASTIC SILT, dark gray ( GLEY1 4/N ), high plasticity, medium dry strength, slow dilatancy, some organic content, moist, very soft.	4.00	<0.25	5.00
	5.00				5.00	<0.25	5.00
	6.00				6.00	<0.25	5.00
	7.00	CH		FAT CLAY, dark gray ( GLEY1 4/N ), high plasticity, high dry strength, trace organic included, soft.	7.00	<0.25	5.00
	8.00				8.00	<0.25	5.00
	9.00	OH		ORGANIC CLAY with SAND, dark grayish brown ( 10YR 4/2 ), medium plasticity, medium dry strength, rapid dilatancy, intercalated by thin fine sand lenses, very soft.	9.00	<0.25	10.00
	10.00				10.00	<0.25	10.00
	10.45	SM		SILTY SAND, gray ( 10YR 5/1 ), About 70 % predominantly fine to medium grained sand, about 30% silty fines with low plasticity, uncemented, loose.	11.00	<0.25	10.00
	11.00				11.00	<0.25	10.00
	11.15			FAT CLAY, bluish gray ( GLEY2 5/1 ), high plasticity, high to medium dry strength, slightly silty, moist, very soft to soft.	12.00	<0.25	12.00
	12.00				12.00	<0.25	12.00
	13.00				13.00	<0.25	12.00

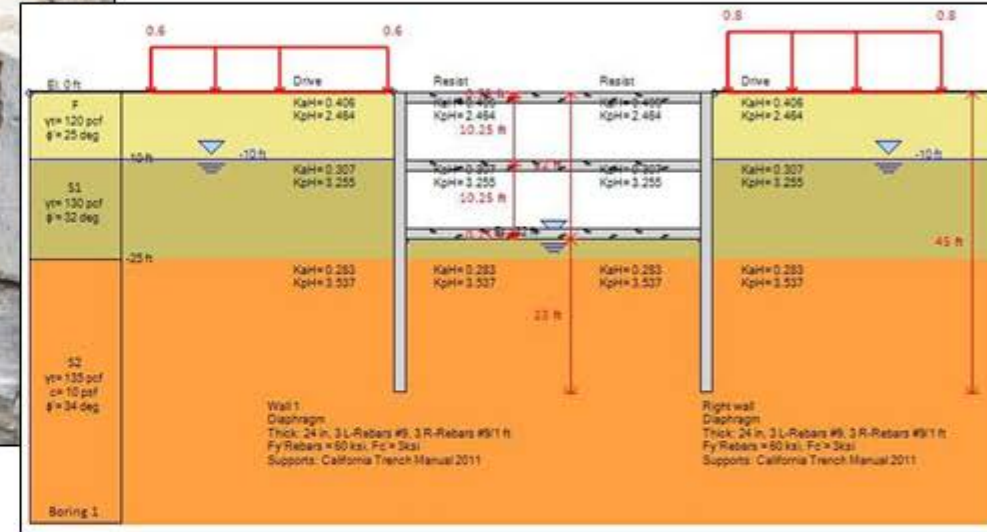


## Geotechnical Engineer

- Selection of soil properties.
- Choose suitable retaining system.
- Choose suitable support system.
- Perform flow & stability analysis.
- Evaluate impact of CST variance.

## Structural Engineer

- Design of sheet piles.
- Design of tangent/secant piles.
- Design of struts and waler.
- Design of concrete slab.
- Design of raker.



## Construction Engineer

- Info on site physical constraints.
- Study of various CST sequences.
- Feedback on wall/support system.
- Develop schedule of CST works.
- Supervise on site instrumentation.

# Main Modeling Challenges

## 1. Select appropriate soil properties.

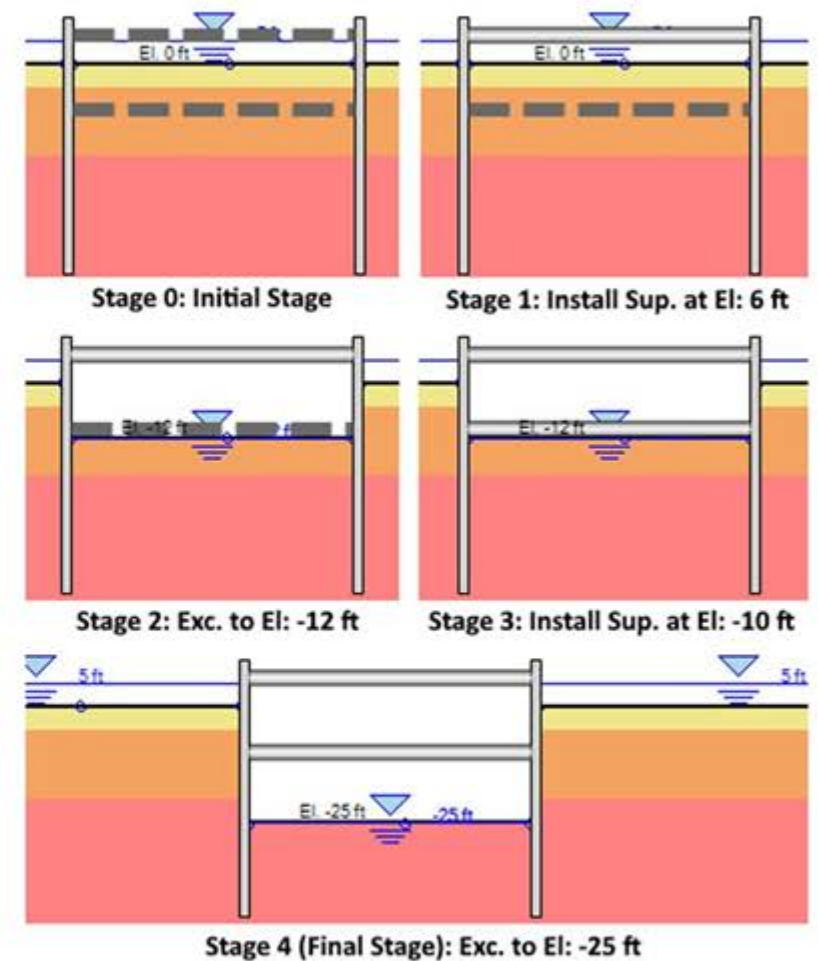
## 2. Calculate wall/support strength.

- Design loop between geotechnical-structural engineers (e.g. secant pile, sheet pile).
- Ground anchor capacity.

## 3. Establish robust cost-effective solution.

- Sensitivity study:
  - Check potential soil variations.
  - Check of design robustness (e.g. excessive external load, over-excavation, etc.).
- Value engineering for the retaining/support system.

In many cases, **70%-80% of the time** spent for the deep excavation modeling, is **for selecting soil properties** and **calculating wall/support capacity**. In the end, only little time left for doing model iterations.



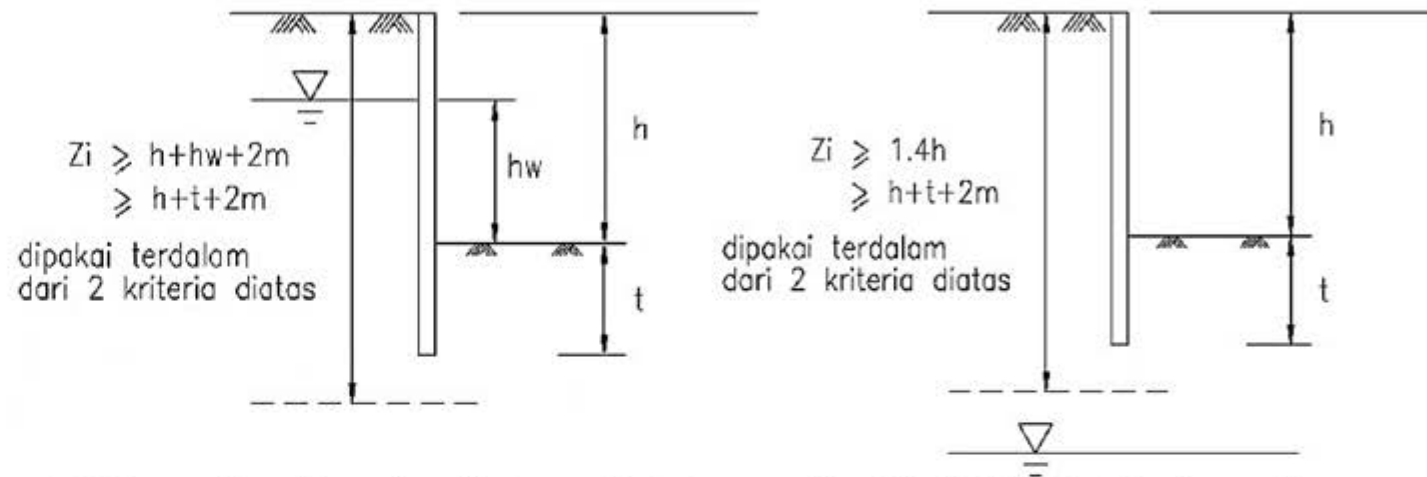
Staged-construction in DeepEX  
(Sheet-pile cofferdam)



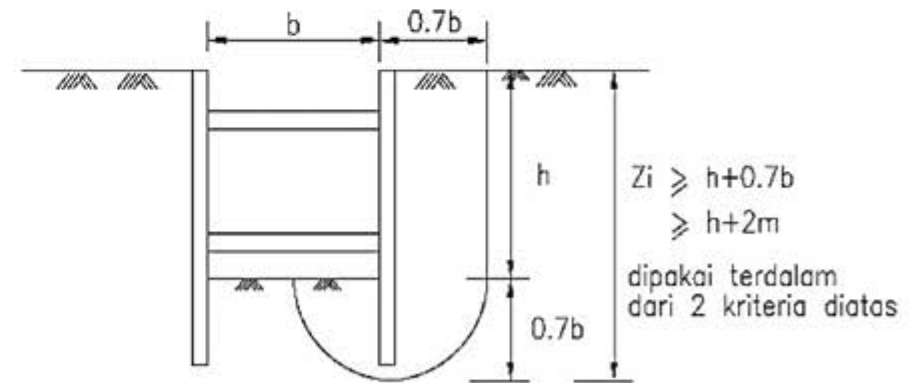
# Soil Data for Deep Excavation

- Definition: Deep excavation is an **excavation with depth  $\geq 3\text{m}$**  (SNI 8460, section 11.1).
- Min recommended soil data for deep excavation: **3-5 points** at the critical section\*.
- Min recommended testing depth: See figure\*.
- Important parameters for modeling :
  - Soil stiffness (E).
  - Undrained shear strength ( $c, \varphi$ ).
  - Drained shear strength ( $c', \varphi'$ ).
  - Permeability (k).

Tips: Even when we have sufficient information; these data (e.g. field and lab data), they should be cross-checked with each other.



Soil investigation depth for retaining wall with GWL (left) above the base of excavation; (right) below the base of excavation.



Soil investigation depth for trench excavation

# Soil Properties: Correlations

DeepEX offers various correlation for determining soil engineering properties (from CPT, SPT, etc).

## Correlating soil properties from SPT data:

- Sand :  $\phi_{\text{sand}}$  based on Peck et. al correlations.
- Clay :  $S_u = 6 \text{ N-SPT}$ .
- Silt :  $\phi_{\text{silt}} = 85\% \phi_{\text{sand}}$  and  $c' = 25\% S_u$

## Correlating undrained shear strength from CPT data:

$$S_u = \frac{q_c - \sigma_v}{N_K}$$

Where:

- $q_c$  = Cone resistance.
- $\sigma_v$  = Total vertical stress.
- $N_K$  = Cone factor (typically between 10-20).

Note: PI may also be required (when  $N_K \neq 15$ ).

Tips: Selecting an appropriate set of soil properties needs a thorough evaluation of soil investigation results. **Correlation should only be used as the first order estimate.**

# Soil Properties: SPT Correlation

The screenshot displays the 'Soil Types' dialog box in GeoStruktur. The left sidebar lists soil types: F, O1, O2, S1 (selected), Clay, GT, and Rock. The main panel is divided into several sections:

- 1. Name and Basic Soil Type:** Soil Name: S1, Description: Medium sand.
- 2. Soil Type - Behaviour:** Silt.
- 3. Default drained-undrained behavior for clays:** Drained.
- 4. Unit Weights - Density:**  $\gamma_t$ : 19.2 kN/m<sup>3</sup>,  $\gamma_{bulk}$ : 19.2 kN/m<sup>3</sup>,  $\gamma' = 9.2$ .
- 5. Strength Parameters and Poisson Ratio:**  $c'$ : 15.2 kPa,  $\phi$ : 25.4 degrees,  $\nu$ : 0.35. Includes peak-constant vol. properties for  $\phi_{cv}$  and  $\phi_{peak}$ .
- 6. Permeability:**  $K_x$ : 9.999999 m/sec,  $K_z$ : 9.999999 m/sec.
- 8. At-rest coefficients:**  $KoNC$ : 0.57,  $nOCR$ : 0.5,  $Ko = KoNC * (OCR)^{nOCR}$ .

The right panel shows the 'SPT Estimator' tab with a table of parameters and their corresponding SPT values:

Parameter	0	10	20	30	40	50	60
Nspt							
$\gamma_t$	17	18	19	20	21	22	23
$\phi$	20	30	40	50	60		
$c'$	0	25	50	75	100		
Su	0	100	200	300			

An arrow points to the slider for Nspt, which is currently set to 10. A callout box contains the text: 'Slider for SPT correlation'. Below the table is an 'Important Note' regarding the use of ultimate skin friction for tieback capacity calculations.

# Soil Properties: CPT Correlation

The screenshot shows the 'Soil Types' software interface. On the left, a list of soil types includes 'Clay' (selected). The main window is divided into several sections:

- 1. Name and Basic Soil Type:** Soil Name: Clay, Description: Stiff clay.
- 2. Soil Type - Behaviour:** Clays (drained and undrained).
- 3. Default drained-undrained behavior for clays (See Theory Manual):** Undrained behaviour (selected).
- 4. Unit Weights - Density:**  $\gamma_t$  20 kN/m<sup>3</sup>,  $\gamma_{bulk}$  19 kN/m<sup>3</sup>,  $\gamma_w$  10.
- 5. Strength Parameters and Poisson Ratio:**  $c'$  0 kPa,  $\phi$  28 degrees,  $S_u$  6.667 kPa,  $\nu$  0.45,  $\phi_{cv}$  30 degrees,  $\phi_{peak}$  21.1 degrees.
- 6. Permeability:**  $K_x$  9.999999 m/sec.
- 7. Minimum Pressures for clays (L...):** Min sh 0 kPa, Min Ka 0.
- 8. At-rest coefficients:**  $K_{oNC}$  0.5,  $n_{OCR}$  0.5,  $K_o = K_{oNC} \cdot (OCR)^{n_{OCR}}$ .

The right-hand side of the window shows 'Test Data' for SPT and CPT:

- 1. Standard Penetration Test Data - Relative Density:** Ave. N 0, N60 Omitted, Hammer Efficiency n= 65 %, DR Omitted.
- 2. Specimen In-situ stresses and Plasticity Index:**  $\sigma_v$  100 kPa,  $\sigma'_v$  Omitted kPa, OCR 1, PI 25,  $D_{50}$  Omitted mm.
- 3. Cone Penetrometer Data:**  $Q_{shaft}$  Omitted kPa,  $Q_{tip}$  200 kPa, Cone Factor 15.
- Consolidation:**  $E_{oed}$  300 ksf,  $e_o$  0.6,  $C_c$  0.5,  $C_r$  0.05,  $C_v$  100 m<sup>2</sup>/day,  $C_h$  300 m<sup>2</sup>/day.
- 4. Pressuremeter Tests:**  $P_l$  Omitted MPa.
- User specified ultimate bearing pressure:**  $q_{Bearing,ULT}$  .01 psi.

Buttons on the left include 'Add New Soil', 'Copy Soil', 'Delete Selected Soil', 'Paste Soil', and 'Clone'. At the bottom are 'Database' buttons and 'OK/Cancel' buttons.

Click for CPT correlation

Required data for  $S_u$  correlation from CPT data

# Soil Properties: Permeability Estimation

Soil Types

Soil Types

F  
O1  
O2  
S1  
Clay  
GT  
Rock

1. Name and Basic Soil Type

Soil Name S1 Color

Description Medium sand

2. Soil Type - Behaviour

Silt Show test data (SPT, CPT, Etc)

Not defined

3. Default drained-undrained behavior for clays (See Theory Manual)

Undrained behaviour  Drained

A. General C. Elasto-plastic D. Bond E. Adv. F. Piles

4. Unit Weights - Density

$\gamma_t$  21 kN/m<sup>3</sup>  $\gamma_{bulk}$  19 kN/m<sup>3</sup>  $\gamma_w$  11

5. Strength Parameters and Poisson Ratio

Drained strength properties

$c'$  0 kPa  $\phi$  34 degrees

Peak - constant vol. (for estimation)

$\phi_{cv}$  Omittec degrees

$\phi_{peak}$  Omittec degrees

$v$  0.35

6. Permeability

$K_x$  9.999999 m/sec  $K_z$  9.999999 m/sec

8. At-rest coefficients

$KoNC$  0.4408071  $nOCR$  0.5  $Ko = KoNC \cdot (O$

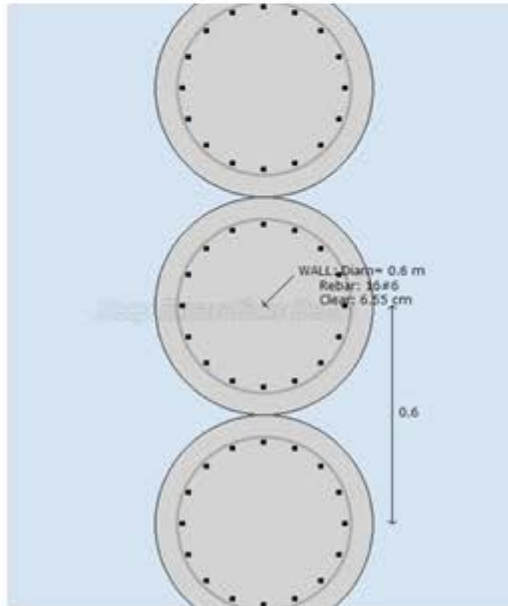
FEM properties (summary-tools)

Database Database OK Cancel

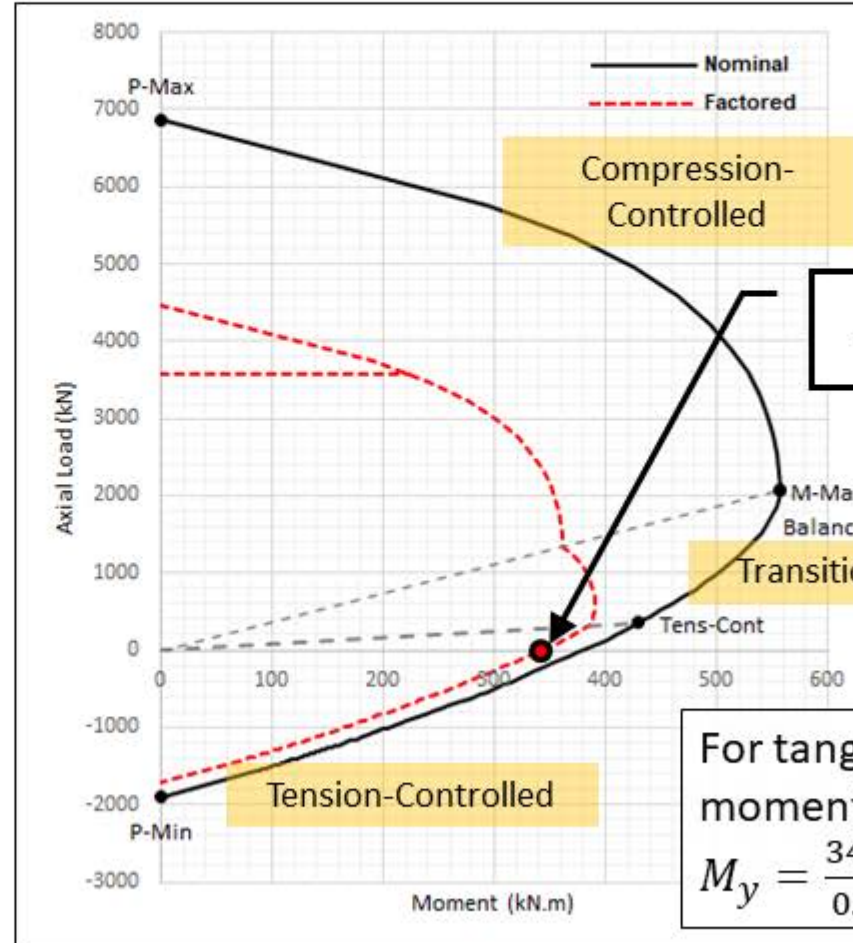
Gravel  $K_z = 0.1$  cm/sec  
Clean Sand  $K_z = 0.01$  cm/sec  
Fine Sand  $K_z = 0.001$  cm/sec  
Silt  $K_z = 10^{-5}$  cm/sec  
Silty Clay  $K_z = 10^{-7}$  cm/sec  
Clay  $K_z = 10^{-8}$  cm/sec

# Wall: Concrete Tangent Pile (1/5)

- **Wall Type:** Tangent Piles.
- **Properties:**
  - Diameter 600 mm.
  - Concrete cover 75 mm.
  - Concrete strength  $f'_c = 21$  MPa.
  - Rebar 16-D19 ( $\rho = 1.6\%$ ).
  - Rebar yield strength  $f_y = 420$  MPa.



- **Conventional Way:** Ask structural engineer to create the P-M diagram\*.



For tangent piles, spaced 600mm, the moment capacity (per m) equals to

$$M_y = \frac{340}{0.6} = 566.67 \text{ kN-m/m}$$

\* Refer to ACI 318 and/or SNI 2847 for details.

# Wall: Concrete Tangent Pile (2/5)

**1. Select Tangent Pile Wall**

**2. Set geometrical properties**

**3. Set material properties**

**Edit Wall Properties**

Wall Sections  
Wall 1

A. Wall Type D. Concrete-Rebar F. Draw

1. Wall Type  
Tangent pile wall with reinforced concrete piles

2. Wall Name  
Wall 1

3. General Section Data

4. Dimensions

5. Structural Materials

6. Pile offset options (double row of piles for soldier piles and tangent pile walls only)

Width d 0.6 m

Hor. Space S 0.6 m

Passive width (below exc.) 0.6 m

Active width (below exc.) 0.6 m

Water width (below exc.) 0.6 m

Pile offset 0 m

Stiffness factor for  $A \times (0.5 \text{ offset})^2$  0 %

Concrete - Rebar Materials

Rebar steel mat.  
Grade 60 Edit

Concrete mat.  
Fc 3kcal Edit

Database Database OK Cancel

Redimension wall automatically

# Wall: Concrete Tangent Pile (3/5)

**Edit Wall Properties**

Wall Sections  
Wall 1

A. Wall Type D. Concrete-Rebar F. Draw

1. Concrete Section Type  
 Use more than one reinforcement sections  Define custom reinforcement

A 28.743 cm<sup>2</sup> b<sub>x</sub> 636172.51 cm<sup>4</sup> **Recalculate b<sub>x</sub> - slice analysis**  
Eff. conc 25 % Used with recal button and for secant piles

3. Longitudinal Reinforcement (Tension - Compression)  
Top Rebars (left side) N 16 Bars # #6 = As<sub>Top</sub> 45.42 cm<sup>2</sup> Top 7.5 cm

4. Shear Reinforcement  
Bar# #5 = As 1.99999 cm<sup>2</sup> sV 15.24 cm  
 Shear reinforcement is spiral Metric Rebars D10 for 10mm Diam  
 Treat wall as slab for shear capacity calculations (diaphragm walls only)

4. Longitudinal reinforcement

5. Shear reinforcement

Deep Excavations Demo

Elevation view  
Shear reinforcement  
Sv 15.24 cm L L D

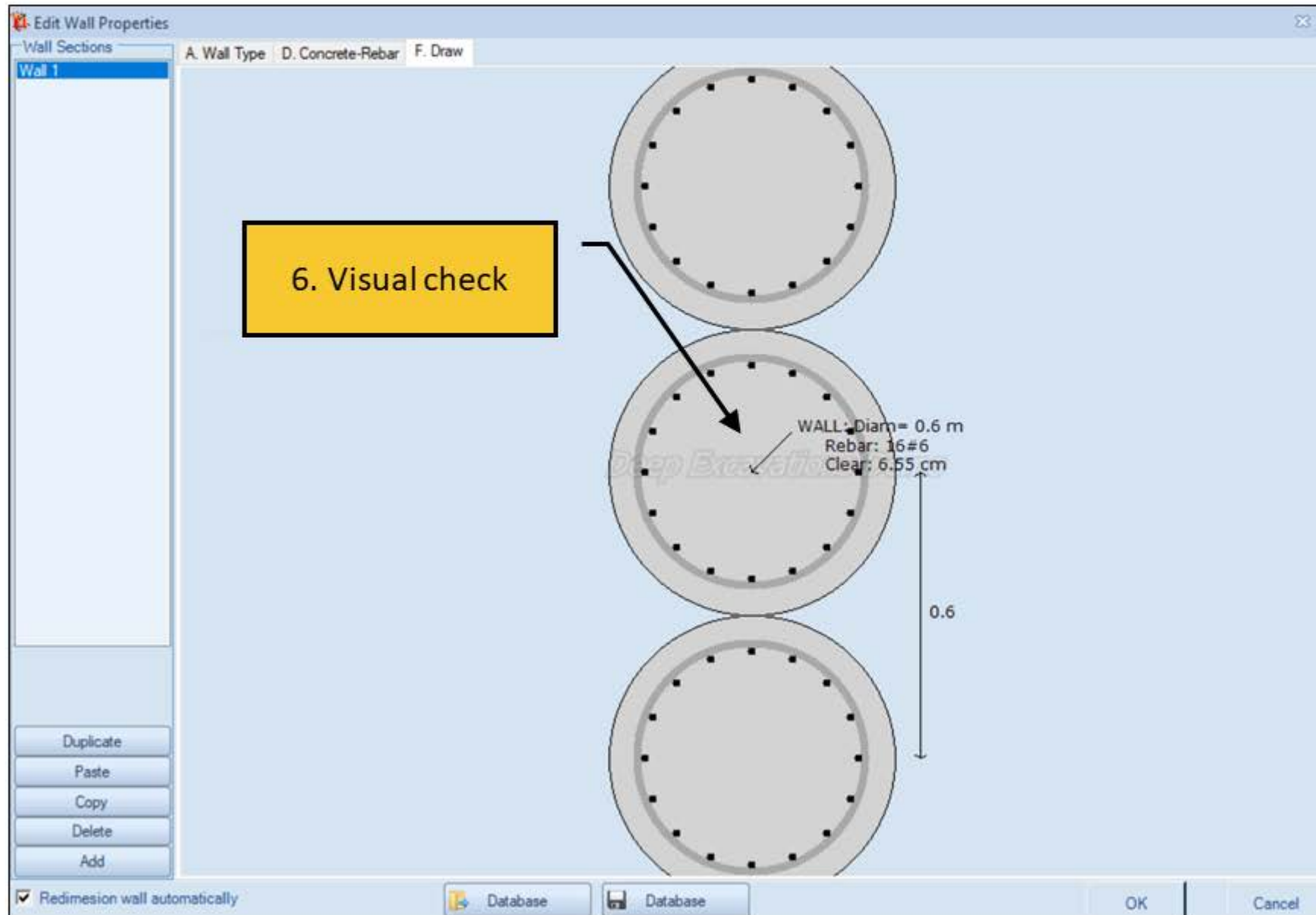
Top view  
Shear reinforcement  
C D

Draw Concrete Section

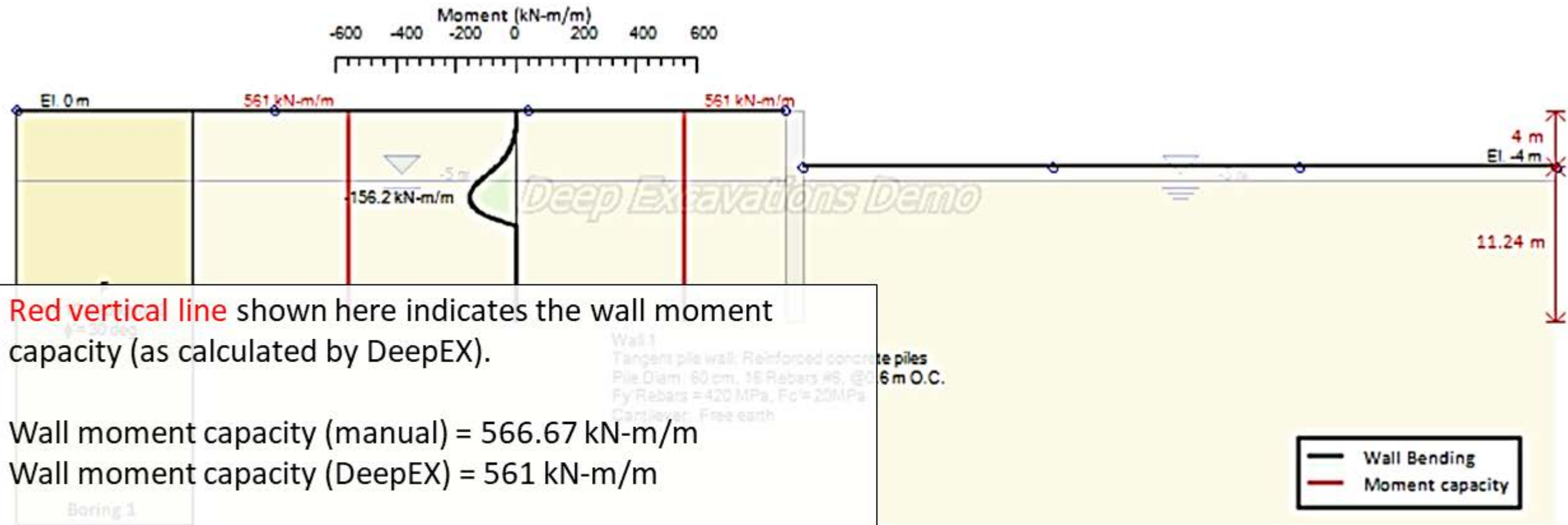
✓ Redimension wall automatically Database Database OK Cancel



# Wall: Concrete Tangent Pile (4/5)

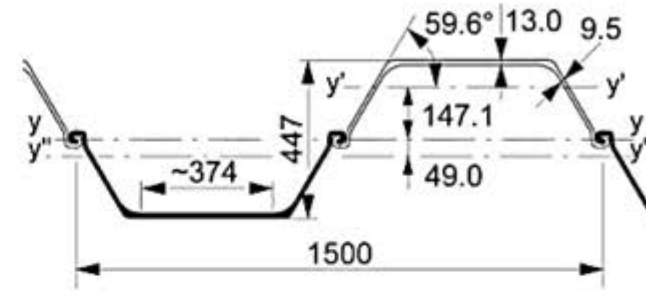


# Wall: Concrete Tangent Pile (5/5)



# Wall: Steel Sheet Pile (1/5)

- **Wall Type:** Steel Sheet Piles.
- **Properties:**
  - Geometry, as shown (A23)\*.
  - Steel Grade A36,  $f_y = 250$  MPa.
- **Conventional Way:** Manual calculation as per referred standard (e.g. AISC 360).



1. Assume  $Z_x = S_x$  (conservative).

$$Z_x = \frac{I_{xx}}{y} = \frac{50700}{44.7/2} = 2268.46 \text{ cm}^3/\text{m}$$

2. Calculate nominal capacity:

$$M_n = F_y Z_x = \frac{250(2268.46)}{10^3} = 567.11 \text{ kN-m}$$

3. Calculate factored capacity

$$\frac{M_n}{\Omega_b} = \frac{1}{1.67} (567.11) = 339.59 \text{ kN-m}$$

- Note:  $\Omega_b$  is the safety factor for flexure.

## AU 23

	A	G	$I_y$	$W_{el,y}$	$r_g$	$A_L$
	cm <sup>2</sup>	kg/m	cm <sup>4</sup>	cm <sup>3</sup>	cm	m <sup>2</sup> /m
<b>Per S</b>	130.1	102.1	9 830	579	8.69	1.03
<b>Per D</b>	260.1	204.2	76 050	3 405	17.10	2.04
<b>Per T</b>	390.2	306.3	104 680	3 840	16.38	3.05
<b>Per m of wall</b>	173.4	136.1	50 700	2 270	17.10	1.36

A	Sectional area
G	Mass per meter
$I_y$	Moment of inertia about the main neutral axis y-y
$W_{el,y}$	Elastic section modulus
$r_g$	Radius of gyration about the y-y axis
$A_L$	Coating area. One side, excludes inside of interlocks
S	Single pile: considered neutral axis y'-y'
D	Double pile, wall: considered neutral axis y-y
T	Triple pile: considered neutral axis y''-y''

\* Link: <https://sheetpiling.arcelormittal.com/products/au-23-3/>

# Wall: Steel Sheet Pile (2/5)

**1. Select Steel Sheet Pile Wall**

**2. Set geometrical properties**

**3. Set material properties**

1. Wall Type: Steel sheet pile wall

2. Wall Name: Wall 1

3. General Section Data

Sheet Piles: AU23

4. Dimensions

Width d	0.45	m
Hor. Space S	1	m
Passive width (below exc.)	1	m
Active width (below exc.)	1	m
Water width (below exc.)	1	m

5. Structural Materials

Steel Beam Materials: A36

Buttons: Duplicate, Paste, Copy, Delete, Add, Database, Database, OK, Cancel

# Wall: Steel Sheet Pile (3/5)

Edit Wall Properties

Wall Sections  
Wall 1

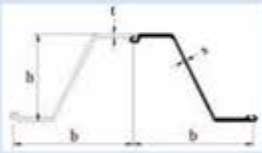
A. Wall Type C. Sheet Piles F. Draw

1. Section Designation (from database)  
Section AU23

2. Sheet pile properties

h	44.7	cm	A	173	cm <sup>2</sup> /m	Interlock type	DH	Select Interlock type
b	75	cm	t <sub>f</sub>	1.3	cm			
I <sub>xx</sub>	50700	cm <sup>4</sup> /m	s	0.95	cm			
S <sub>xx</sub>	2270	cm <sup>3</sup> /m	α	45	degrees			

Unsupported Length L<sub>x</sub>  
factor below excavation 5 x wall Width



MANUFACTURER: ArcelorMittal, LuxembourgLuxembourg. SHAPE: U  
HOT/COLD ROLLED: HR

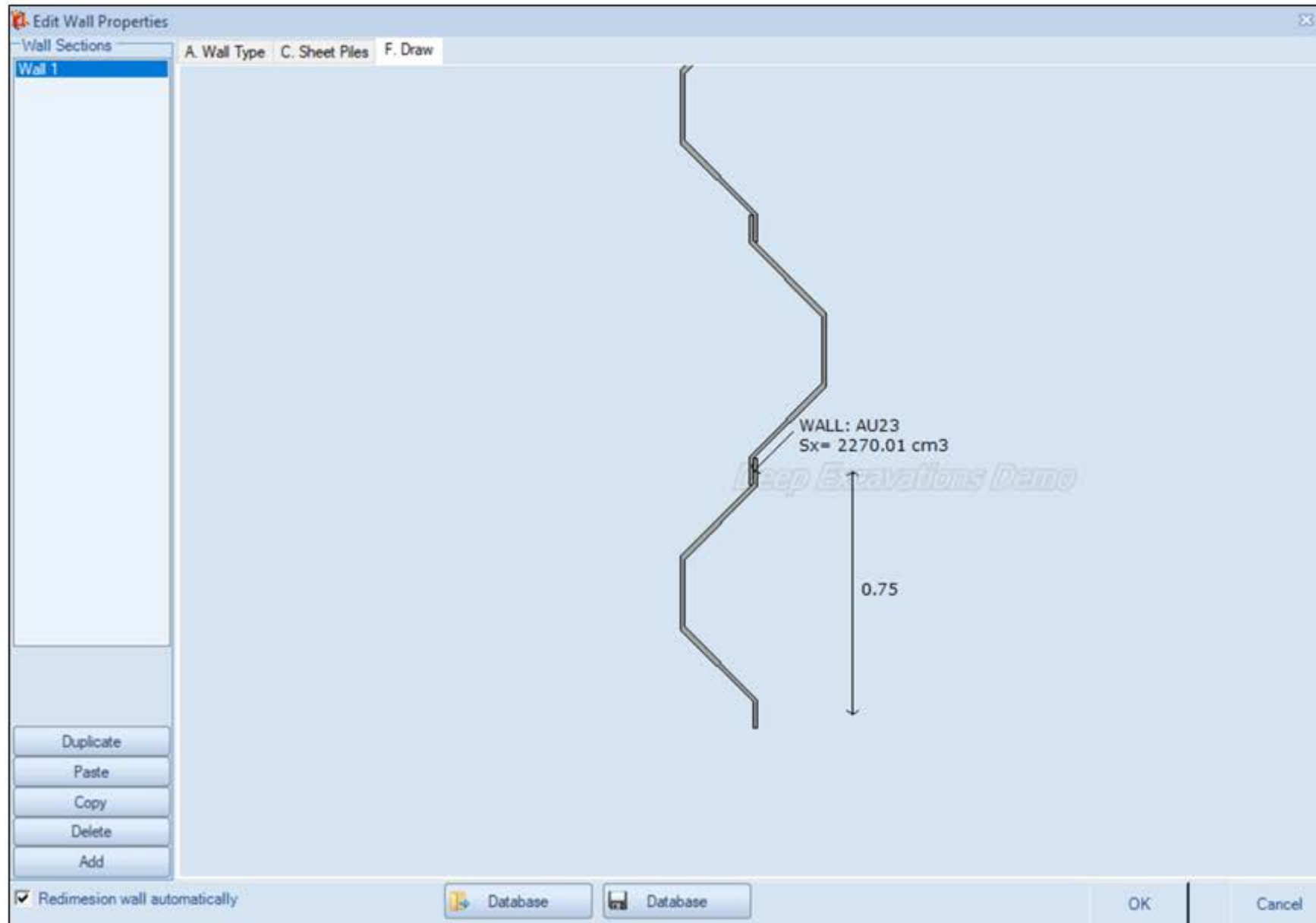
Deep Excavations Demo

4. Detail Properties

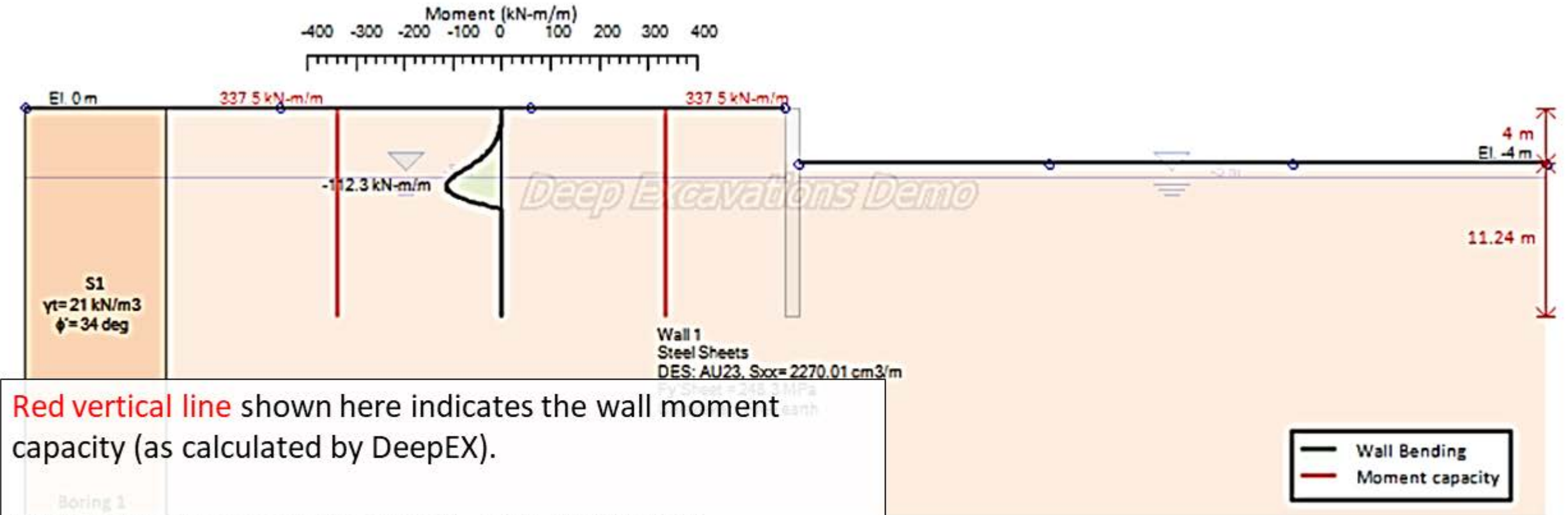
Duplicate  
Paste  
Copy  
Delete  
Add

Redimension wall automatically Database Database OK Cancel

# Wall: Steel Sheet Pile (4/5)



# Wall: Steel Sheet Pile (5/5)



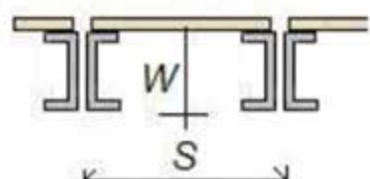
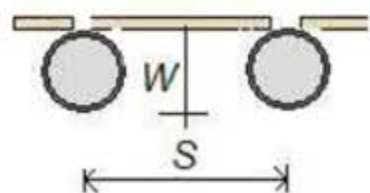
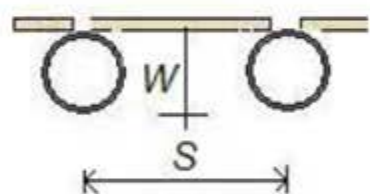
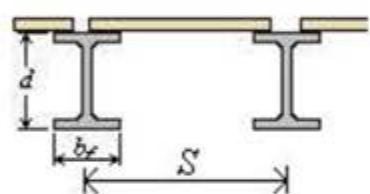
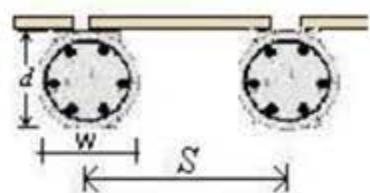
Wall moment capacity (manual) = 339.59 kN-m/m

Wall moment capacity (DeepEX) = 337.5 kN-m/m

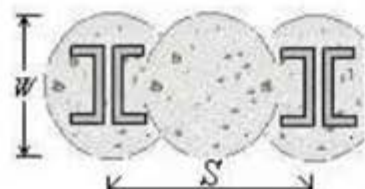
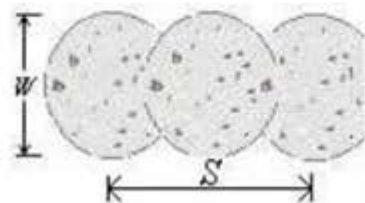
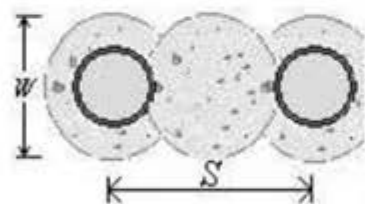
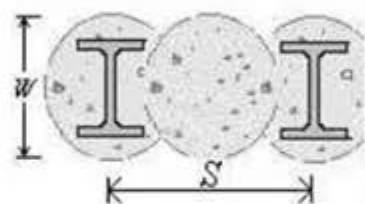
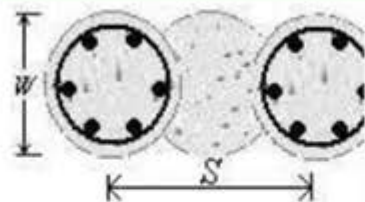
Results are in good agreement !!

# Other Wall Types

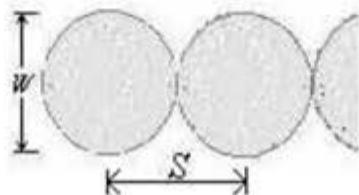
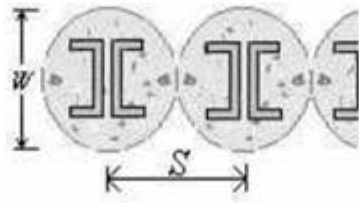
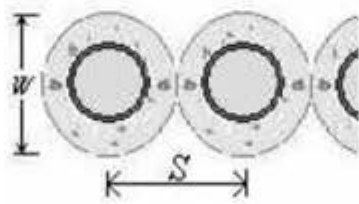
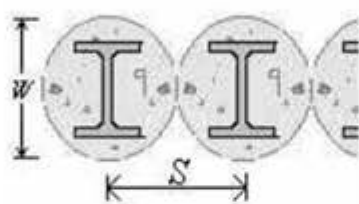
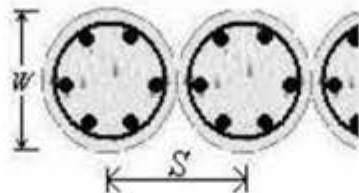
## Soldier Pile



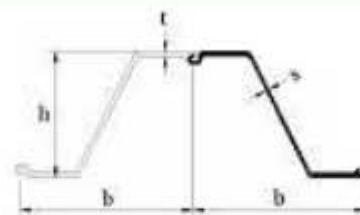
## Secant Pile



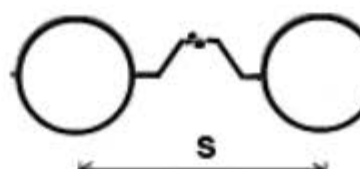
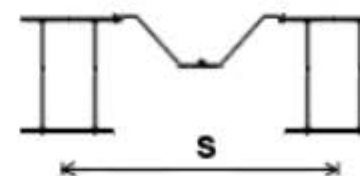
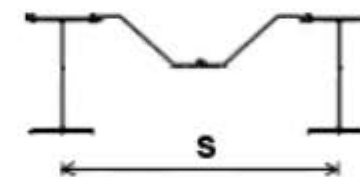
## Tangent Pile



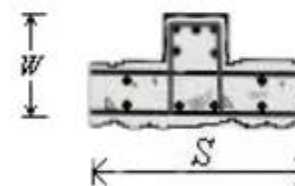
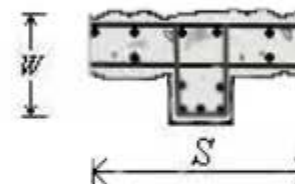
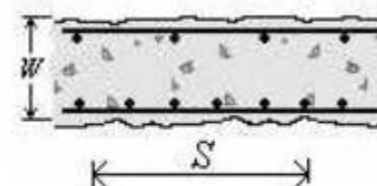
## Sheet Pile



### Wooden Sheet Piles



## Diaphragm Wall





# Support: Strut (1/5)

- **Support Type:** Steel Strut.
- **Properties:**
  - Geometry, as shown (W30x99).
  - Steel Grade A50,  $f_y = 344.74$  MPa.
  - Unbraced length  $\approx 15$ m.
  - Horizontal spacing = 5m.
- **Conventional Way:** Manual calculation as per referred standard (e.g. AISC 360).

Strut Properties

1. Name: W30x99

2. Section Type

- Use a steel I-Section (W30x99)
- Use a pipe section
- Use hollow sections

Section Rotation

- Flat
- Vertical

Double member options

- Single member
- Double member

Steel material: A50

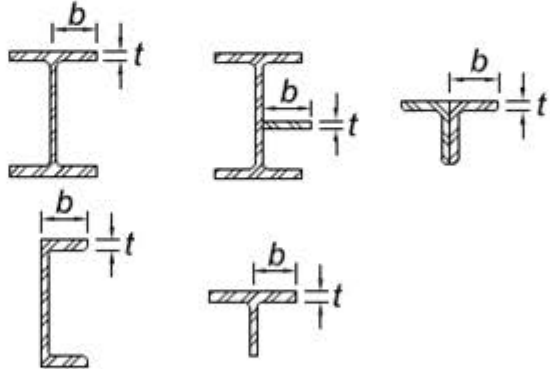
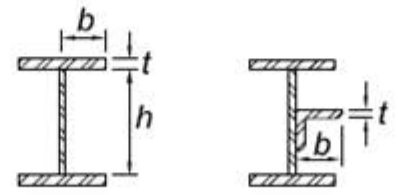
Model strut section as non-yielding (in nonlinear analysis)

Edit strut properties manually

3. Section Dimensions - Mechanical Properties

D	75.438	cm	A	187.74	cm <sup>2</sup>	f <sub>y</sub>	344.8	MPa	E	200100	MPa	r <sub>x</sub>	29.718	cm
b <sub>f</sub>	26.67	cm	t <sub>f</sub>	1.702	cm	t <sub>w</sub>	1.321	cm	k	3.353	cm	r <sub>y</sub>	5.334	cm
I <sub>xx</sub>	166076.0	cm <sup>4</sup>	I <sub>yy</sub>	5327.8	cm <sup>4</sup>	J	156.9	cm <sup>4</sup>	W	1.44	kN/m	r <sub>T</sub>	6.528	cm
S <sub>xx</sub>	4408.1	cm <sup>3</sup>	S <sub>yy</sub>	401.5	cm <sup>3</sup>	Z <sub>xx</sub>	5112.8	cm <sup>3</sup>	Z <sub>yy</sub>	632.5	cm <sup>3</sup>	C <sub>w</sub>	7196761	cm <sup>6</sup>

# Support: Strut (2/5)

<b>TABLE B4.1a</b> <b>Width-to-Thickness Ratios: Compression Elements</b> <b>Members Subject to Axial Compression</b>					
Case	Description of Element	Width-to-Thickness Ratio	Limiting Width-to-Thickness Ratio $\lambda_r$ (nonslender/slender)	Examples	
Slender Elements	1	Flanges of rolled I-shaped sections, plates projecting from rolled I-shaped sections, outstanding legs of pairs of angles connected with continuous contact, flanges of channels, and flanges of tees	$b/t$	$0.56 \sqrt{\frac{E}{F_y}}$	
	2	Flanges of built-up I-shaped sections and plates or angle legs projecting from built-up I-shaped sections	$b/t$	$0.64 \sqrt{\frac{k_c E}{F_y}}$ [a]	

Strut design starts with determining the section classification (non-slender/slender), figure from AISC 360.

# Support: Strut (3/5)

## E3. FLEXURAL BUCKLING OF MEMBERS WITHOUT SLENDER ELEMENTS

This section applies to nonslender-element compression members, as defined in Section B4.1, for elements in axial compression.

**User Note:** When the torsional effective length is larger than the lateral effective length, Section E4 may control the design of wide-flange and similarly shaped columns.

The nominal compressive strength,  $P_n$ , shall be determined based on the limit state of flexural buckling:

$$P_n = F_{cr} A_g \quad (\text{E3-1})$$

The critical stress,  $F_{cr}$ , is determined as follows:

$$\text{(a) When } \frac{L_c}{r} \leq 4.71 \sqrt{\frac{E}{F_y}} \quad \left(\text{or } \frac{F_y}{F_e} \leq 2.25\right)$$

$$F_{cr} = \left(0.658 \frac{F_y}{F_e}\right) F_y \quad (\text{E3-2})$$

$$\text{(b) When } \frac{L_c}{r} > 4.71 \sqrt{\frac{E}{F_y}} \quad \left(\text{or } \frac{F_y}{F_e} > 2.25\right)$$

$$F_{cr} = 0.877 F_e \quad (\text{E3-3})$$

where

$A_g$  = gross cross-sectional area of member, in.<sup>2</sup> (mm<sup>2</sup>)

$E$  = modulus of elasticity of steel = 29,000 ksi (200 000 MPa)

$F_e$  = elastic buckling stress determined according to Equation E3-4, as specified in Appendix 7, Section 7.2.3(b), or through an elastic buckling analysis, as applicable, ksi (MPa)

$$F_e = \frac{\pi^2 E}{\left(\frac{L_c}{r}\right)^2} \quad (\text{E3-4})$$

$F_y$  = specified minimum yield stress of the type of steel being used, ksi (MPa)

$r$  = radius of gyration, in. (mm)

**User Note:** The two inequalities for calculating the limits of applicability of Sections E3(a) and E3(b), one based on  $L_c/r$  and one based on  $F_y/F_e$ , provide the same result for flexural buckling.

## E4. TORSIONAL AND FLEXURAL-TORSIONAL BUCKLING OF SINGLE ANGLES AND MEMBERS WITHOUT SLENDER ELEMENTS

This section applies to singly symmetric and unsymmetric members, certain doubly symmetric members, such as cruciform or built-up members, and doubly symmetric members when the torsional unbraced length exceeds the lateral unbraced length, all without slender elements. These provisions also apply to single angles with  $b/t > 0.71 \sqrt{E/F_y}$ , where  $b$  is the width of the longest leg and  $t$  is the thickness.

The nominal compressive strength,  $P_n$ , shall be determined based on the limit states of torsional and flexural-torsional buckling:

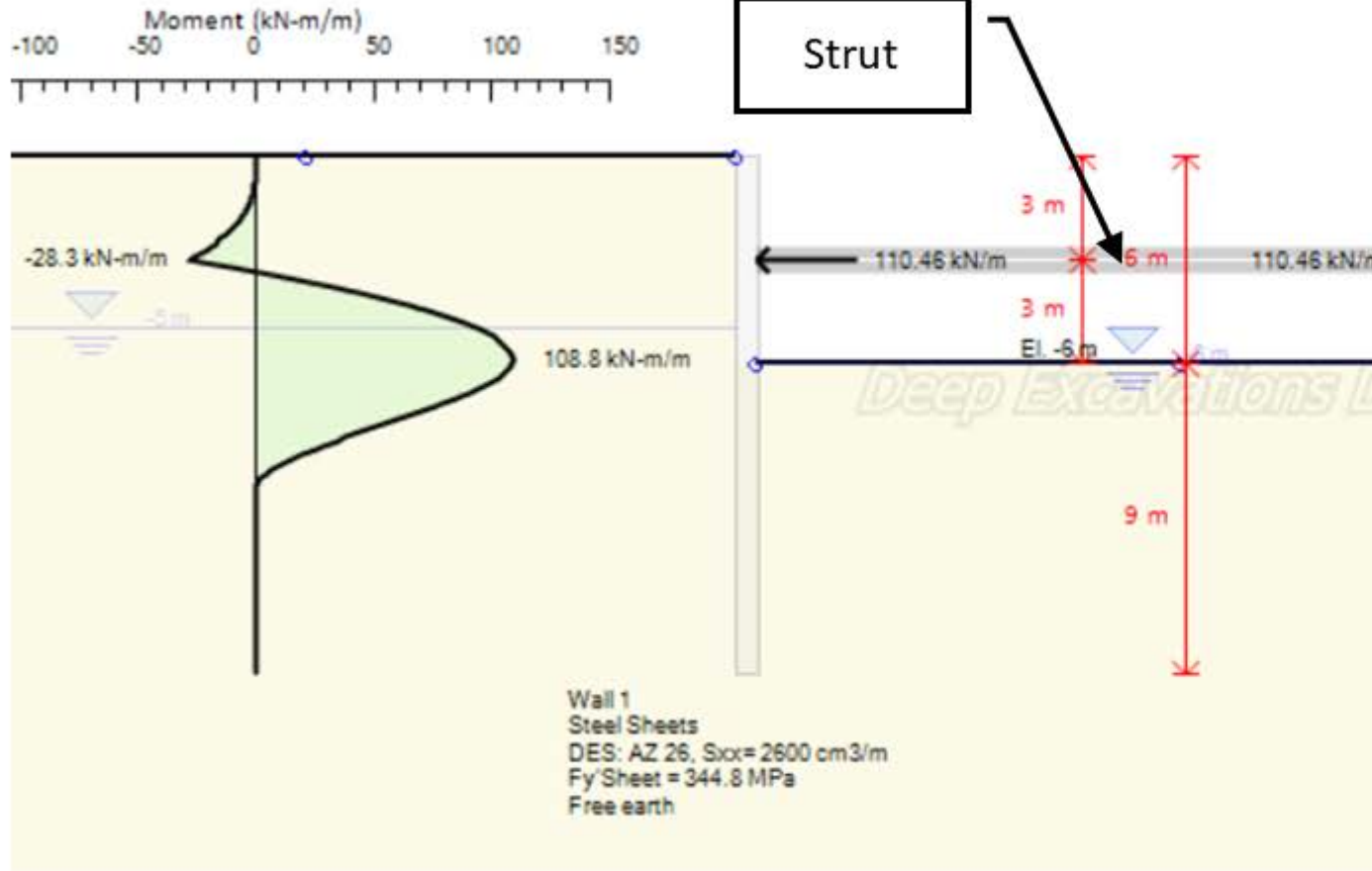
$$P_n = F_{cr} A_g \quad (\text{E4-1})$$

The critical stress,  $F_{cr}$ , shall be determined according to Equation E3-2 or E3-3, using the torsional or flexural-torsional elastic buckling stress,  $F_e$ , determined as follows:

(a) For doubly symmetric members twisting about the shear center

$$F_e = \left( \frac{\pi^2 E C_w}{L_c^2} + GJ \right) \frac{1}{I_x + I_y} \quad (\text{E4-2})$$

# Support: Strut (4/5)



The screenshot shows the "Edit Support Data" dialog box for a strut. The "Strut Arrangement" section is highlighted in yellow. The "1.1 Coordinates at Wall" section shows X: 0.427 m and Z: -3 m. The "1.2 Angles" section shows  $\alpha$ : 180 deg. The "1.3 Lengths" section shows Lfree: 14.573 m and Horizontal Spacing: 5 m. The "2. Support Type and Structural Section Used" section shows Structural Section: W30x99. The "2. Unbraced Lengths Options" section shows "Use user-defined unbraced lengths" checked, with Horizontal Unbraced Length LuH: 0 m and Vertical Unbraced Length LuV: 0 m. The "3. Activate/Deactivate Support - Permanent or Temporary" section shows "Activate support for this stage" checked and "Temporary support" selected. The "Nonlinear Behaviour" section shows "Linear elastic". The "Wall Index" is 0, End: 1. The "Show full calculations" button is visible. The "OK" and "Cancel" buttons are at the bottom right.

Apply Prestress

Horizontal Spacing

Unbraced Length

# Support: Strut (5/5)

The screenshot displays a software window titled "Edit Support Data, Stage: 0" with a yellow highlight on the "Strut Load and Capacity" section. The main window shows a "Results" tab with the following data:

- Force: 110.5 kN/m
- Moment M: 38.2 kN-m

Below this, there are two panels for capacity checks:

- 2. Support Structural - Geotechnical Checks**
  - Stress Check = 2.347
  - Calculated Axial Support Capacities**
    - Pall = 258.4 kN
    - Pult = 388.4 kN
- 3.1 Geotechnical Capacity**
  - Pall = N/A kN
  - Pult = N/A kN
- 3.2 Structural Capacity**
  - Pall = 258.4 kN
  - Pult = 388.4 kN
  - MxAll = 182.3 kN-m
  - MxUlt = 274.1 kN-m
  - MyAll = 104 kN-m
  - MyUlt = 156.3 kN-m
  - Used FS STR = 1

A red dashed line connects the "Strut Load and Capacity" section to the "Calculated Axial Support Capacities" section. A red box highlights the "3.2 Structural Capacity" section in the main window, which is also shown in a larger inset window on the right. The inset window shows the same data as the main window, with the "Pult = 388.4 kN" value highlighted in yellow.

Strut axial capacity (manual) = 390.86 kN (details not shown)  
Strut axial capacity (DeepEX) = 388 kN  
Results are in good agreement !!

# Support: Ground Anchor (1/6)

- **Support Type:** Ground Anchor.
- **Properties:**
  - Fixed Length = 5m; Free Length = 5 m.
  - Orientation = 45°.
  - 4-Strand Tendon 270ksi,  $f_y = 1862$  MPa.
  - Anchor diameter = 15 cm.
  - Horizontal spacing = 3 m.
- **Bond Resistance:** Manually calculated (e.g. refer SNI 8460).
- **Remarks:** Prestressing force of 75%-100% anchor force shall be applied (to avoid excessive deflection).

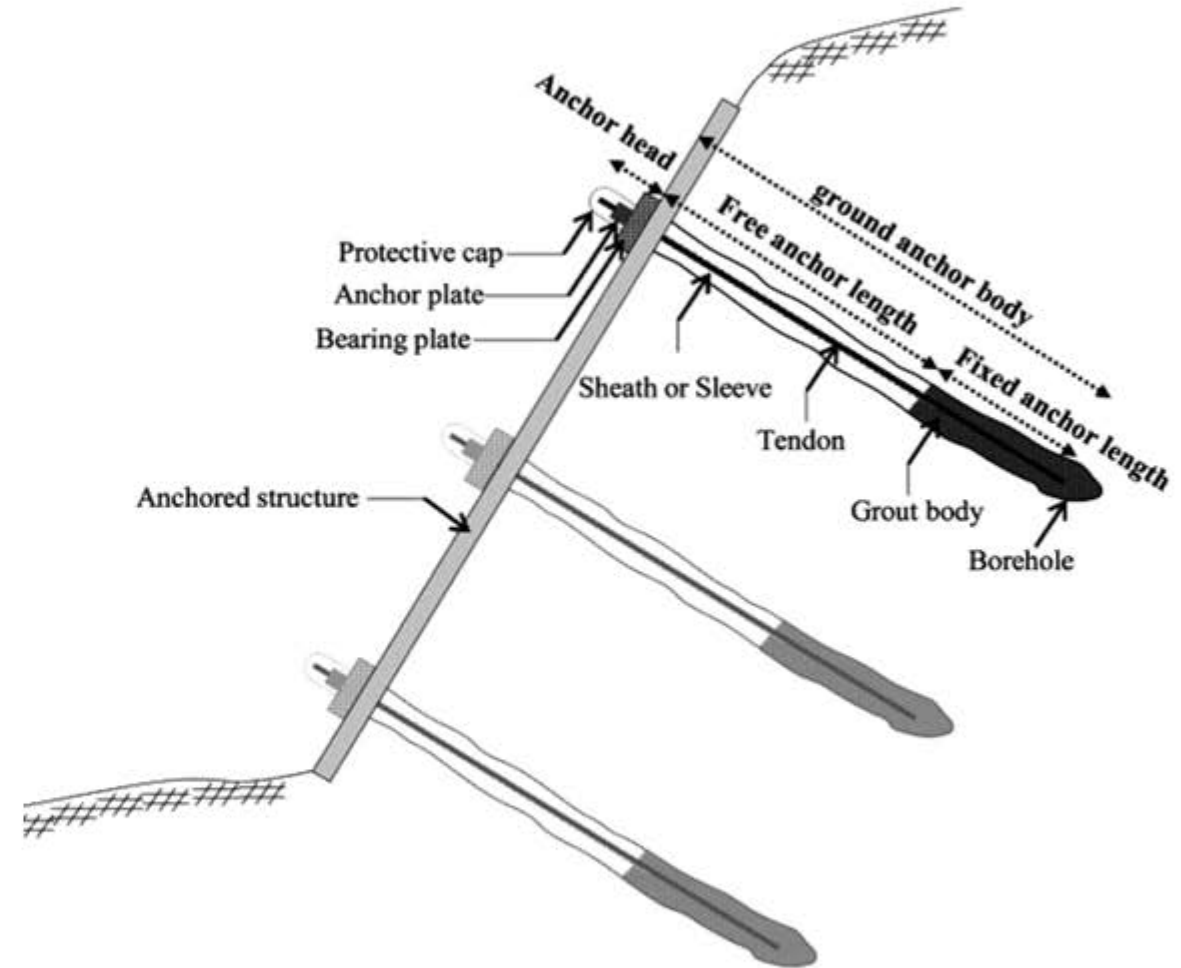
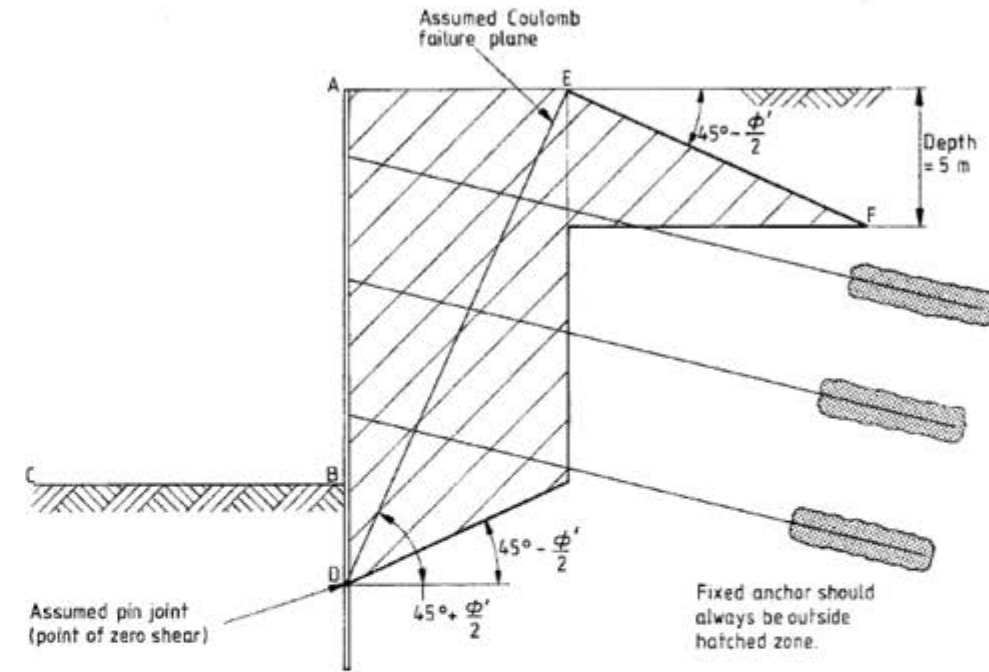


Illustration of Ground Anchors

# Support: Ground Anchor (2/6)

- Fixed length requirements:
  - At least 5m below the ground.
  - Located outside the failure surface.
  - Embedded in N-SPT  $\geq 25$  (non-cohesive) and N-SPT  $\geq 20$  (cohesive).
- Geometry recommendations:
  - Spacing  $\geq 1.5\text{m}$  for anchor with  $D \leq 20\text{ cm}$  (to avoid group effect).
  - Anchor angle between  $30^\circ$ - $45^\circ$ .
- Length requirements:
  - Free Length (Min): 3.0m (bar tendon) and 4.5m (strand tendon).
  - Fixed Length (Min): 3.0m.
  - Fixed Length (Max): 13.0m (unless proved from pullout test).
- SF requirements:

Category	Tendon (STR)	Interface (GEO)
Temporary (<6 months)	1.4	2.0
Temporary (<24 months)	1.6	2.5
Permanent or when in corrosive environment	2.0	3.0



Location of anchor fixed length (BS-8081)

# Support: Ground Anchor (3/6)

- Anchor capacity in cohesive soil:

$$R_{ult} = \alpha A_s L_s S_{u,avg} = q_{ult} A_s L_s$$

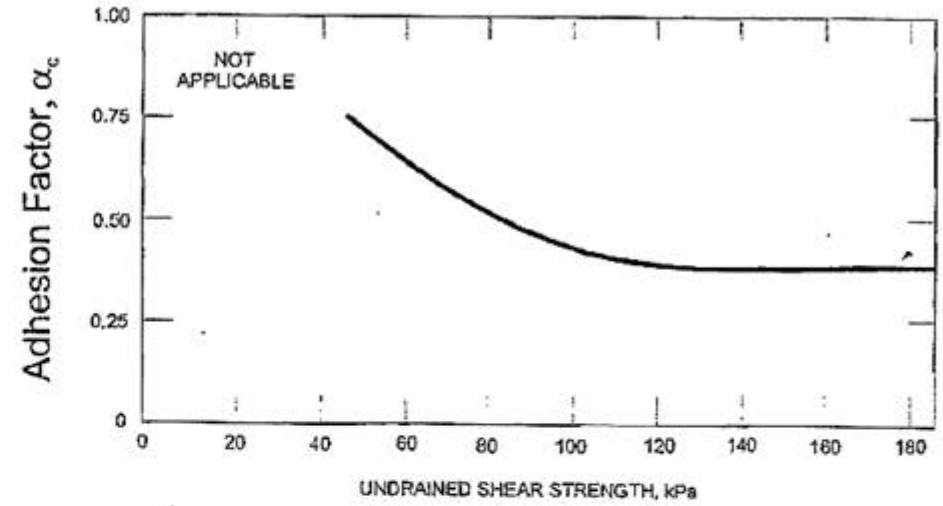
- Anchor capacity in non-cohesive soil:

$$R_{ult} = \sigma'_v A_s L_s K_s = q_{ult} A_s L_s$$

- Where:

- $R_{ult}$  = Ground anchor ultimate capacity.
- $q_{ult}$  = Ultimate skin friction capacity.
- $A_s$  = Unit shaft area.
- $L_s$  = Fixed length.
- $S_{u,avg}$  = Avg. undrained shear strength along fixed length.
- $\alpha$  = Adhesion factor.
- $\sigma'_v$  = Eff. ver. stress at mid-part of fixed length.
- $K_s$  = Anchor coefficient.

For example, assuming cohesive soil with  $S_{u,avg} = 180$  kPa and  $\alpha = 0.35 \rightarrow q_{ult} = 63$  kPa.



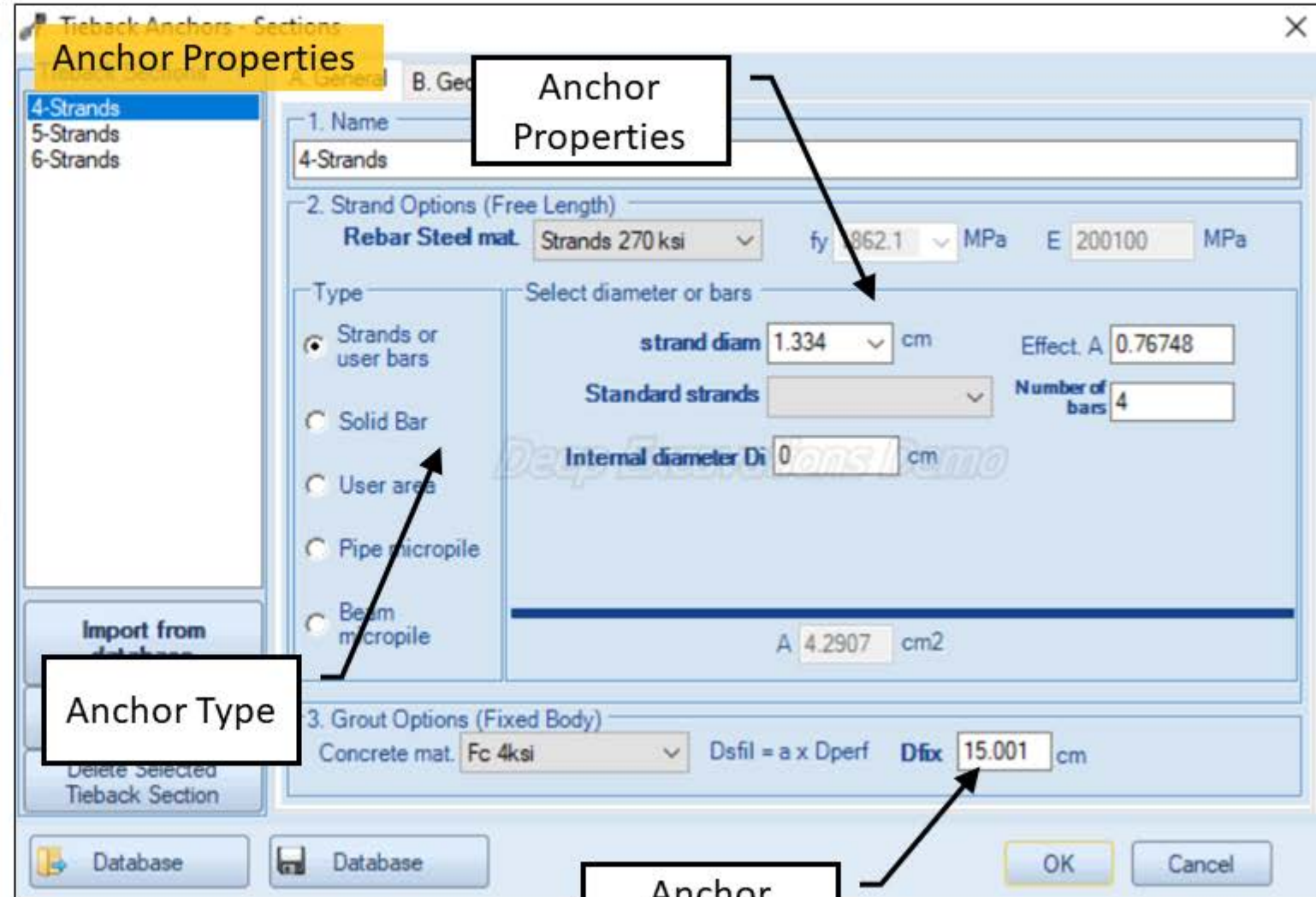
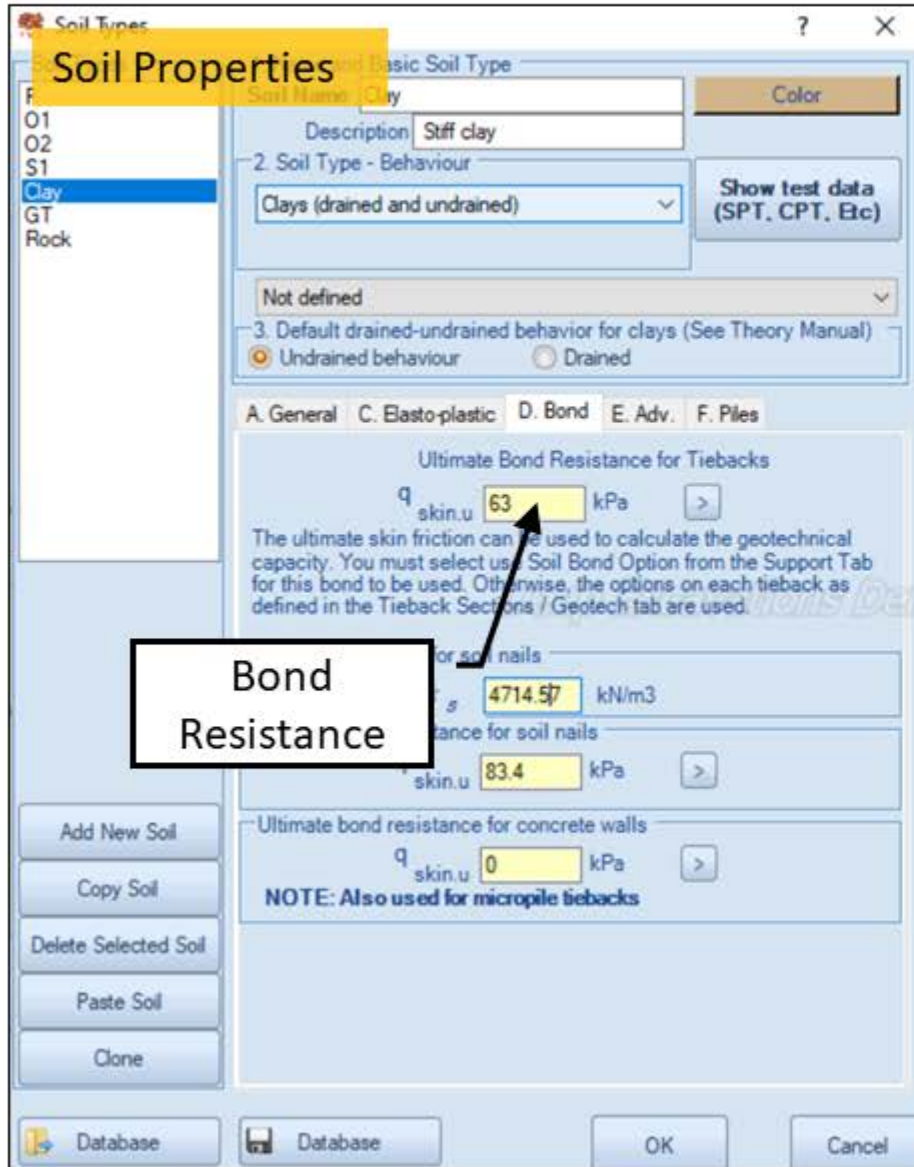
Adhesion Factor\*

Category	Loose	Compact	Dense
Non-Plastic Silt	0.1	0.4	1.0
Fine Sand	0.2	0.6	1.5
Medium Sand	0.5	1.2	2.0
Coarse Sand	1.0	2.0	3.0

Anchor Coefficient



# Support: Ground Anchor (4/6)



# Support: Ground Anchor (5/6)

The diagram illustrates a ground anchor system for a retaining wall. The wall is divided into a 'Drive' section (left) and a 'Resist' section (right). The 'Drive' section is shown with a water table at -5m and two ground anchors installed at a 45-degree angle. The 'Resist' section is a vertical wall. The soil properties are defined as  $K_a C_v H = 0.333$  and  $K_p C_v H = 3$  for both sections. The wall is labeled 'Wall 1 Steel Sheets' with a design of 'DES: AZ 26,  $S_{xxx} = 2600 \text{ cm}^3/\text{m}$ ' and a yield strength of  $F_y \text{ Sheet} = 344.8 \text{ MPa}$ .

The software interface, 'Edit Support Data, Stage: 0', shows the configuration for an 'Anchor Arrangement'. The parameters are as follows:

- 1.1 Lengths:  $R = 0.427 \text{ m}$ ,  $Z = -6 \text{ m}$
- 1.2 Angles:  $\alpha = 45 \text{ deg}$
- 1.3 Lengths:  $L_{\text{free}} = 5 \text{ m}$ ,  $L_{\text{fix}} = 5 \text{ m}$ , Effective  $L_{\text{fix}} = 50\% \text{ } L_{\text{fix}}$ , Horizontal Spacing =  $3 \text{ m}$
- 1.4 Prestress options:  Adjust Support Prestress,  $0 \text{ kN}$
- Section Used: Structural Section 4-Strands
- 3. Activate/Deactivate Support - Permanent or Temporary:  Activate support for this stage, Temporary support
- Nonlinear Behaviour: Linear elastic

Callouts in the image point to the following elements:

- Ground Anchor (pointing to the anchors in the diagram)
- Free and Fixed Length (pointing to  $L_{\text{free}}$  and  $L_{\text{fix}}$  in the software)
- Horizontal Spacing (pointing to the Horizontal Spacing field in the software)
- Prestress Load (pointing to the Prestress Load field in the software)

# Support: Ground Anchor (6/6)

The screenshot shows a software interface for editing support data. The main window is titled 'Edit Support Data, Stage: 0' and has a yellow header 'Anchor Load and Capacity'. Below the header, there are fields for 'kN = -0.9 kN/m' and 'Moment M = 0 kN-m'. A section titled '2. Support Structural - Geotechnical Checks' includes a 'Stress Check = 0.037' field. Below this is a table of 'Calculated Axial Support Capacities':

Capacity Type	Value
Pull	74.2 kN
Pult	148.5 kN

Section 3.1 'Geotechnical Capacity' shows 'Pull = 74.2 kN' and 'Pult = 148.5 kN', with a 'Used FS Pullout = 2' field. Section 3.2 'Structural Capacity' shows 'Pull = 479.4 kN' and 'Pult = 719.2 kN'. At the bottom, there are calculation formulas: 'From qSkin.ultimate each soil type, Pall geo = Pult\_GEO / FS\_GeoUser x FS\_GeoBond.Code = 148.45/(2 x 1) = 74.225 kN' and 'Pdes.str = STR.des x As x Fy = 0.6 x 4.2907 x 1862.1 = 479.38 kN'. The bottom of the dialog has 'Wall Index: 0, End: -1', 'Show full calculations', 'OK', and 'Cancel' buttons.

Bond ult. capacity (manual) =  $63 \text{ kPa} (\pi D) (5) = 148.4 \text{ kN}$   
Bond ult. capacity (DeepEX) = 148.5

Tendon ult. capacity:

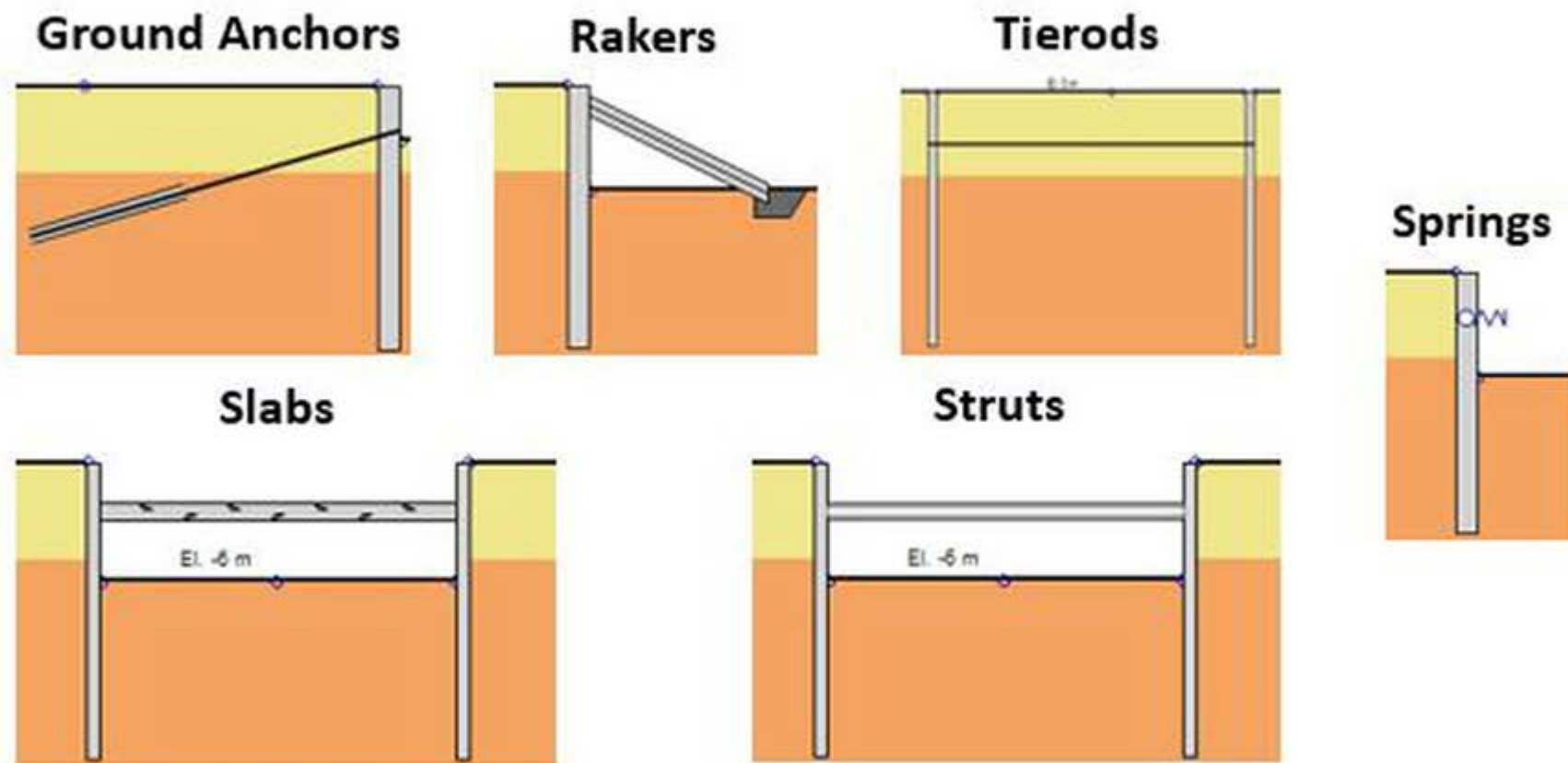
$$P_{ult} = \alpha A f_y = 0.6(798.97) = 479.38 \text{ kN}$$

Bond  
Strength

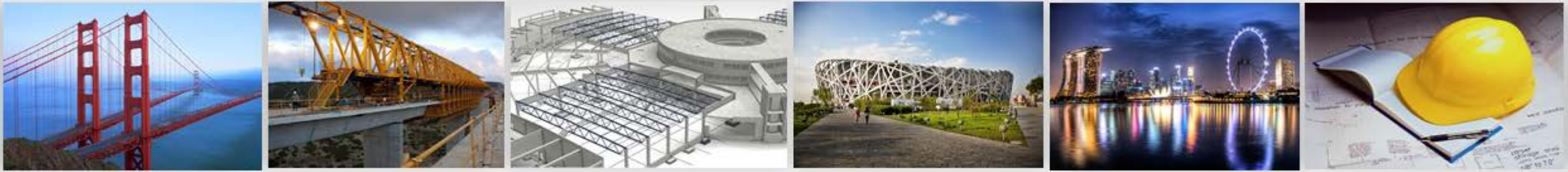
Tendon  
Strength

# Other Support Types

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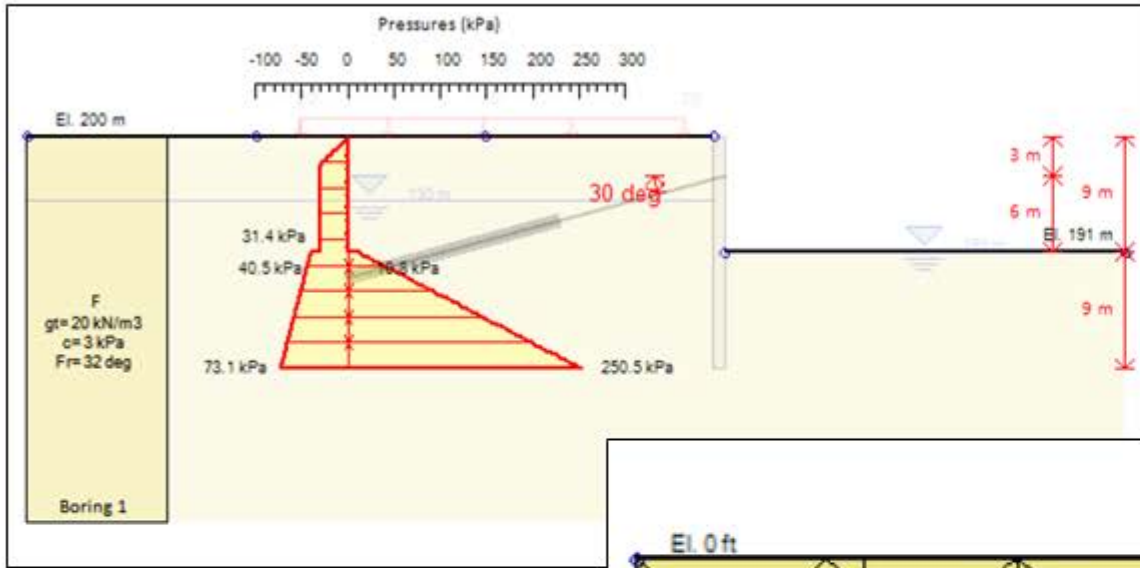
# Effective Deep Excavation Analysis and Design



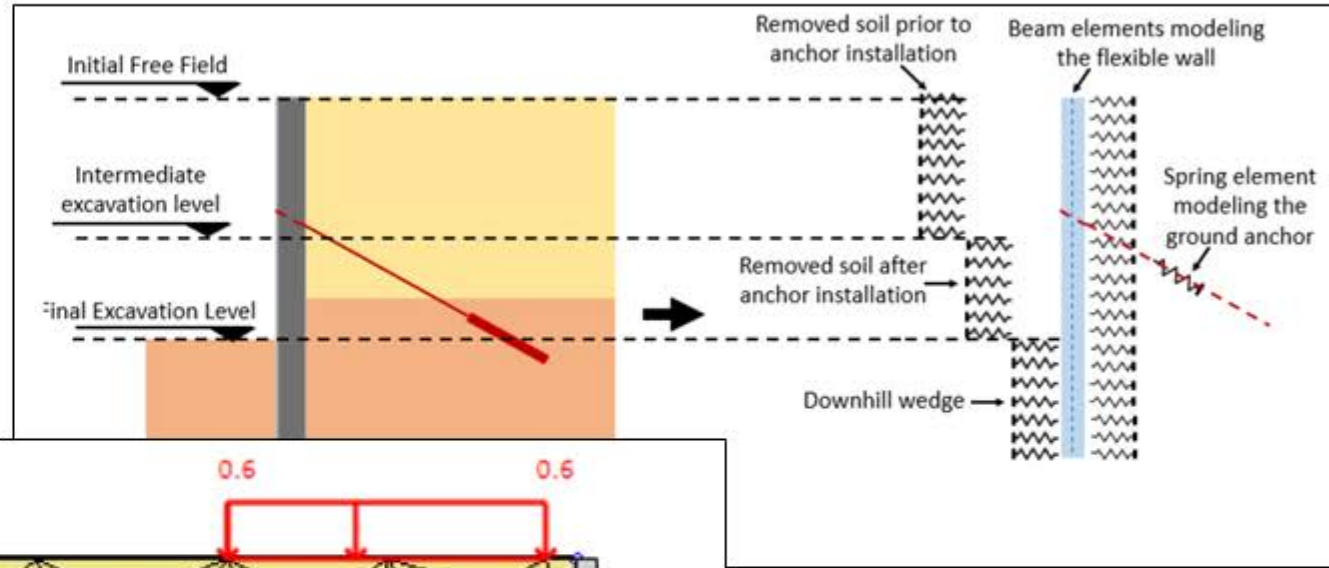
## LEM Approaches and Design Check



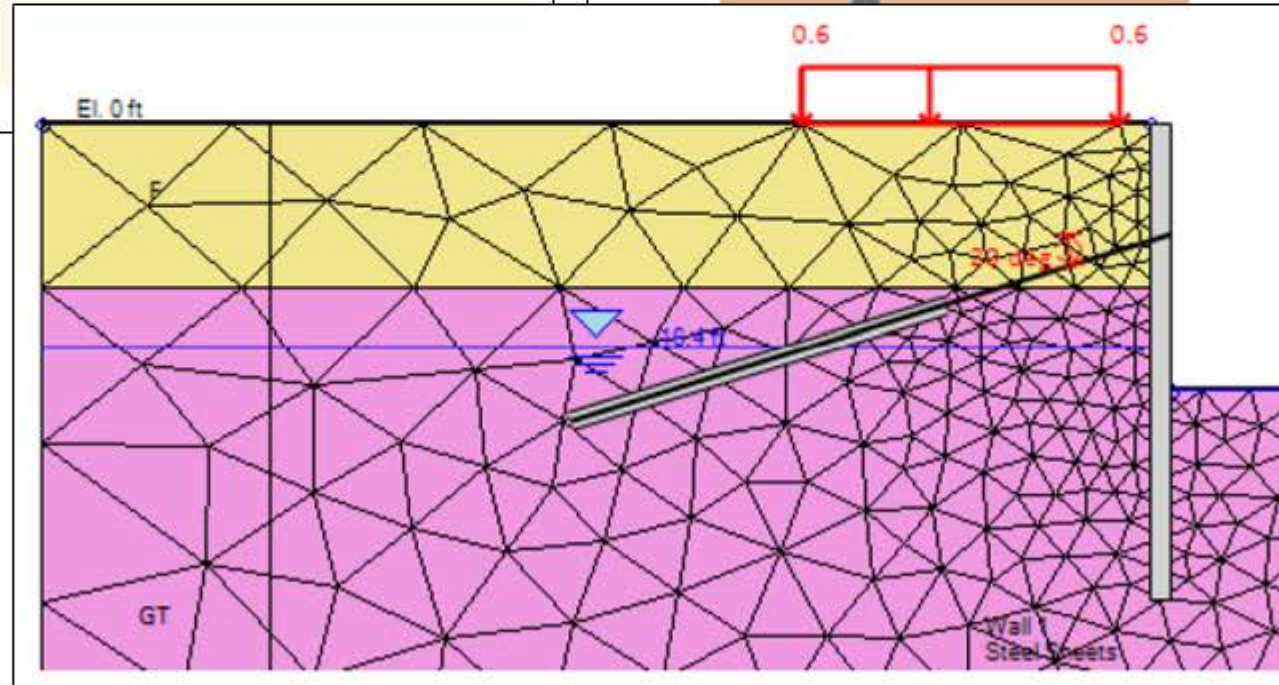
# Modeling Approaches



Limit Equilibrium Method



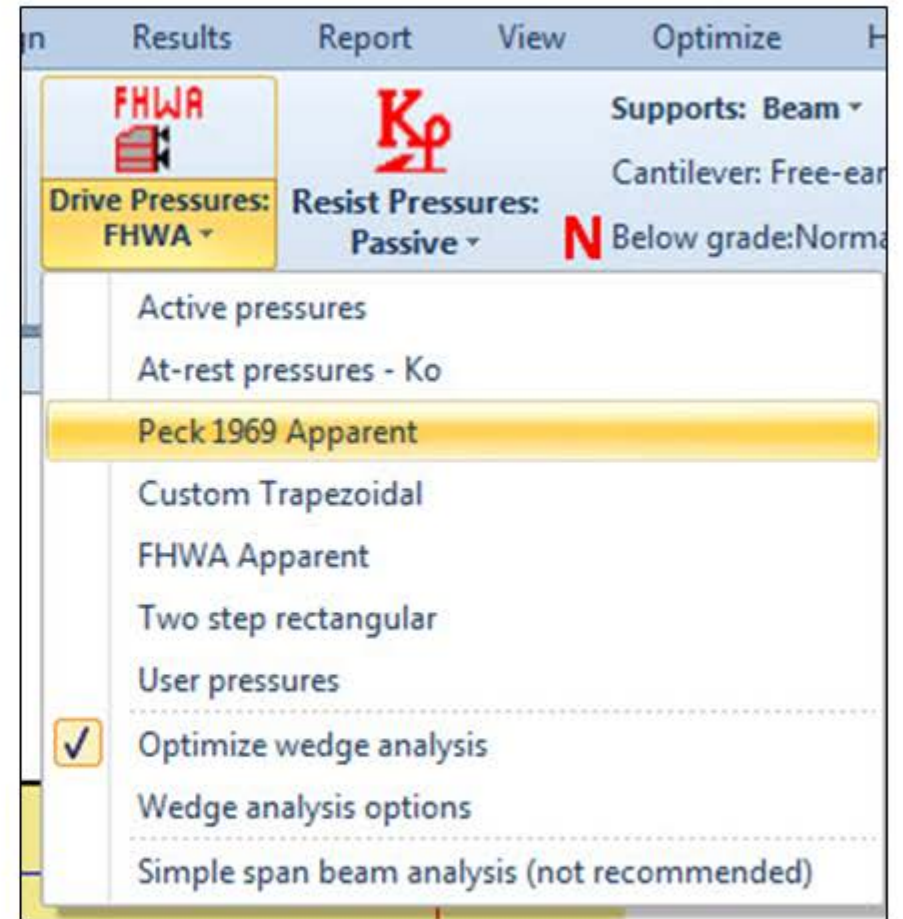
Non-Linear Springs Method



Finite Element Method

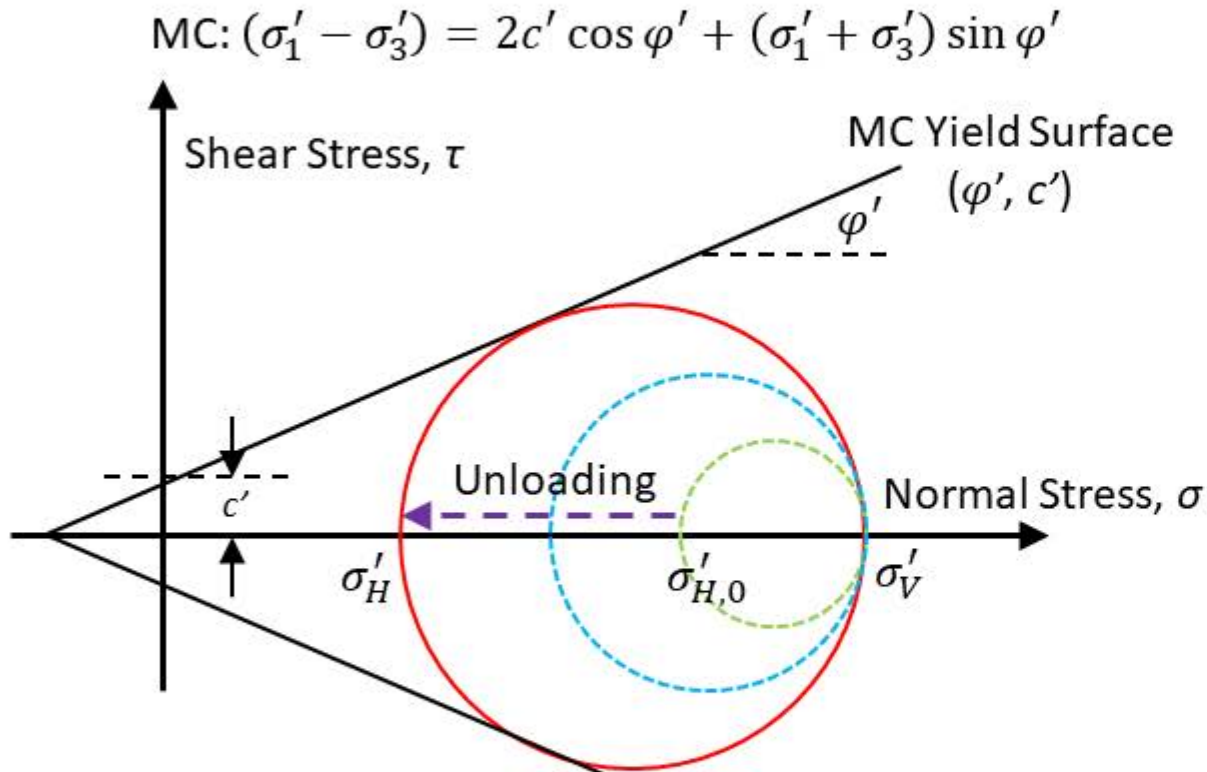
# Limit Equilibrium Method

- Well known and widely-used method (classical) in geotechnical engineering → Relatively **easy to verify**.
- Satisfy static equations in the presumed failure mode.
- Each limit equilibrium approach (e.g. Rankine, Coulomb, at-rest pressure, Peck, FHWA, etc) employs separate set of assumptions → By default, **DeepEX selects automatically** the most appropriate approach.
- Typically requires only soil properties at failure.
- Limitations:
  - Ignore stress path → Each stage is calculated independently.
  - Ignore strain-compatibility → Generally inaccurate displacement prediction.
  - Ignore soil-structure interaction.



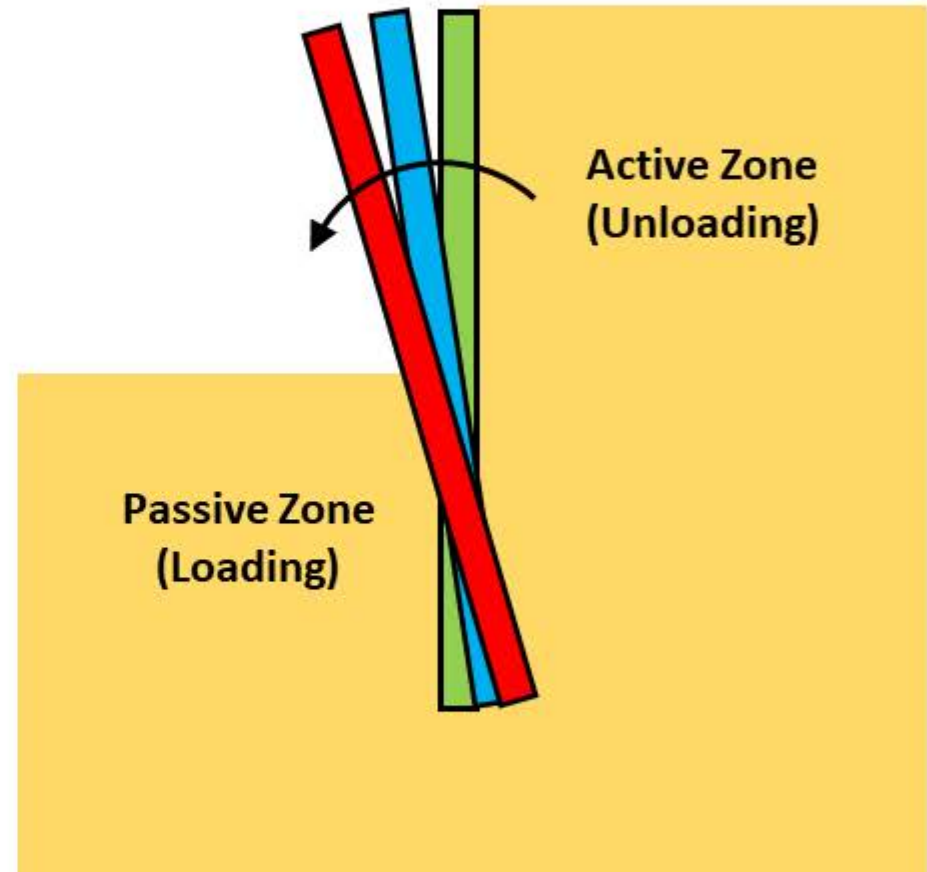
Options for drive (active) pressures

# Rankine: Active Pressure



$$\sigma'_H = \sigma'_V \tan^2 \left( 45 - \frac{\varphi'}{2} \right) - 2c' \tan \left( 45 - \frac{\varphi'}{2} \right)$$

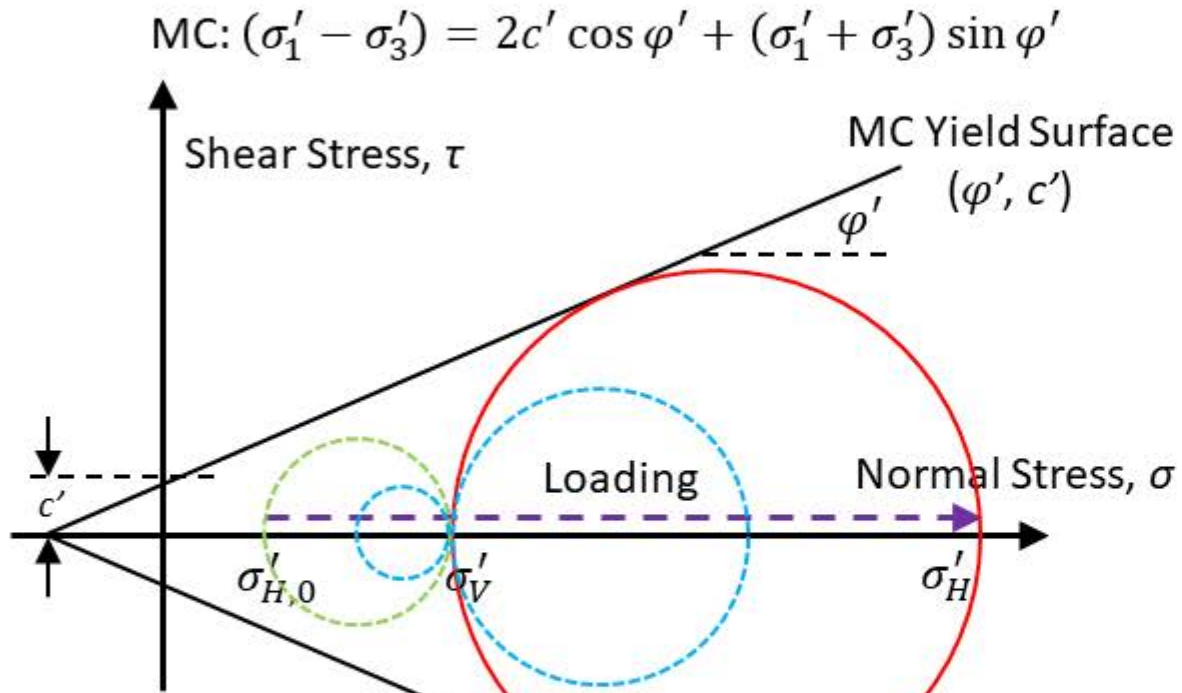
Note:  $K_a = \tan^2 \left( 45 - \frac{\varphi'}{2} \right) = \frac{1 - \sin(\varphi')}{1 + \sin(\varphi')}$



Rotation of cantilever wall due to excavation



# Rankine: Passive Pressure



Limitations of Rankine's earth pressure:

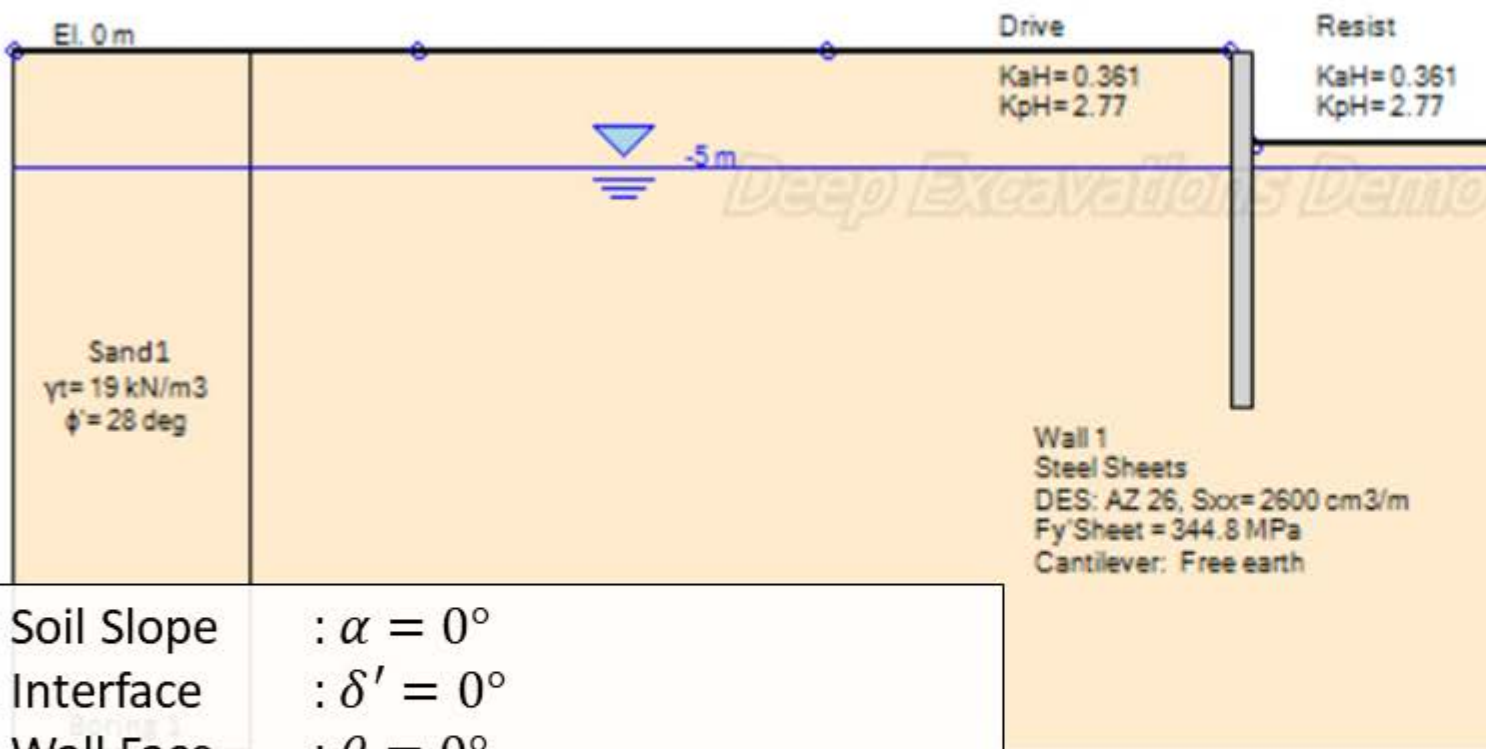
- Applies only for **frictionless** wall.
- Applies only for **vertical** wall.
- Applies only for **horizontal** slope surface.
- Does **not consider seismic** load.

Tips: Cohesion shall be used with caution as it will reduce the active pressure and increase the passive pressure → **Conservatively, neglect cohesion !!**

$$\sigma'_H = \sigma'_V \tan^2 \left( 45 + \frac{\varphi'}{2} \right) + 2c' \tan \left( 45 + \frac{\varphi'}{2} \right)$$

$$\text{Note: } K_p = \tan^2 \left( 45 + \frac{\varphi'}{2} \right) = \frac{1 + \sin(\varphi')}{1 - \sin(\varphi')}$$

# Earth Pres.: Flat Slope, No Wall Friction



**Soil Types**

Soil Name: Sand1

Description:

Soil Type - Behaviour: Sand

Default drained-undrained behavior for clays (See Theory Manual):  Undrained behaviour  Drained

A. General C. Elasto-plastic D. Bond E. Adv.

Unit Weights - Density:  $\gamma_t$  19 kN/m<sup>3</sup>  $\gamma_{dry}$  16 kN/m<sup>3</sup>  $\gamma_s$  9

Strength Parameters and Poisson Ratio

Drained strength properties:  $c'$  0 kPa  $\phi'$  28 degrees

Peak - constant vol. (for estimation):  $\phi_{cv}$  Omittec degrees  $\phi_{peak}$  Omittec degrees

$\nu$  0.35

Permeability:  $K_x$  0.1 m/sec  $K_z$  0.1 m/sec

At-rest coefficients:  $K_{oNC}$  0.531  $n_{OCR}$  0.8  $K_o = K_{oNC} \cdot (OCR)^{n_{OCR}}$

Buttons: Add New Soil, Copy Soil, Delete Selected Soil, Paste Soil, Clone, Database, OK, Cancel

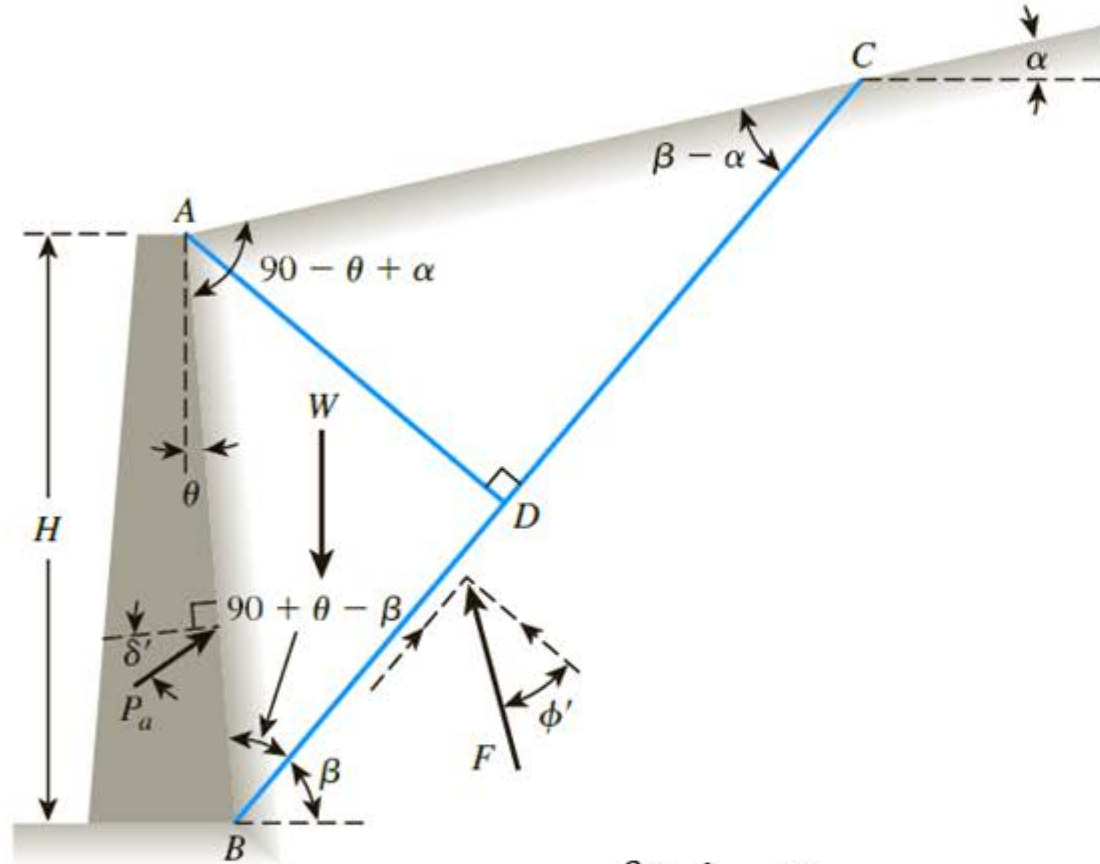
Soil Slope :  $\alpha = 0^\circ$   
 Interface :  $\delta' = 0^\circ$   
 Wall Face :  $\theta = 0^\circ$

Rankine earth pressure coefficient:

$$K_a = \frac{1 - \sin(\phi')}{1 + \sin(\phi')} \rightarrow K_a(\phi' = 28^\circ) = 0.361$$

$$K_p = \frac{1 + \sin(\phi')}{1 - \sin(\phi')} \rightarrow K_p(\phi' = 28^\circ) = 2.77$$

# Coulomb: Active Pressure



Coulomb's assumes **soil failure wedge** ( $\Delta ABC$ )  $\rightarrow$  Active and passive earth pressure coefficients are calculated based on the static stability of this wedge.

Symbols:

$\varphi'$  : Soil friction angle

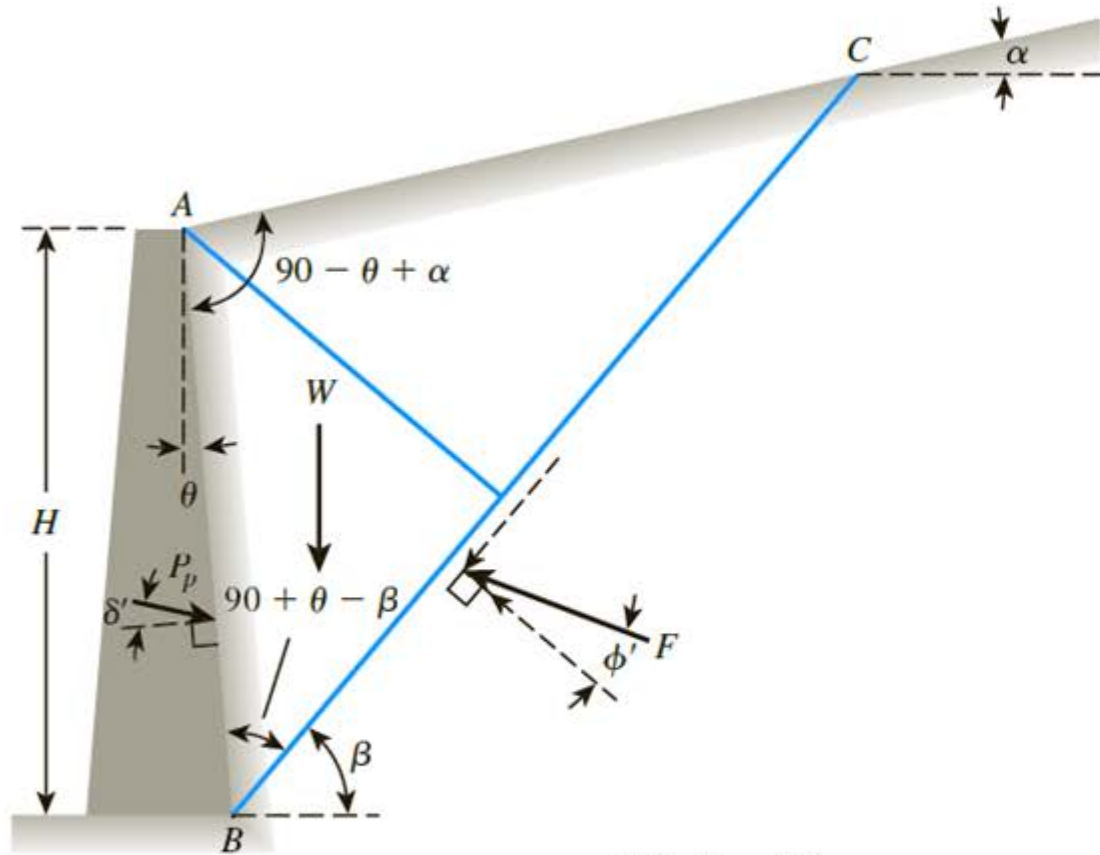
$\delta'$  : Soil-wall interface friction.

$\alpha$  : Soil slope angle.

$\theta$  : Inclination of wall upstream face.

$$K_a = \frac{\cos^2(\varphi' - \theta)}{\cos^2(\theta) \cos(\delta' + \theta) \left( 1 + \sqrt{\frac{\sin(\delta' + \varphi') \sin(\varphi' - \alpha)}{\cos(\delta' + \theta) \cos(\theta - \alpha)}} \right)^2}$$

# Coulomb: Passive Pressure



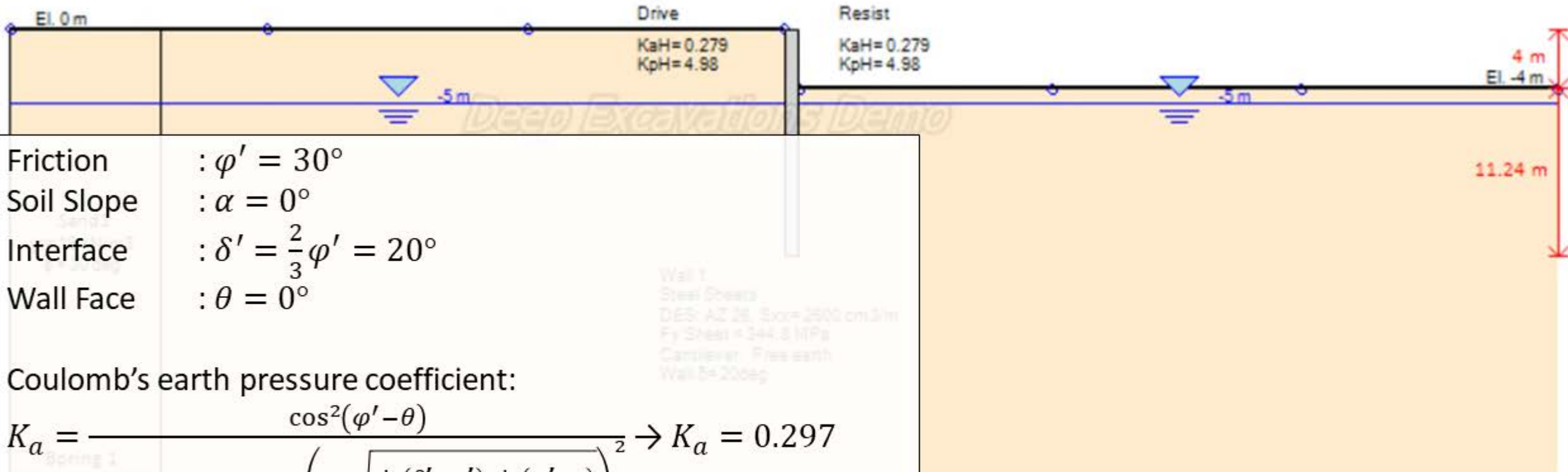
$$K_p = \frac{\cos^2(\varphi' + \theta)}{\cos^2(\theta) \cos(\delta' - \theta) \left( 1 - \sqrt{\frac{\sin(\delta' + \varphi') \sin(\varphi' + \alpha)}{\cos(\delta' - \theta) \cos(\alpha - \theta)}} \right)^2}$$

Coulomb's earth pressure consider interface friction ( $\delta'$ ), non-horizontal soil slope ( $\alpha$ ), and non-vertical wall face ( $\theta$ ).

When plugging  $\delta' = 0$ ,  $\alpha = 0$ , and  $\theta = 0$  into Coulomb's formula, we will get Rankine's formula.

For interface friction angle  $\delta' \neq 0$ , the resultant force direction makes an angle  $\delta'$  from horizontal.

# Earth Pres.: Flat Slope, With Wall Friction (1/2)

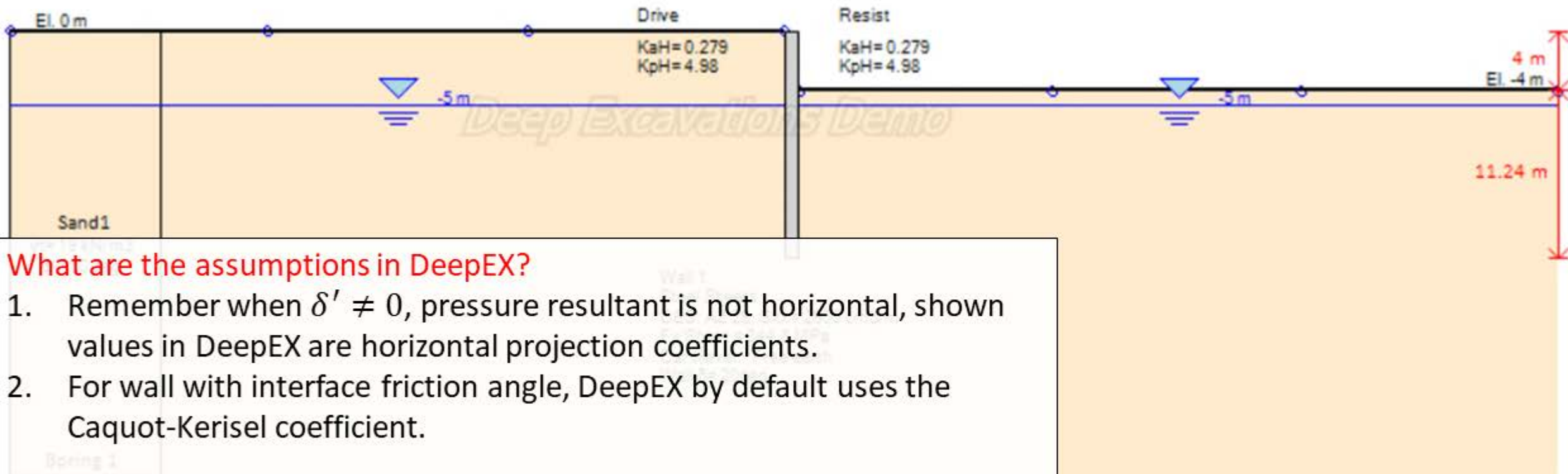


Coulomb's earth pressure coefficient:

$$K_a = \frac{\cos^2(\phi' - \theta)}{\cos^2(\theta) \cos(\delta' + \theta) \left( 1 + \sqrt{\frac{\sin(\delta' + \phi') \sin(\phi' - \alpha)}{\cos(\delta' + \theta) \cos(\theta - \alpha)}} \right)^2} \rightarrow K_a = 0.297$$

$$K_p = \frac{\cos^2(\phi' + \theta)}{\cos^2(\theta) \cos(\delta' - \theta) \left( 1 - \sqrt{\frac{\sin(\delta' + \phi') \sin(\phi' + \alpha)}{\cos(\delta' - \theta) \cos(\alpha - \theta)}} \right)^2} \rightarrow K_p = 6.105$$

# Earth Pres.: Flat Slope, With Wall Friction (2/2)



## What are the assumptions in DeepEX?

1. Remember when  $\delta' \neq 0$ , pressure resultant is not horizontal, shown values in DeepEX are horizontal projection coefficients.
2. For wall with interface friction angle, DeepEX by default uses the Caquot-Kerisel coefficient.

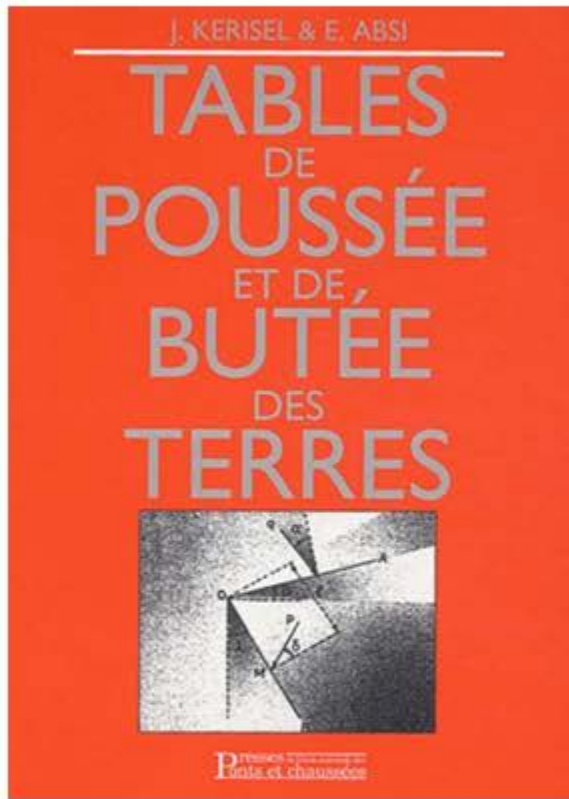
$$K_{ah}(Coulomb) = 0.297 \cos(20) = 0.279$$

$$K_{ph}(Coulomb) = 6.105 \cos(20) = 5.73$$

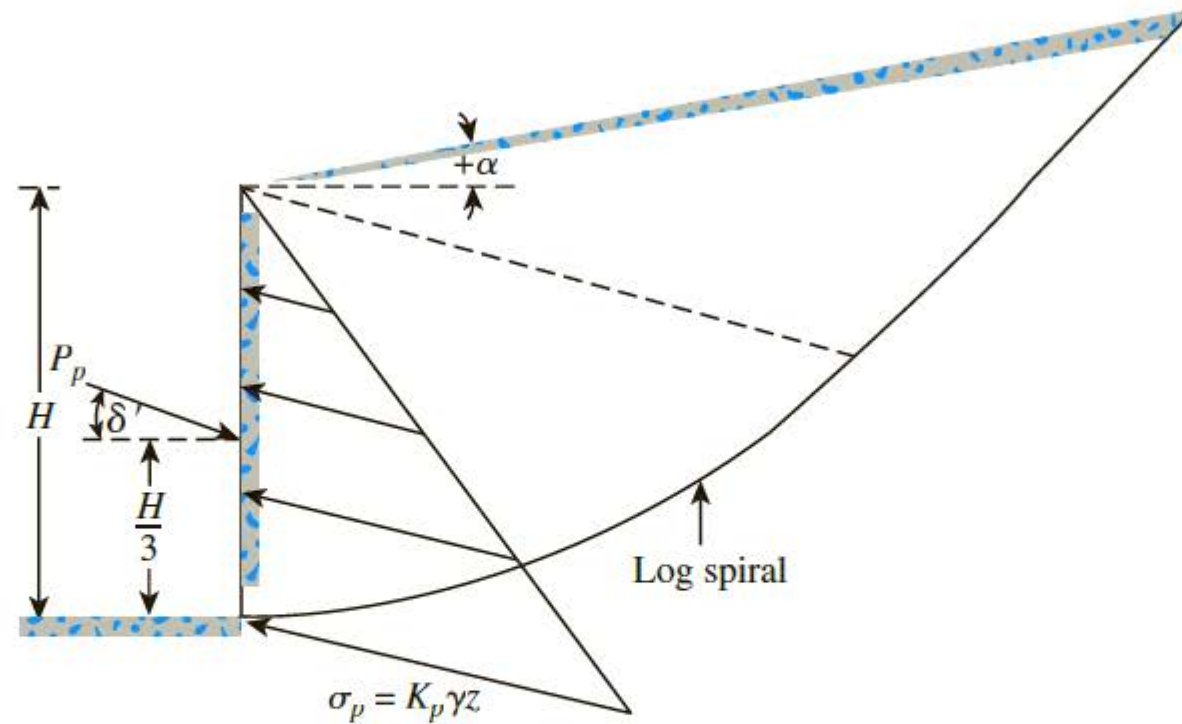
$$K_{ph}(CK) = K_p \cos(20) = 5.30 \cos(20) = 4.98$$

Note: CK (Caquot-Kerisel) coefficients can be obtained from table.

# Caquot-Kerisel: Passive Pressure

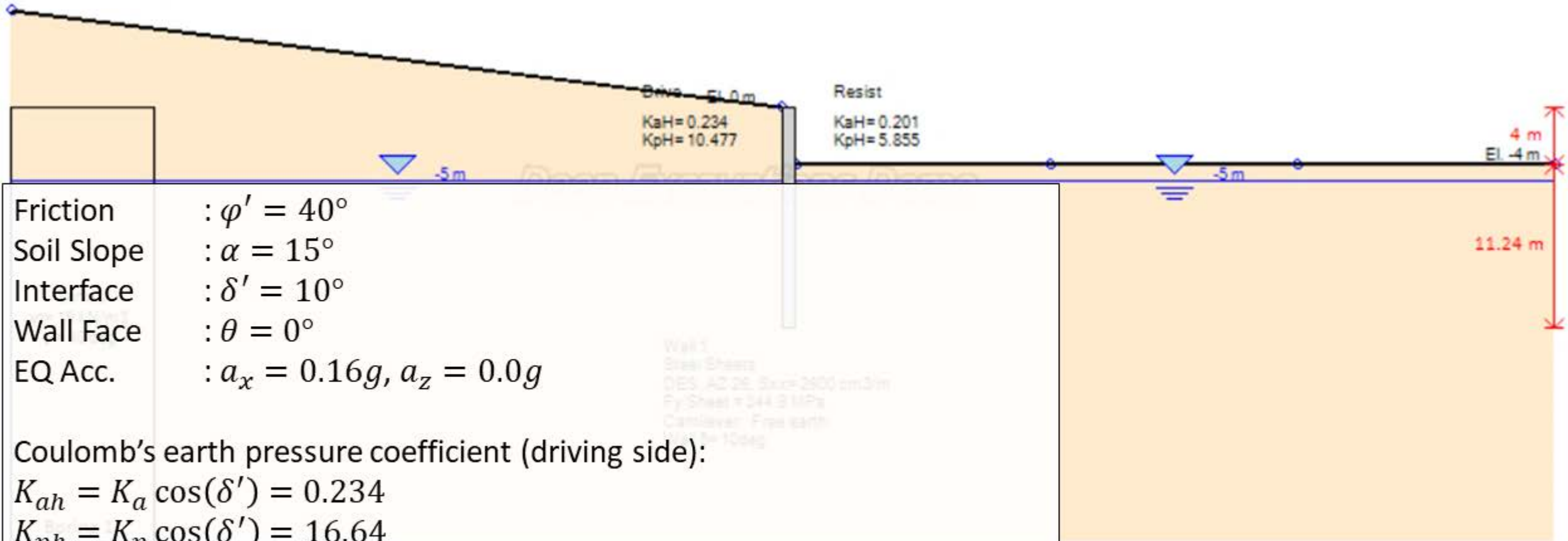


Active and passive earth pressure coefficient book (Caquot-Kerisel)



- Caquot-Kerisel assumes a **logarithmic spiral** failure surface → More realistic (compared to Coulomb's).
- In general, it provides **more conservative passive pressure** (Coulomb 5.73 vs CK 4.98 in the last example).

# Earth Pres.: Non-Flat Slope, Wall Friction, Seismic





# Lancellota: Seismic Passive Pressure

- [Lancellota, 2007] → Conservative (lower-bound) seismic passive pressure.

- Parameters:

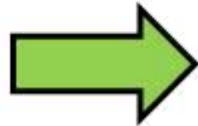
- $\beta = \tan^{-1} \left( \frac{a_x}{1 \pm a_z} \right)$
- $2\theta = \sin^{-1} \left( \frac{\sin(\delta')}{\sin(\varphi')} \right) + \sin^{-1} \left( \frac{\sin(\alpha - \beta)}{\sin(\varphi')} \right) + \delta' + (\alpha - \beta) + 2\beta$
- $\gamma_1 = \left( (1 \pm a_z)^2 + a_x^2 \right)^{0.5}$

- Seismic passive pressure coefficient:

- $K_{pe} = \frac{\cos(\delta')}{\cos(\alpha - \beta) - \sqrt{\sin^2(\delta') - \sin^2(\alpha - \beta)}} \left( \cos(\varphi') + \sqrt{\sin^2(\delta') - \sin^2(\alpha - \beta)} \right) e^{2\theta \tan(\varphi')}$
- $K_{ph} = K_{pe} \gamma_1 \cos(\alpha - \beta)$

From prev. slide:

$$\begin{aligned}\varphi' &= 40^\circ \\ \alpha &= 15^\circ \\ \delta' &= 10^\circ \\ \theta &= 0^\circ \\ a_x &= 0.16g \\ a_z &= 0.0g\end{aligned}$$



Using Lancellota:

$$\begin{aligned}\beta &= 9.09^\circ \\ 2\theta &= 1.029 \\ \gamma_1 &= 1.013 \\ K_{pe} &= 10.401 \\ K_{ph} &= 10.477\end{aligned}$$

- For comparison, using Coulomb's extension for earthquake forces (Mononobe-Okabe), we would get  $K_{ph} = 15.54$ .
- Hence using Lancellota (lower-bound) is a conservative (safe) assumption.

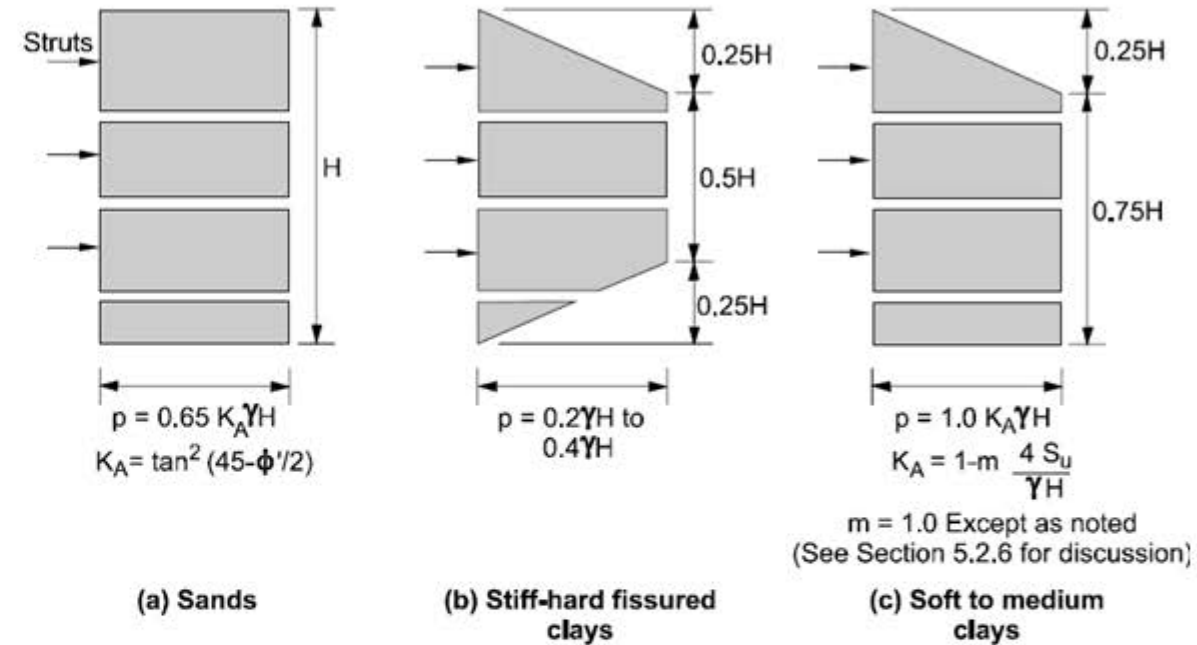
# Summary: Active & Passive Coefficients in DeepEX

Method	Active				Passive			
	Available	Soil Slope	Interface	EQ*	Available	Soil Slope	Interface	EQ
Rankine	Yes	No	No	No	Yes	No	No	No
Coulomb	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Caquot-Kerisel	No	-	-	-	Yes	Yes	Yes	No
Lancellota	No	-	-	-	Yes	Yes	Yes	Yes

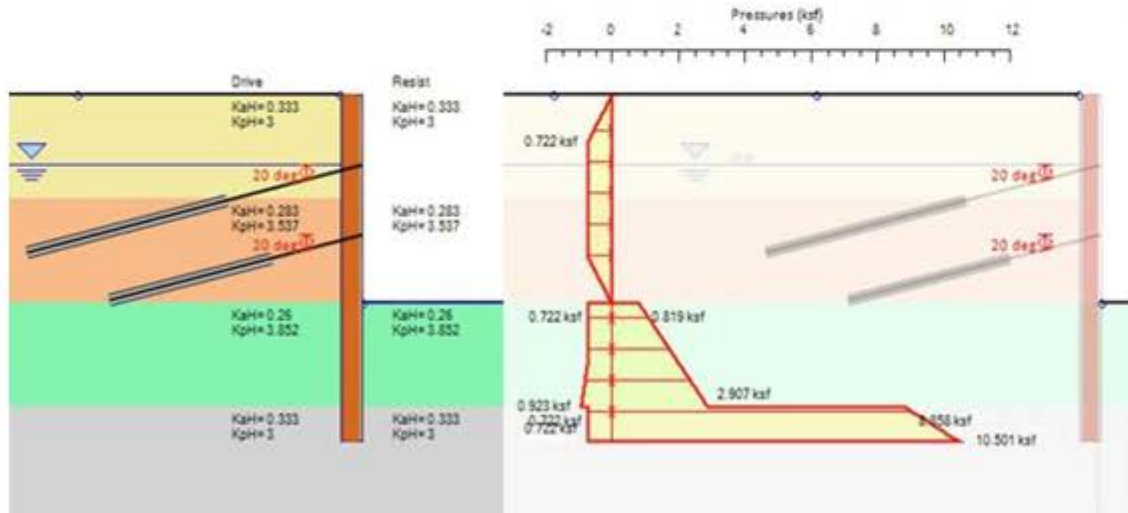
\* Seismic effects are added separately.

# Apparent Earth Pressure

- In reality, for anchored/strutted system, it is found that the deformation pattern is not consistent from Rankine/Coulomb pressure distribution.
- [Terzaghi and Peck, 1967] and [Peck, 1969] propose loading diagram for conservative design of strut in internally braced excavations → **Apparent Earth Pressure**.
- Some modifications have been done since 1969, particularly by [Henkel, 1971] and [FHWA, 1998] → It is incorporated in **FHWA Apparent Earth Pressure\***.



Peck Apparent Earth Pressure\*

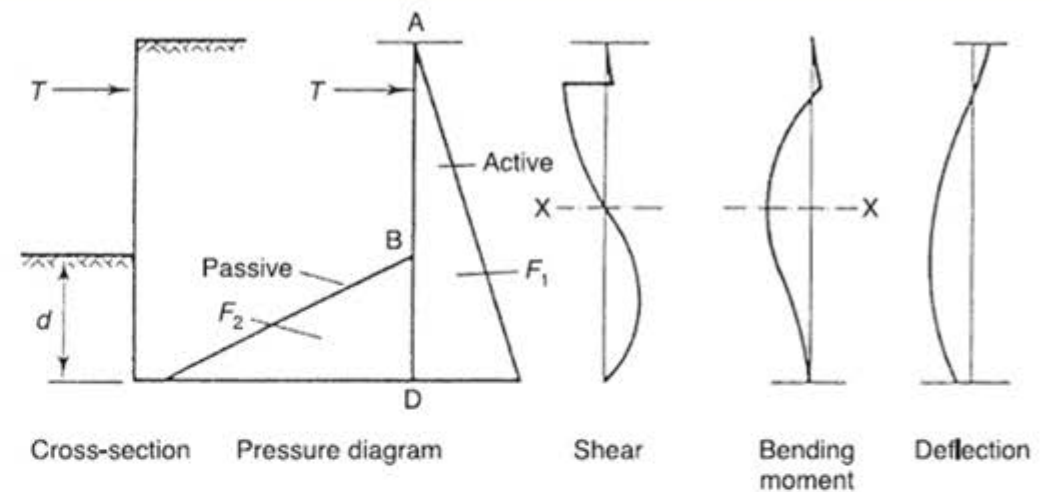


Peck Apparent Earth Pressure in DeepEX

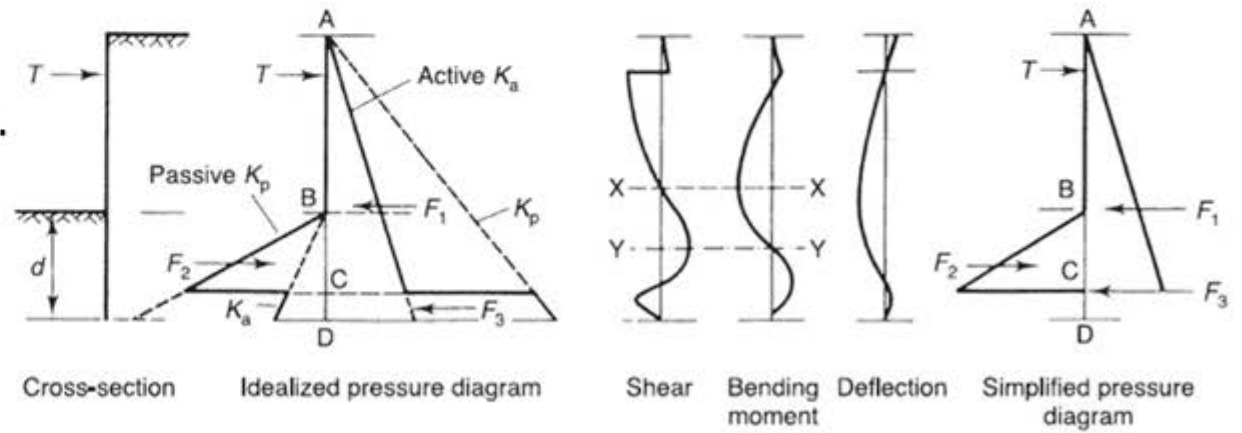
\* FHWA-IF-99-015 Geotechnical Engineering Circular no 4.

# Commonly-Used Stability Calc. Method for LEM

- For cantilever wall:
  - Free-earth support method** → Pile rotates at the tip, applies when the embedment depth is relatively small.
  - Fixed-earth support method** → Pile rotates a pivot point above the pile tip (at fixity point).
- For cases with supports: **Blum's method** → Essentially fixed-earth support method with some modifications\*.
- SNI 8460 also allows the use of **Rowe's moment reduction method** → It considers pile flexibility for reducing the required moment for wall design (use with lots of caution!!).



Free-Earth Support Method\*



Fixed-Earth Support Method\*

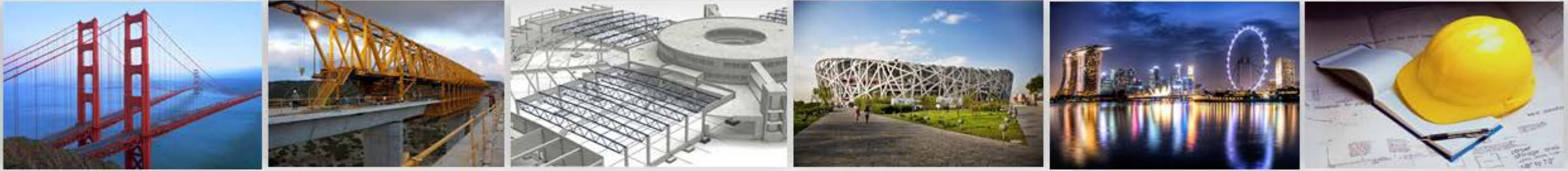
\* [Puller, 2003] Deep Excavations: A Practical Manual 2<sup>nd</sup> Edition.

# Design Check Summary

---

Parameter	Applicability	Description	Requirement
STR Moment Wall Ratio	Wall	Demand capacity ratio of wall (bending)	<1
STR Shear Wall Ratio	Wall	Demand capacity ratio of wall (shear)	<1
STR Support Ratio	Support	Demand capacity ratio of supports	<1
Support Geotechnical Capacity Ratio (Pullout)	Support	Demand capacity geotechnical support	<1
FS Basal	Global	Basal stability safety factor	1.25 (SNI 8460)
Toe FS Passive	LEM	Embedment safety factor (horizontal forces)	2.0 (SNI 8460)
Toe FS Rotation	LEM	Embedment safety factor (rotation)	1.5 (SNI 8460)

# Effective Deep Excavation Analysis and Design



## Essential Design Aspects & Case Study

# Essential Design Considerations (SNI 8460)

---

## Undrained vs Drained Strength

- Embedded wall analysis shall be performed with **soil parameters representing the most critical condition**.
- If unsure, both short-term (undrained) and long-term (drained) analysis shall be performed.

## Lateral Displacement Limit

- Max **tolerable displacement is typically 0.5% H** → Ex. for 10m excavation, max displacement is 5 cm.
- Higher tolerance may be applied (up to 1% H) → Depends on the proximity with nearby facilities and soil type.

## Base Stability Concerns

- If the excavation base is sand, **pipingsand boiling** may occur ( $SF \geq 1.25$ ).
- If a confined aquifer is present, blow-in may happen during an excavation ( $SF \geq 1.5$ ).

## Construction Tolerances

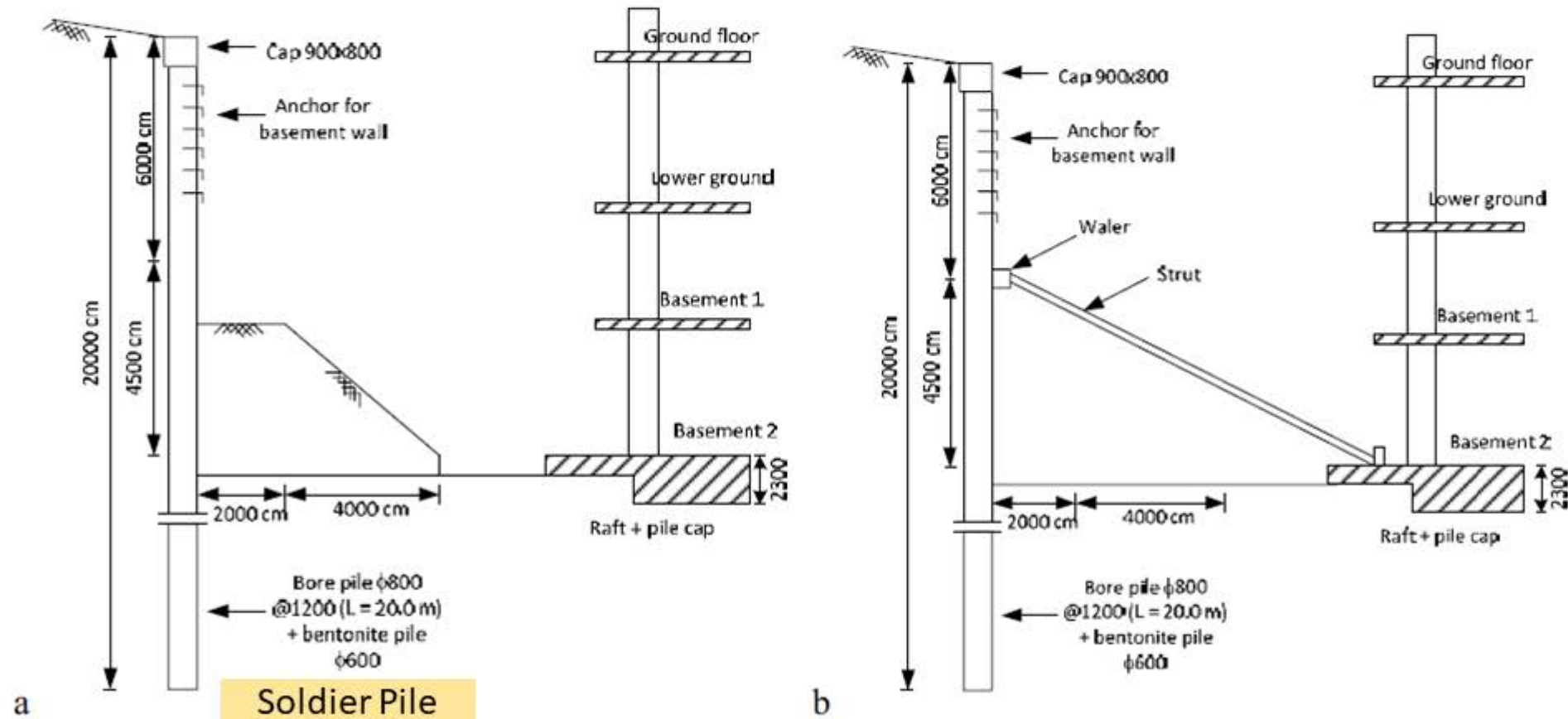
- **Additional load of min 10 kPa**, shall be applied at the upstream face (for equipment, excavated soils, etc).
- **Over-excavation** shall be considered, typically 10% H (but no need greater than 0.5 m).

## Water Pressure

- **Groundwater level fluctuation** shall be considered.
- If the excavation area is susceptible to flood event, ground water level shall be taken at the ground surface.
- Water pressure may be modelled as **hydrostatic or steady-state flow** (preferred for drained, long-term condition).

# Case Study: Deep Excavation with Berm and Raker

- **Objective:** Predict the **maximum lateral displacement** !!
- **Method:** Compare results with LEM, NL, and FEM using DeepEX.





# Case Study: Soil Data

---

Parameter	Symbol	Layer 1	Layer 2	Layer 3
Name		Soft Clay	Clay	Stiff Clay
Material model		Mohr Coulomb	Mohr Coulomb	Mohr Coulomb
Type of material behavior		Undrained	Undrained	Undrained
Unsaturated unit weight (kN/m <sup>3</sup> )	$\gamma_{\text{unsat}}$	16	16.8	17.2
Saturated unit weight (kN/m <sup>3</sup> )	$\gamma_{\text{sat}}$	17	18	18
Stiffness modulus (kN/m <sup>2</sup> )	$E$	7E3	9E3	12E3
Poisson ratio	$\nu$	0.3	0.35	0.35
Cohesion (kN/m <sup>2</sup> )	$c$	11	21	20
Friction angel (°)	$\phi$	12	13	17

# Modeling: Input Soil Data (Top Layer)

1. Name and Basic Soil Type

Soil Name: C1-Initial Color

Description: Organic clay

2. Soil Type - Behaviour

Sand Show test data (SPT, CPT, Etc)

Clean fine sands, and slightly silty sands

Not defined

3. Default drained-undrained behavior for clays (See Theory Manual)

Undrained behaviour  Drained

A. General C. Elasto-plastic D. Bond E. Adv. F. Piles

4. Unit Weights - Density

$\gamma_t$  18 kN/m<sup>3</sup>  $\gamma_{bulk}$  16.8 kN/m<sup>3</sup>;  $\gamma' = 8$

5. Strength Parameters and Poisson Ratio

Drained strength properties

$c'$  11 kPa  $\phi'$  12 degrees

Peak - constant vol. (for estimation)

$\phi_{cv'}$  26 degrees  $\phi_{peak}$  18 degrees

$\nu$  0.3

6. Permeability

$K_x$  9.999999 m/sec  $K_z$  9.999999 m/sec

8. At-rest coefficients

$KoNC$  0.792088  $nOCR$  0.5  $Ko = KoNC * (OCR)^{nOCR}$

1. Name and Basic Soil Type

Soil Name: C1-Initial Color

Description: Organic clay

2. Soil Type - Behaviour

Sand Show test data (SPT, CPT, Etc)

Clean fine sands, and slightly silty sands

Not defined

3. Default drained-undrained behavior for clays (See Theory Manual)

Undrained behaviour  Drained

A. General C. Elasto-plastic D. Bond E. Adv. F. Piles

10. Soil Model and Behavior

Elastic-Plastic (Linear Load-Reload)  
Exponential  
Subgrade-modulus  
HS-Small (approximated procedure)

10.1 Loading Elasticity Parameters

$E_{vc}$  7000 kPa  $\exp$  1  $Pref$  95.8 kPa  $\alpha_v$  1  $\alpha_h$  0

10.3 Reloading Elasticity Modulus

$r_{Eur} = E_{ur}/E_{load}$  3

# Modeling: Assign Soil Data

**Soil Layers**

Available Borings

- Boring 1
- B-FEM
- B-FEM-HS

**1. General Boring Information - Coordinates**

Name: Boring 1

Coordinates X: -20 m Y: 0 m

The x coordinate controls where the boring is shown in your design section view. Each design section uses one boring (soil strata). You can use a different boring on each design section.

**SPT Data Option (Applies to Design Section)**

SPT Record: Not assigned [Add edit SPT records]

Pass same SPT log to boring (3D visualizations)

**CPT Record Option (Applies to Design Section)**

CPT Record: Not assigned [Add edit CPT records]

**2. Boring Layers - Layer Elevations**

	Top Elev.(m)	Soil Type	OCR	Ko	Edit
▶	2	C1-Initial	1	0.7920...	Edit
	-2	C2-Initial	1	0.775	Edit
	-11	C2-Initial	1	0.775	Edit
	-14	C3-Initial	1	0.5	Edit
*					

Buttons: Add New Boring, Delete Selected Boring (Stratigraphy)

Soil Layer Properties:

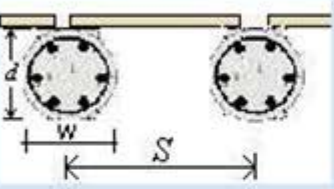
- C1-Initial:  $\gamma_t = 18 \text{ kN/m}^3$ ,  $c = 11 \text{ kPa}$ ,  $\phi = 12 \text{ deg}$
- C2-Initial:  $\gamma_t = 18 \text{ kN/m}^3$ ,  $c = 21 \text{ kPa}$ ,  $\phi = 13 \text{ deg}$
- C3-Initial:  $\gamma_t = 18 \text{ kN/m}^3$ ,  $c = 20 \text{ kPa}$ ,  $\phi = 17 \text{ deg}$

3D Visualization: Shows a boring log with soil layers in yellow, brown, and tan. A water table is indicated at -20m.

# Modeling: Input Wall Data

2. Wall Name  
Wall 1

3. General Section Data



Non-prestressed section  GFRP

4. Dimensions

Width d 0.8 m

Hor. Space S 1.2 m

Passive width (below exc.) 1.2 m >

Active width (below exc.) 1.2 m >

Water width (below exc.) 0.8 m >

The "passive width and active width below exc." are used to multiply soil pressures on the wall element below the excavation grade (see manual).

5. Structural Materials

Concrete - Rebar Materials

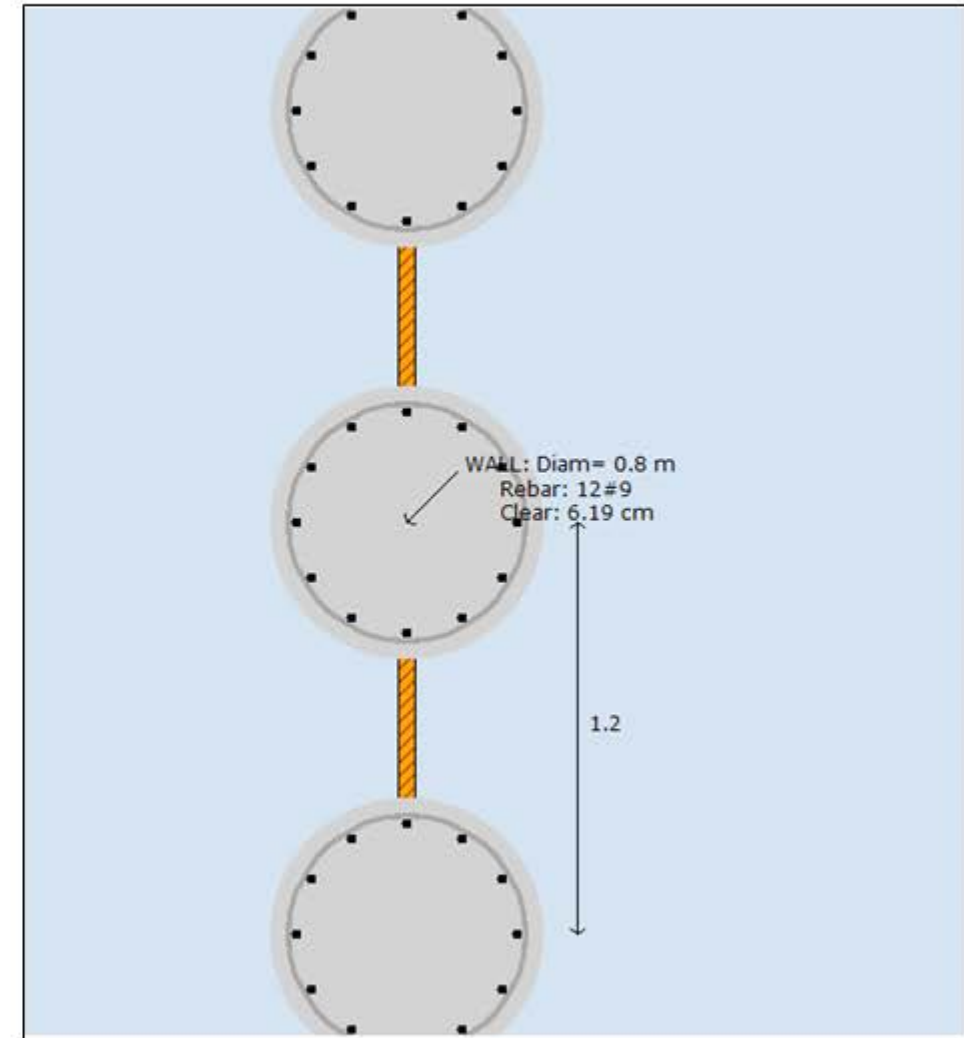
Rebar steel mat.  
Grade 60 Edit

Concrete mat.  
Fc 3ksi Edit

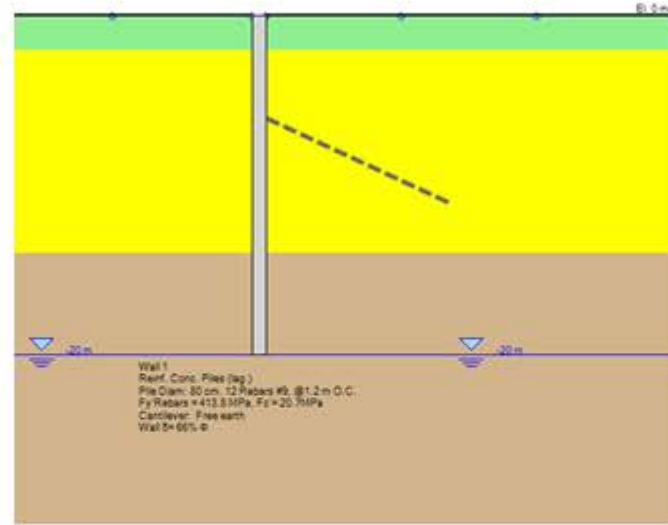
6. Pile offset options (double row of piles for soldier piles and tangent pile walls only)

Use pile offset Pile offset 0 m

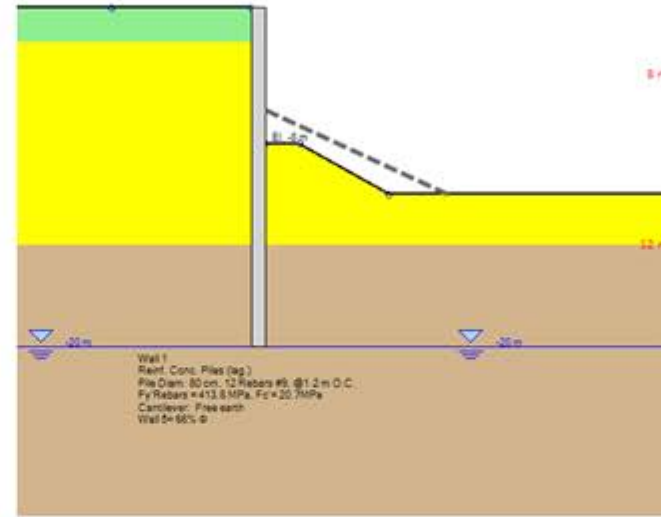
Use stiffness increase Stiffness factor for  $A \times (0.5 \text{ offset})^2$  0 %



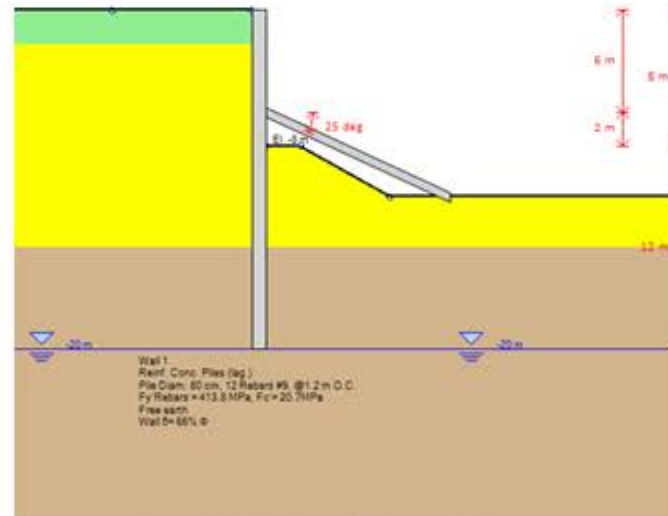
# Modeling: Staged-Construction



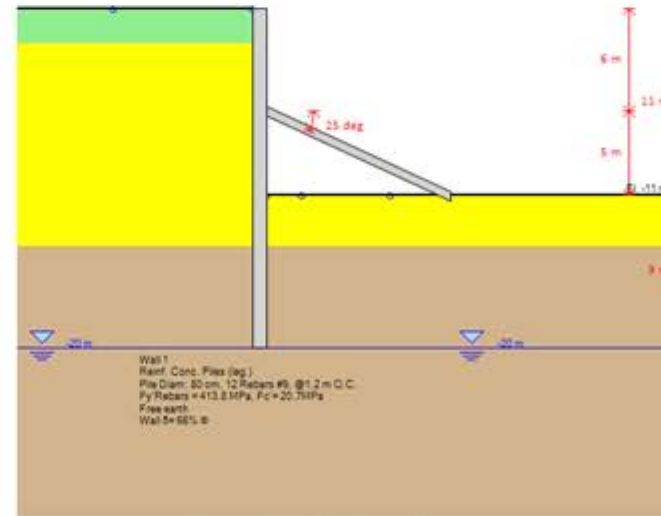
Stage 0: Initial Conditions - No Excavation



Stage 1: Excavate to El: -8m, Create Bench



Stage 2: Raker Installation at El: -6m



Stage 3: Final Excavation

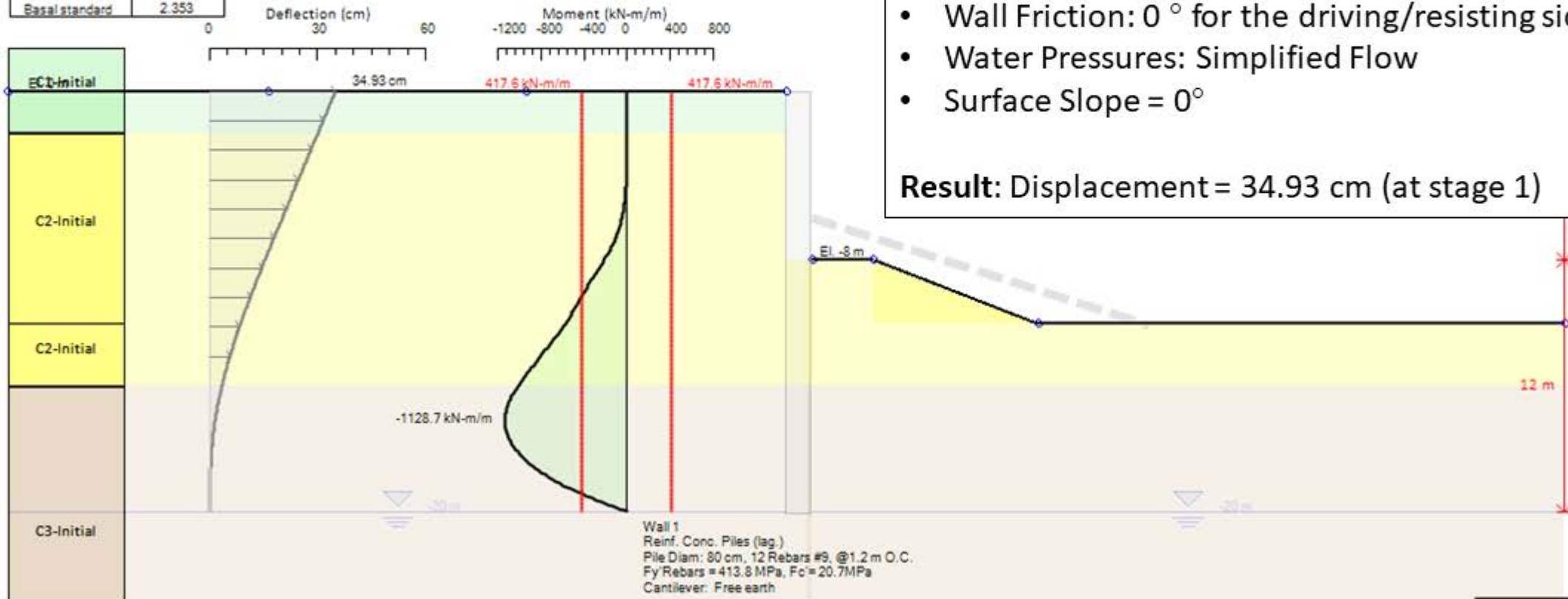
# Result: LEM, Flat Slope, No Wall Friction

Wall Toe Safety:	Wall 1
Min FS=	1
FS Embed=	1
FS pas. =	1.433
FS Rot. =	1.007
Req. toe FS=1:	12 m
Toe El. FS=1:	-20 m
Note:	Toe FS >=1
FS Basal=	2.353
Basal standard	2.353
Basal standard	2.353

## Settings:

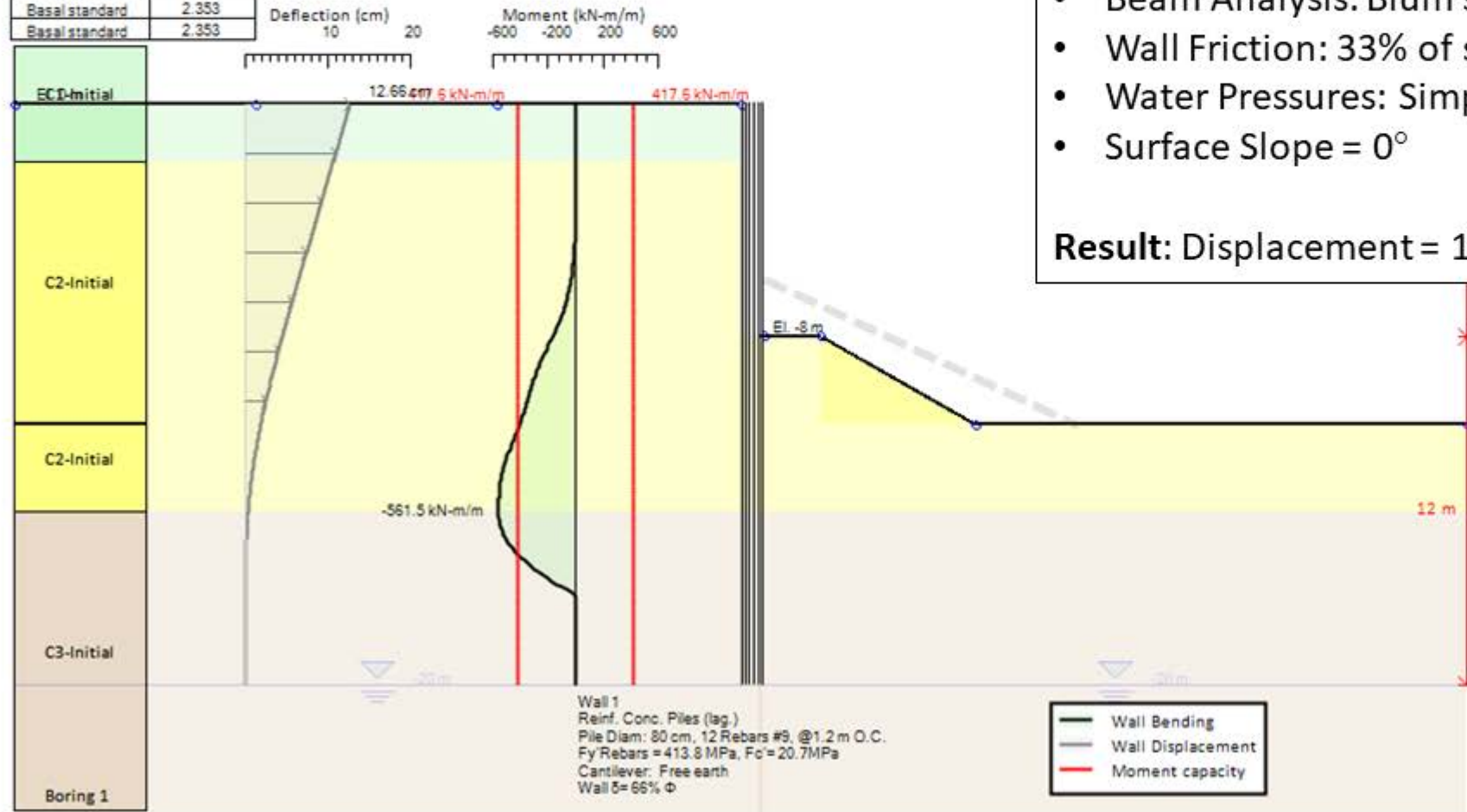
- Soil Pressures: Active/Passive for the cantilever excavation stage, FHWA Apparent/Passive for stages with supports.
- Beam Analysis: Blum's Method
- Wall Friction:  $0^\circ$  for the driving/resisting side.
- Water Pressures: Simplified Flow
- Surface Slope =  $0^\circ$

**Result:** Displacement = 34.93 cm (at stage 1)



# Result: LEM, Flat Slope, With Wall Friction

Wall Toe Safety:	Wall 1
Min FS=	1.342
FS Embed=	1.348
FS pas =	1.957
FS Rot =	1.342
Req. toe FS=1:	8.9 m
Toe El. FS=1:	-16.9 m
Note:	Toe FS >=1
FS Basal=	2.353
Basal standard	2.353
Basal standard	2.353



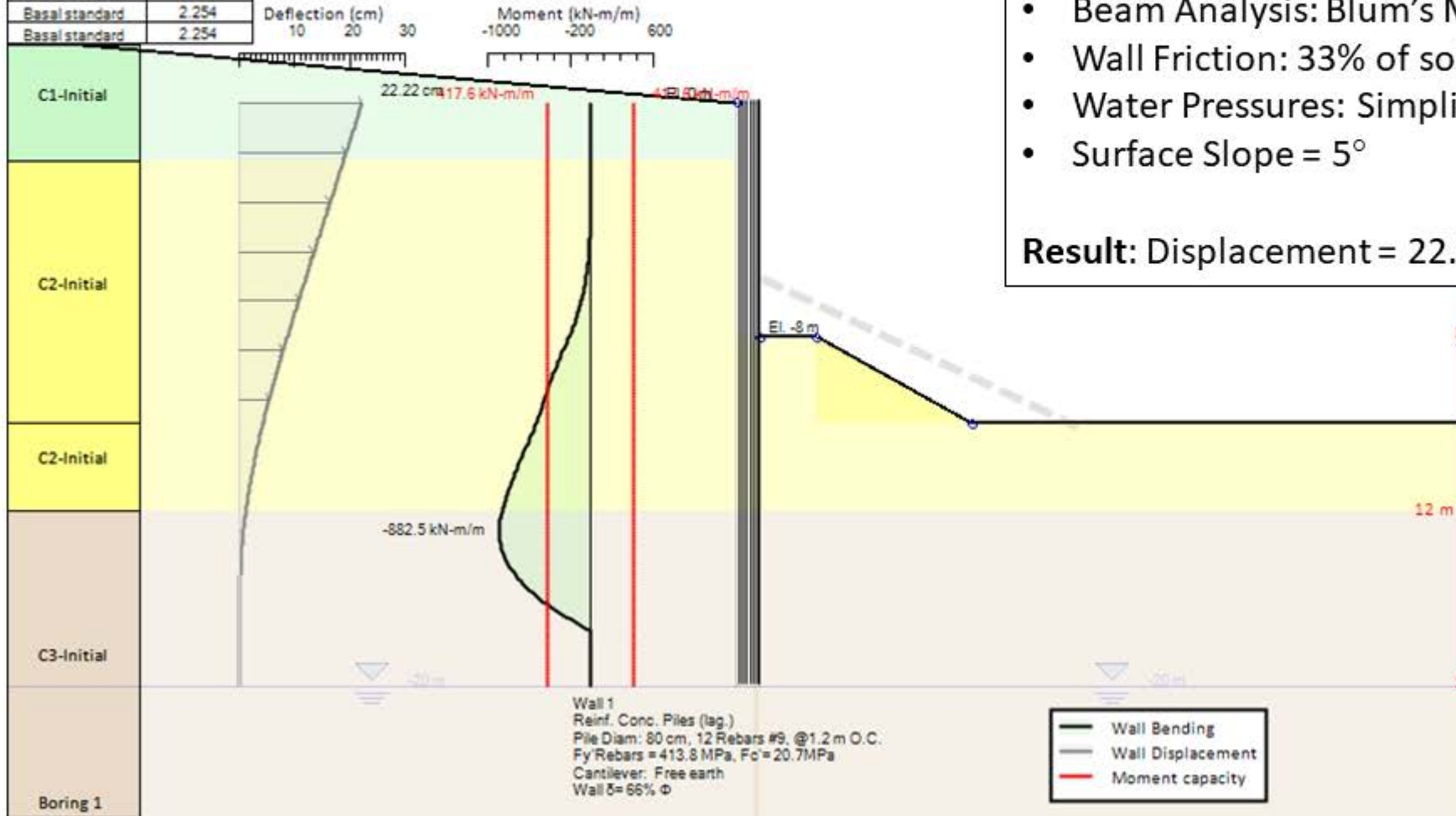
## Settings:

- Soil Pressures: Active/Passive for the cantilever excavation stage, FHWA Apparent/Passive for stages with supports.
- Beam Analysis: Blum's Method
- Wall Friction: 33% of soil friction.
- Water Pressures: Simplified Flow
- Surface Slope = 0°

**Result:** Displacement = 12.66 cm (at stage 1)

# Result: LEM, Non-Flat Slope, With Wall Friction

Wall Toe Safety:	Wall 1
Min FS=	1.188
FS Embed=	1.188
FS pas =	1.746
FS Rot =	1.188
Req. toe FS=1:	10.1 m
Toe El. FS=1:	-18.1 m
Note:	Toe FS >= 1
FS Basal=	2.254
Basal standard	2.254
Basal standard	2.254



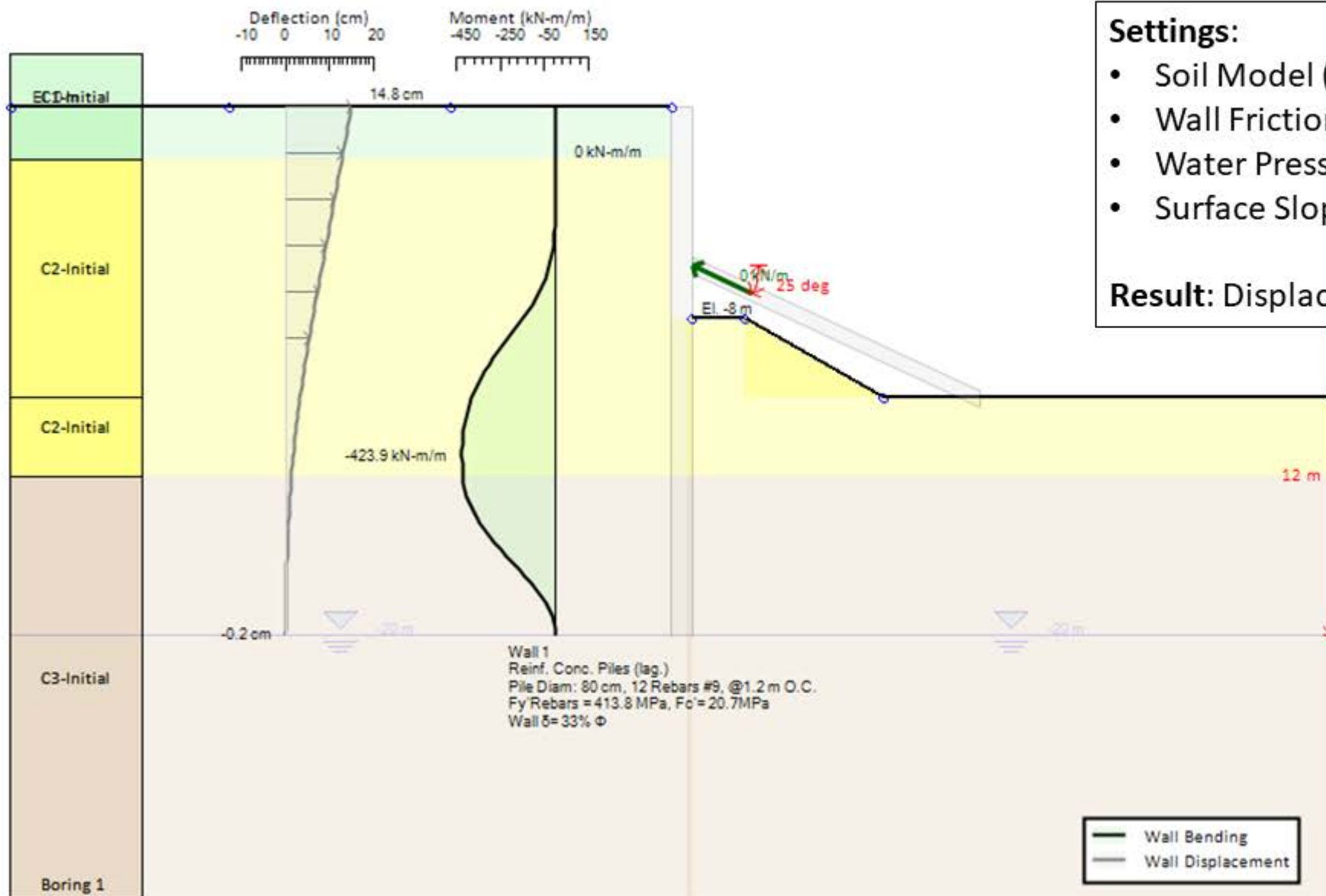
## Settings:

- Soil Pressures: Active/Passive for the cantilever excavation stage, FHWA Apparent/Passive for stages with supports.
- Beam Analysis: Blum's Method
- Wall Friction: 33% of soil friction.
- Water Pressures: Simplified Flow
- Surface Slope = 5°

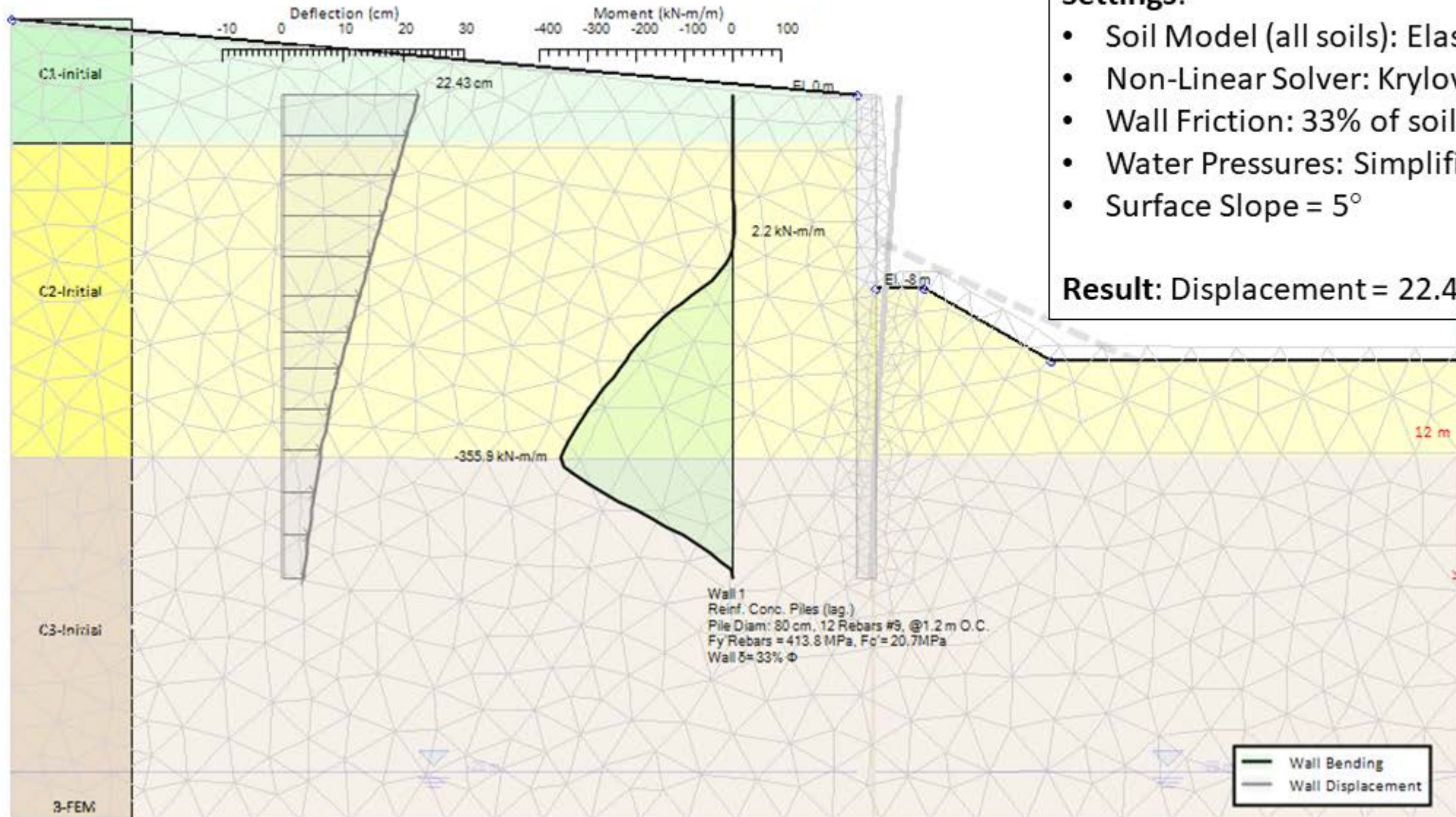
**Result:** Displacement = 22.22 cm (at stage 1)



# Result: NL, Flat Slope, With Wall Friction



# Result: FEM, Non-Flat Slope, With Wall Friction



# Case Study: Summary

- Wall friction has a considerable effect on the wall performance.
- Construction tolerance (represented by 5° slope) has a non-negligible effect on the predicted lateral displacement.
- Using **LEM, NL, and FEM**, also by considering wall friction and construction variance (represented by 5° slope), the estimated **lateral displacement is between 12-23 cm** (among the cases considered).

The screenshot displays the software interface with the following elements:

- Menu Bar:** General, Analysis, Seismic, Slope, Stability+, Design, Results, Report, View, Optimize, Help.
- Toolbars:** Model Wizard, Project Info, Move Model Elev. Dim-Limit, Soil, Structural, Edit 1st wall, Add right wall, Surface Options, Walls, Surface Elev. next to wall.
- Design Sections Panel:** A table with columns 'Design Sections' and 'Mmax (k-ft)'. It lists '0: Base model', '1: New Section 1', and '2: New Section 2'. A context menu is open over this panel with options: Edit Name, Add Section, Add as new section, Add new linked section, Delete Section, and View Selected DS.
- Diagram:** A cross-section showing a drive shaft and a resist section. The top surface is at 'El. 0 ft'. The drive shaft has parameters  $K_aH = 0.333$  and  $K_pH = 3$ . The resist section also has  $K_aH = 0.333$  and  $K_pH = 3$ . A water table is shown at a depth of  $-16.4$  ft.
- Annotation:** A green box with a black border contains the text: 'Tips: All of these cases can be analyzed in single file when using DeepEX'. An arrow points from this box to the 'Design Sections' panel.

# Summary

---

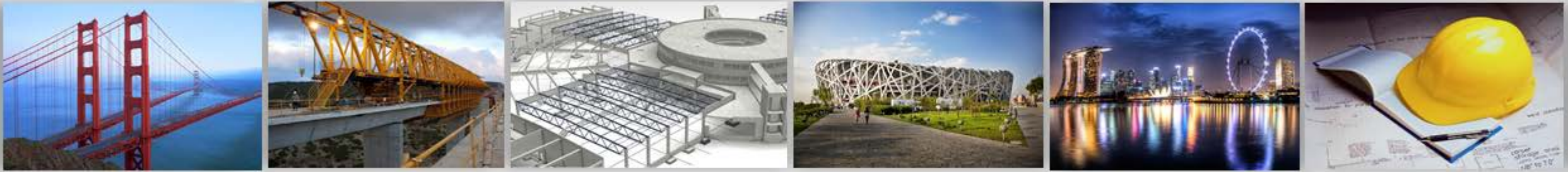
- Modeling challenges and workflow enhancements.
  - Select appropriate soil data.
  - Perform wall STR analysis.
  - Perform support STR and GEO analysis.
- LEM approaches and design check.
  - Various earth pressure coefficient.
  - Calculation method.
- Essential design aspects & case study.
  - Sensitivity analyses.
  - LEM vs NL vs FEM comparison.

Usually, these parts take most of our time

Important part to obtain a **robust design**

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