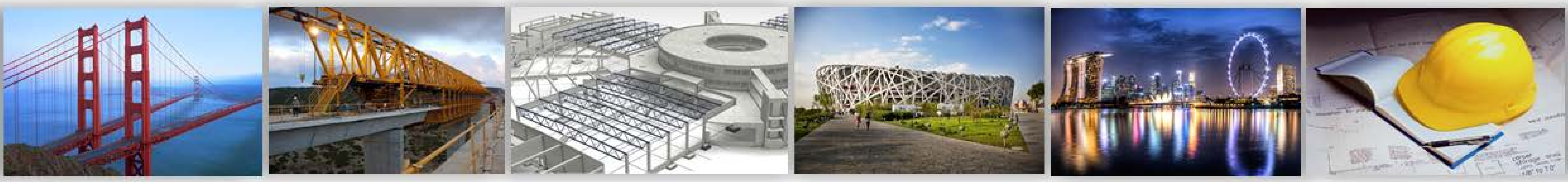
Effective Deep Excavation Analysis and Design using DEEP EX



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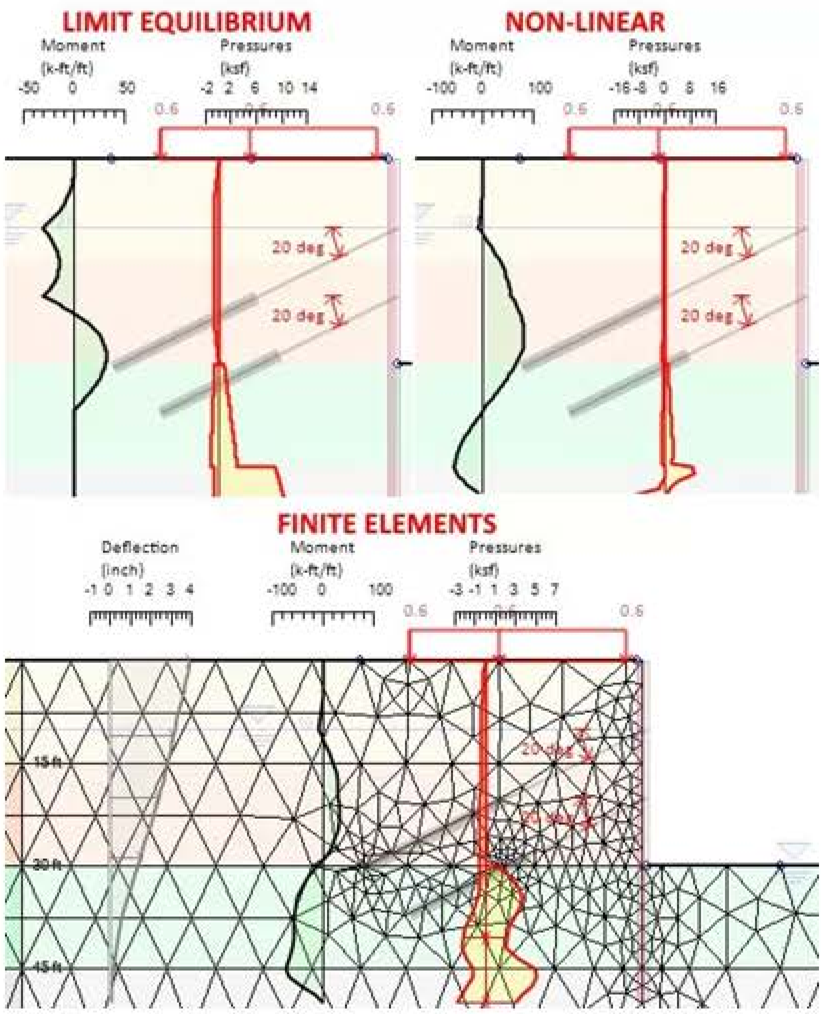
Overview of DeepEX

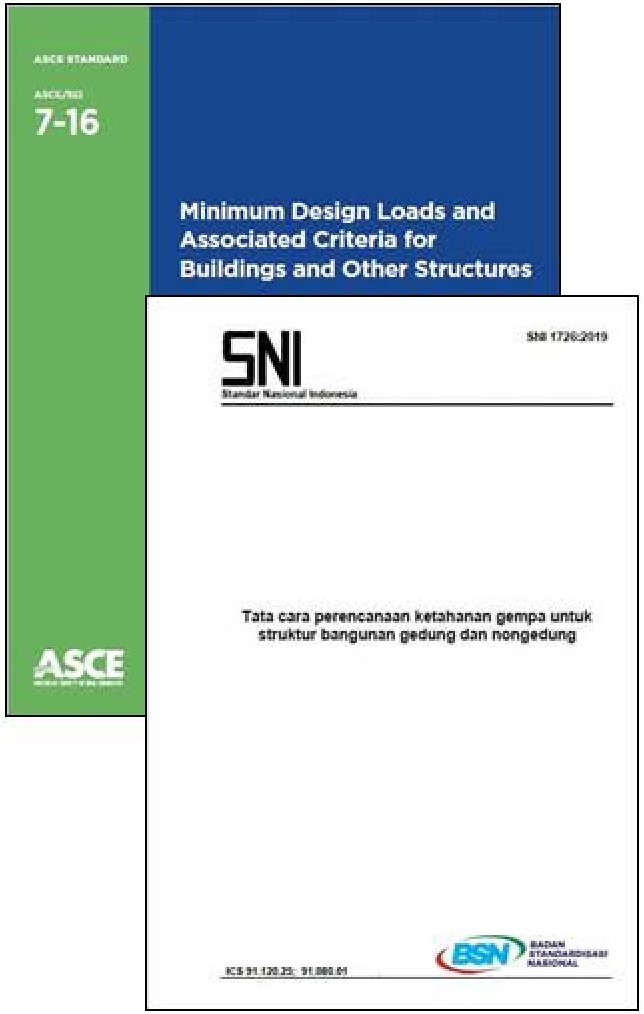
- DeepEX is the specialized software for deep excavation:
  - Wall systems: Soldier pile, tangent pile, secant pile, sheet pile, diaphragm wall, etc.
  - Support systems: Strut, raker, concrete slab, ground anchor, gravity wall*, etc.
- It can use either Limit Equilibrium, Non-Linear, or Finite Element 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

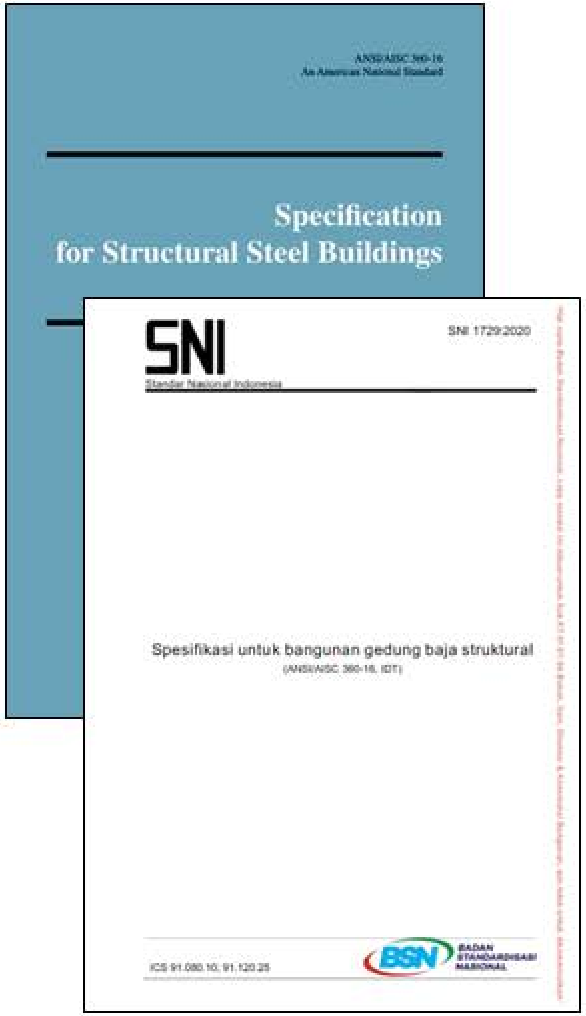
*Need optional module.

Relevant Design Codes (in Indonesia)

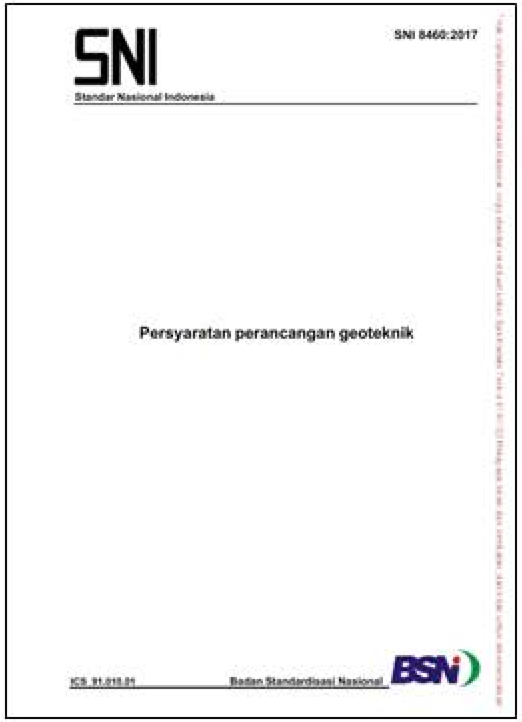


Earthquake-Resistant Design
SNI 1726-2019 (ASCE 7-16)

Concrete Design
SNI 2847-2019 (ACI 318)



Steel Design
SNI 1729-2020 (AISC 360)



Geotechnical Design
SNI 8460-2017

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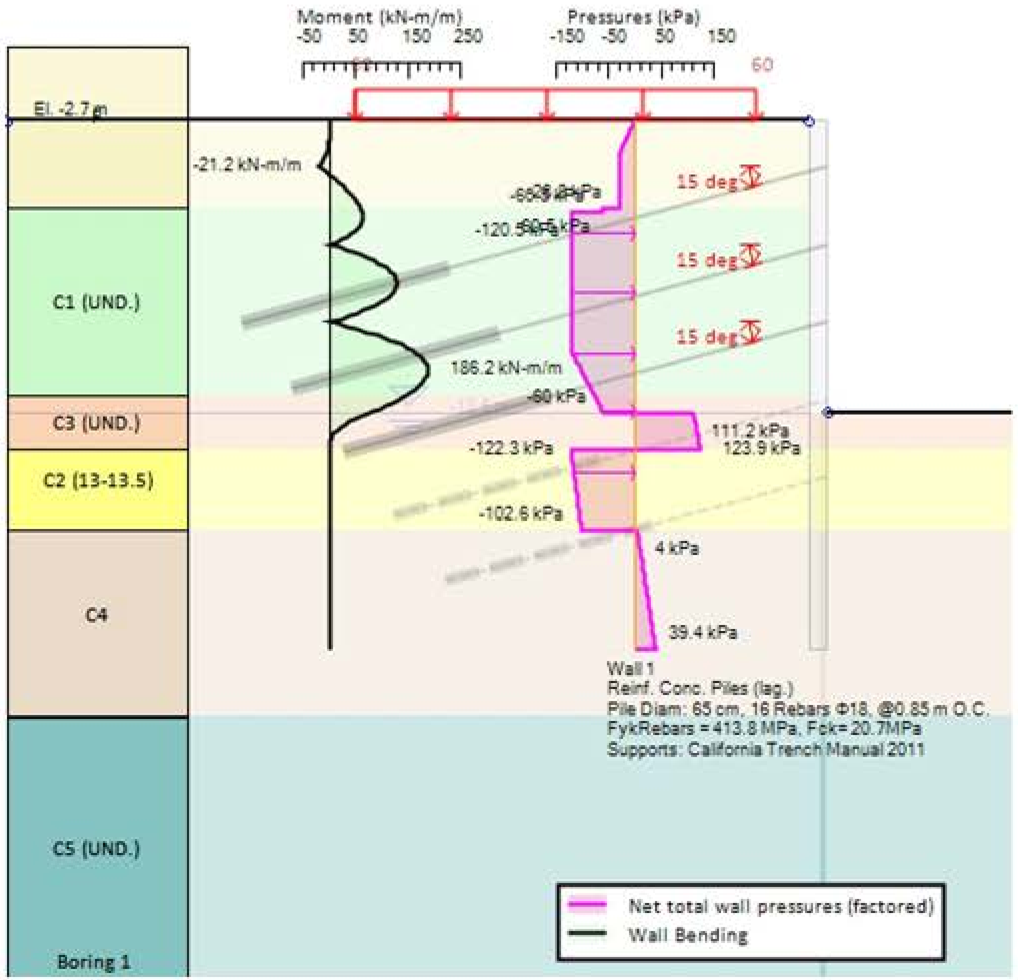
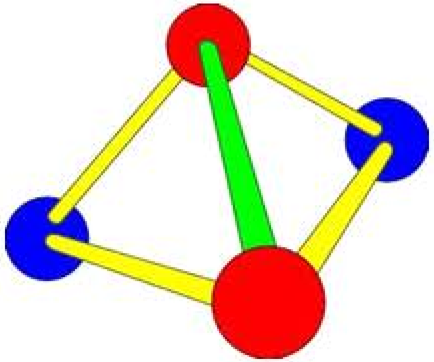
Design Sequences of Deep Excavation

1. Define soil parameters and stratigraphy
2. Determine wall and support system
3. Create construction stages
4. Select analysis method and design codes
5. Perform analysis and check safety ratio
6. Generate report and drawing

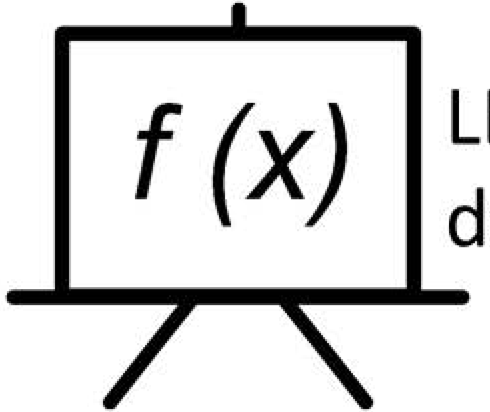


Analysis results in DeepEX
(Cantilever wall with ground anchors)

Outline



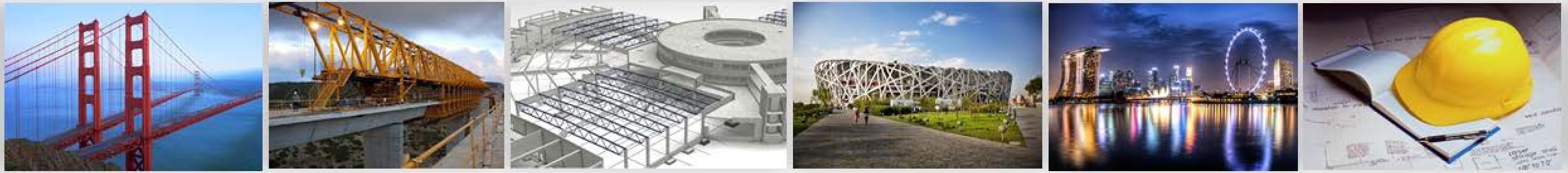
Modeling challenges and workflow enhancements



LEM approaches and design check

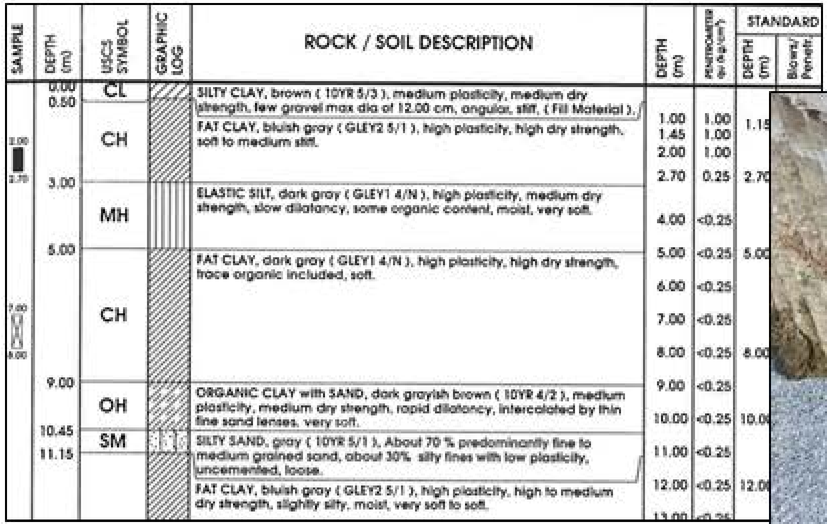
Essential design aspects & case study

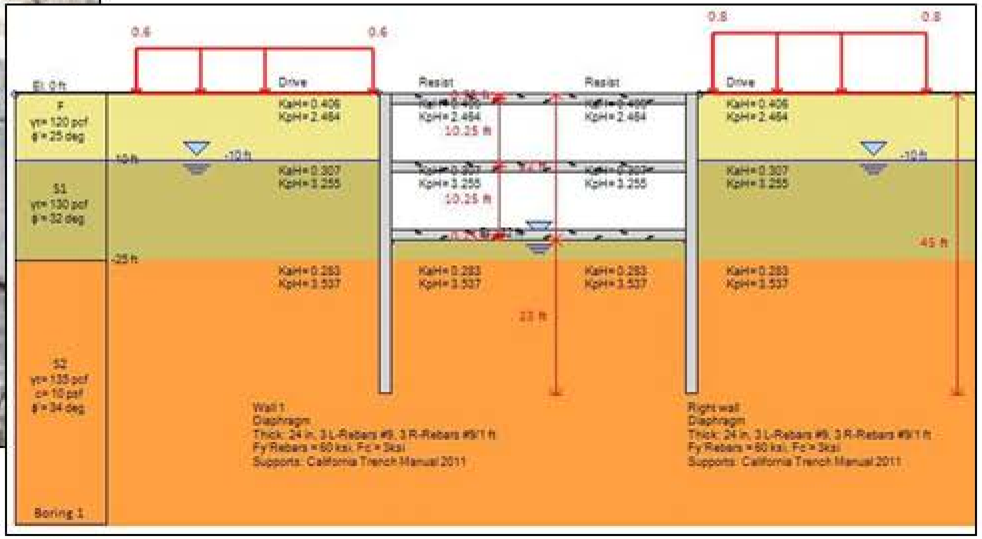
Effective Deep Excavation Analysis and Design



Modeling Challenges and Workflow Enhancements

Scopes in Deep Excavation Design





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.

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Main Modeling Challenges

1. Select appropriate soil properties.

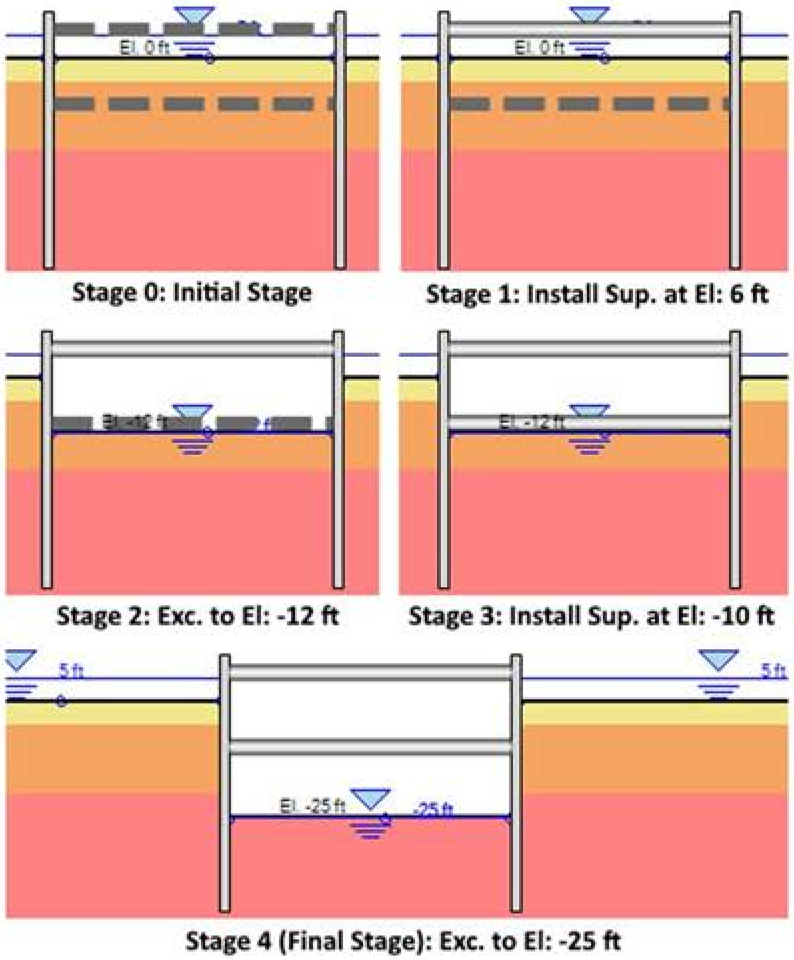
2. Calculate wall/support strength.

- 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)

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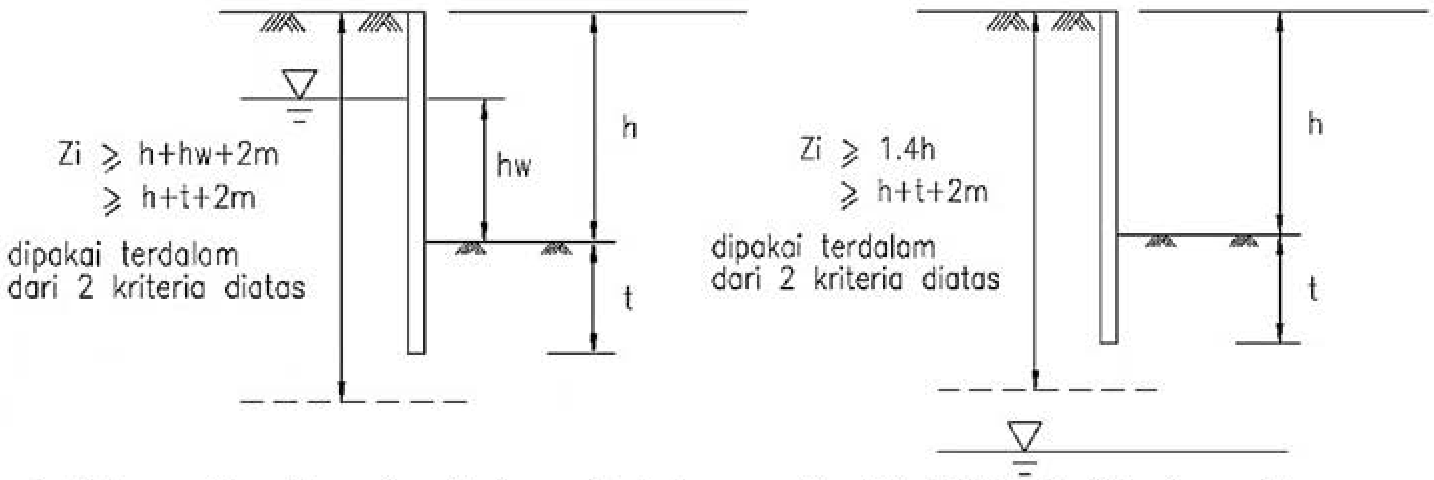
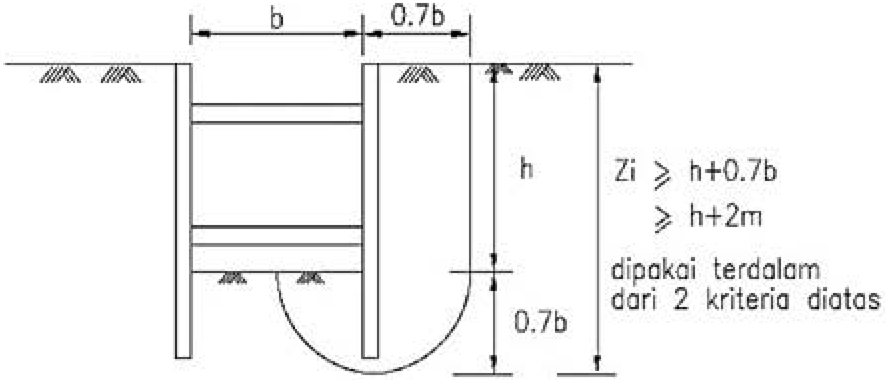
Soil Data for Deep Excavation

- Definition: Deep excavation is an excavation with depth ≥ 3m (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, φ).
    - Drained shear strength (c’, φ’).
    - 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.



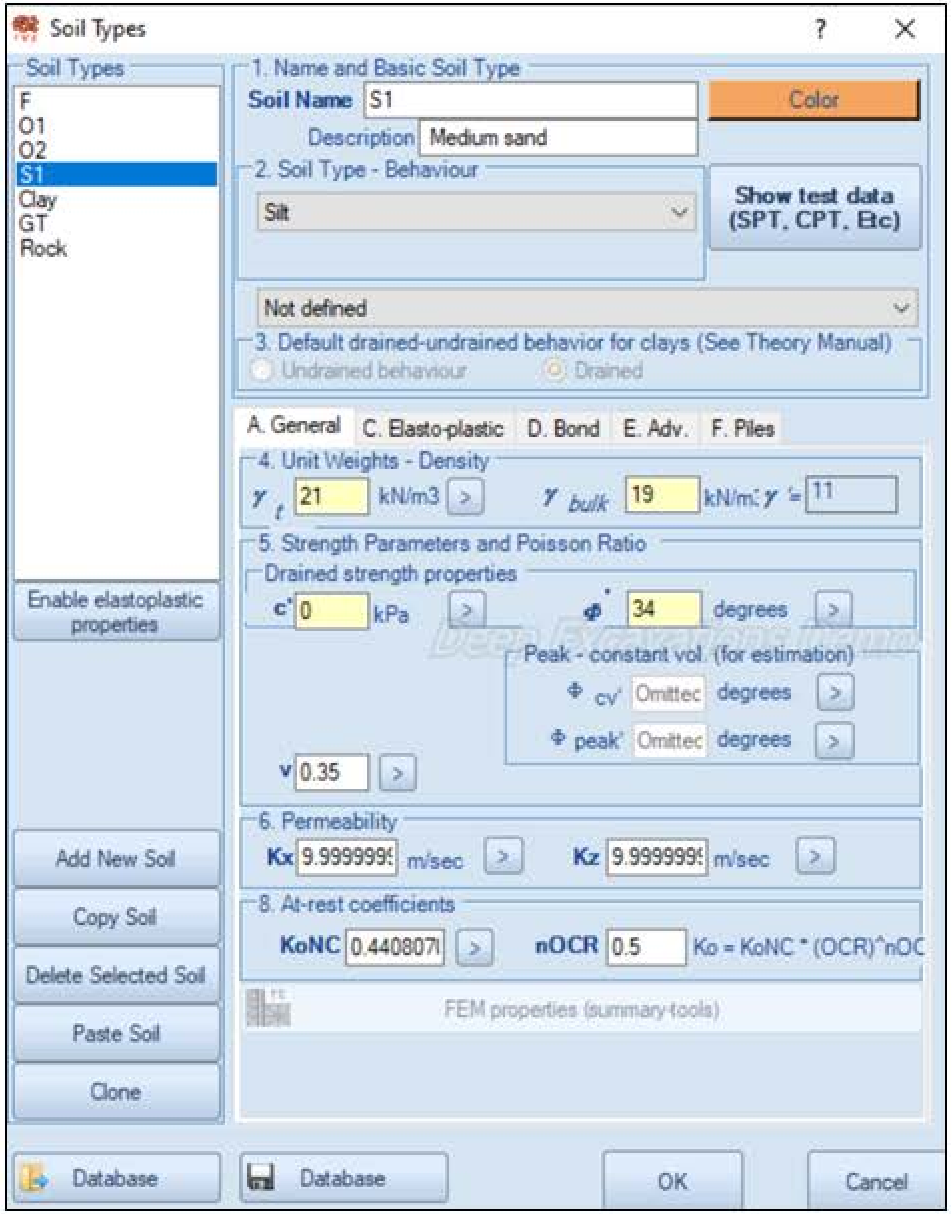
Soil investigation depth for retaining wall with GWL (left) above the base of excavation; (right) below the base of excavation.



Soil investigation depth for trench excavation

Refer to SNI 8460 Table 2 and Figure.

Soil Properties: Correlations



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

Correlating soil properties from SPT data:

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

Correlating undrained shear strength from CPT data:

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

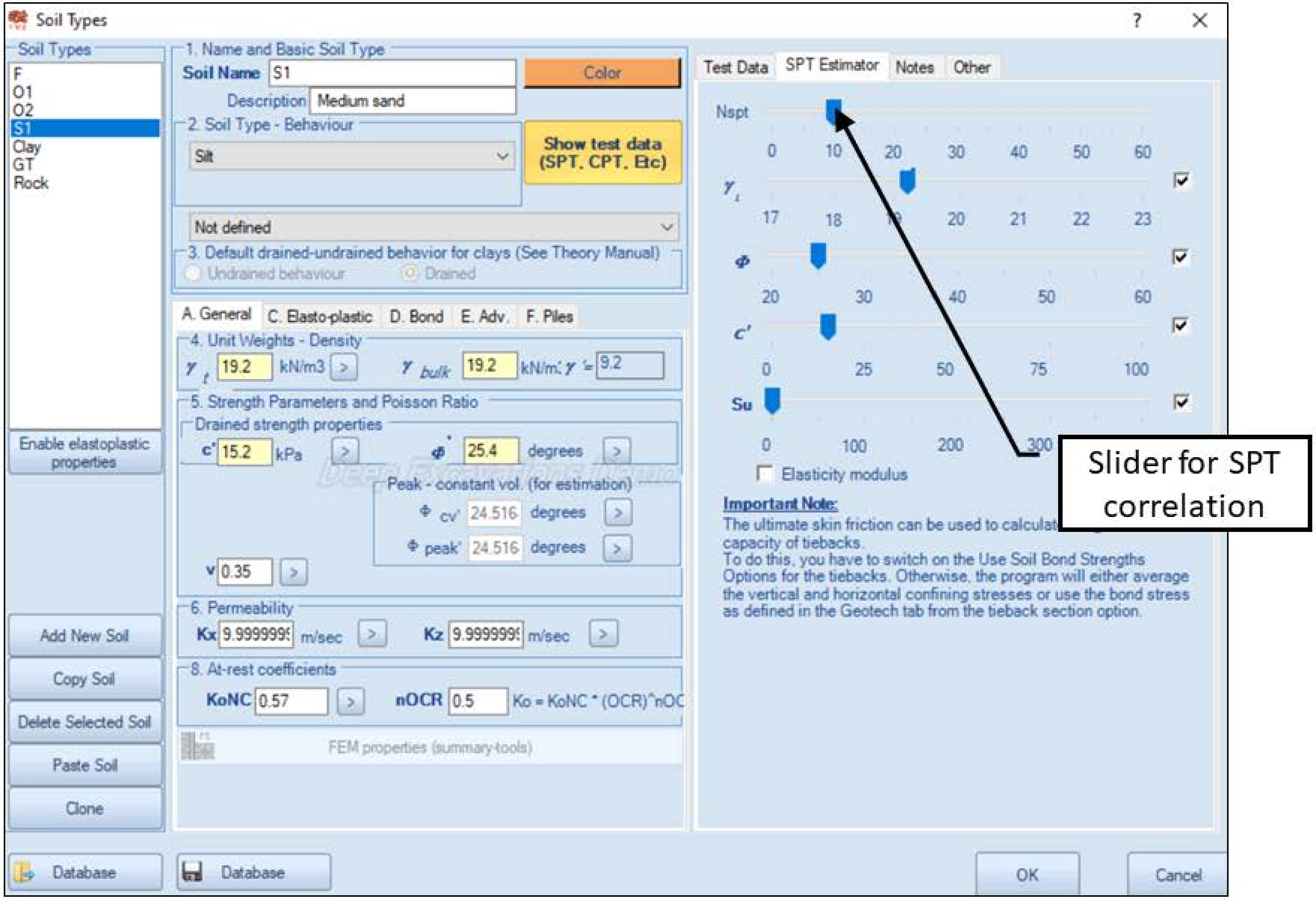
Where:

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

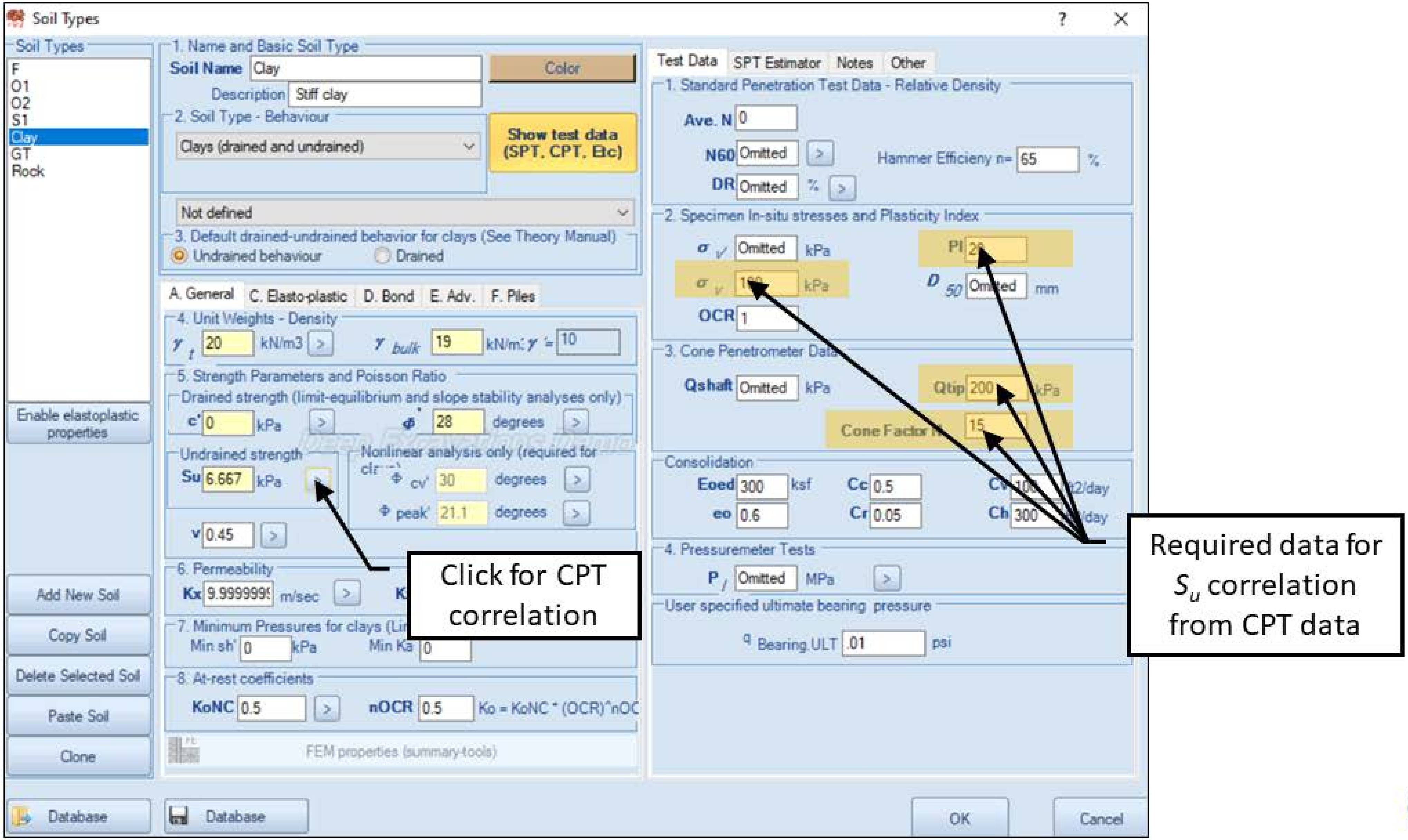
Note: PI may also be required (when $N_K \neq 15$).

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.

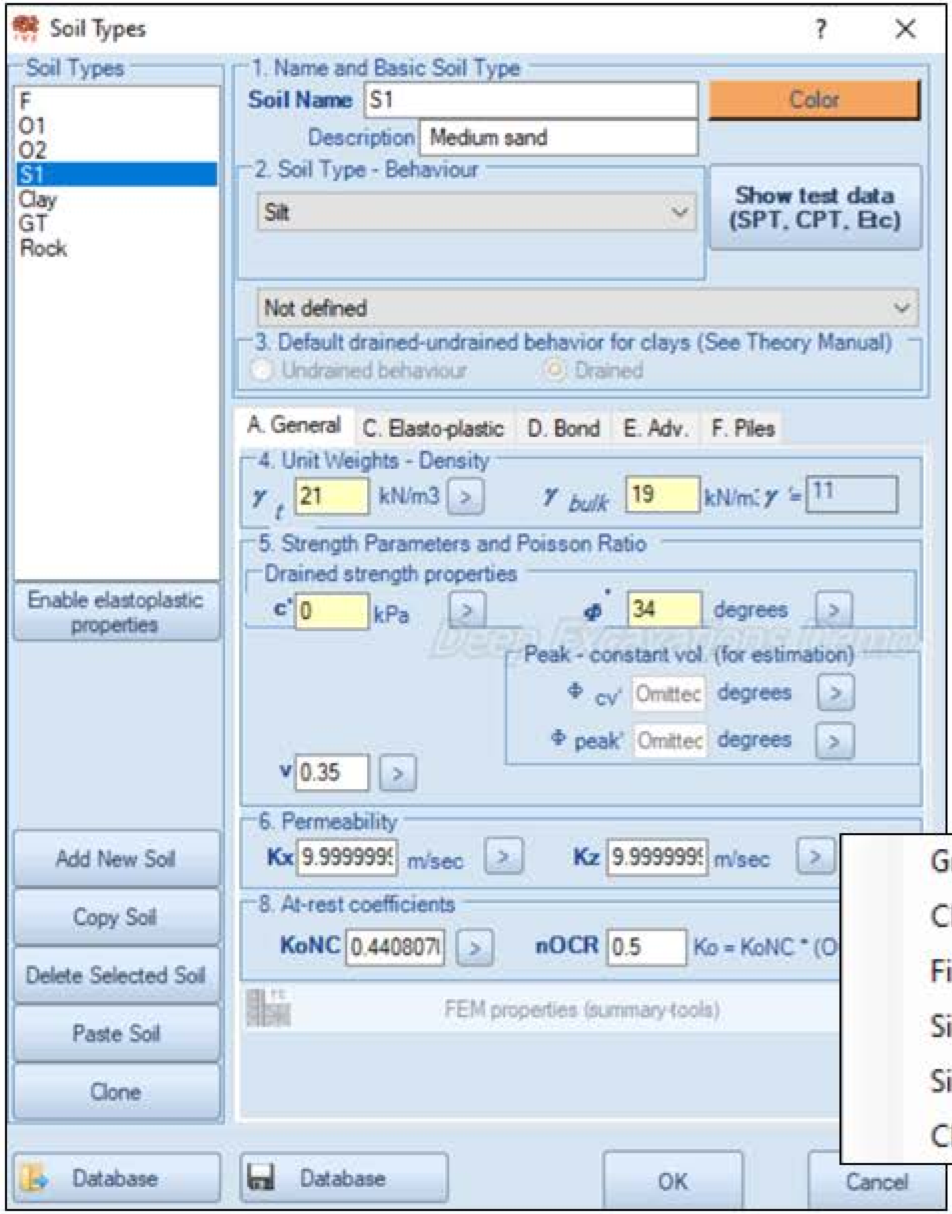
Soil Properties: SPT Correlation



Soil Properties: CPT Correlation



Soil Properties: Permeability Estimation



Gravel Kz= 0.1 cm/sec

Clean Sand Kz= 0.01 cm/sec

Fine Sand Kz = 0.001 cm/sec

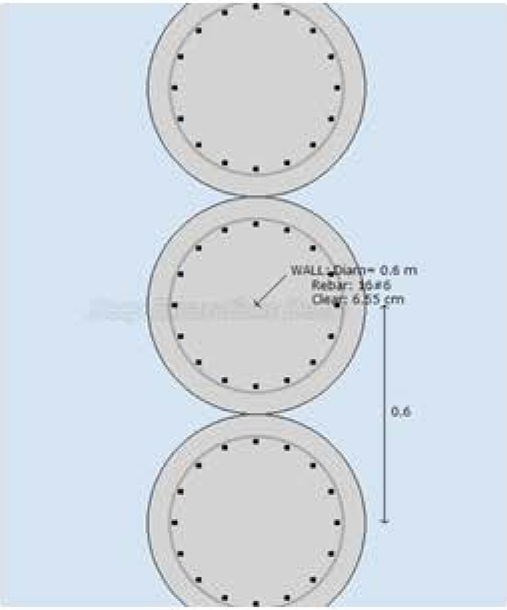
Silt Kz= 10^-5 cm/sec

Silty Clay Kz = 10^-7 cm/sec

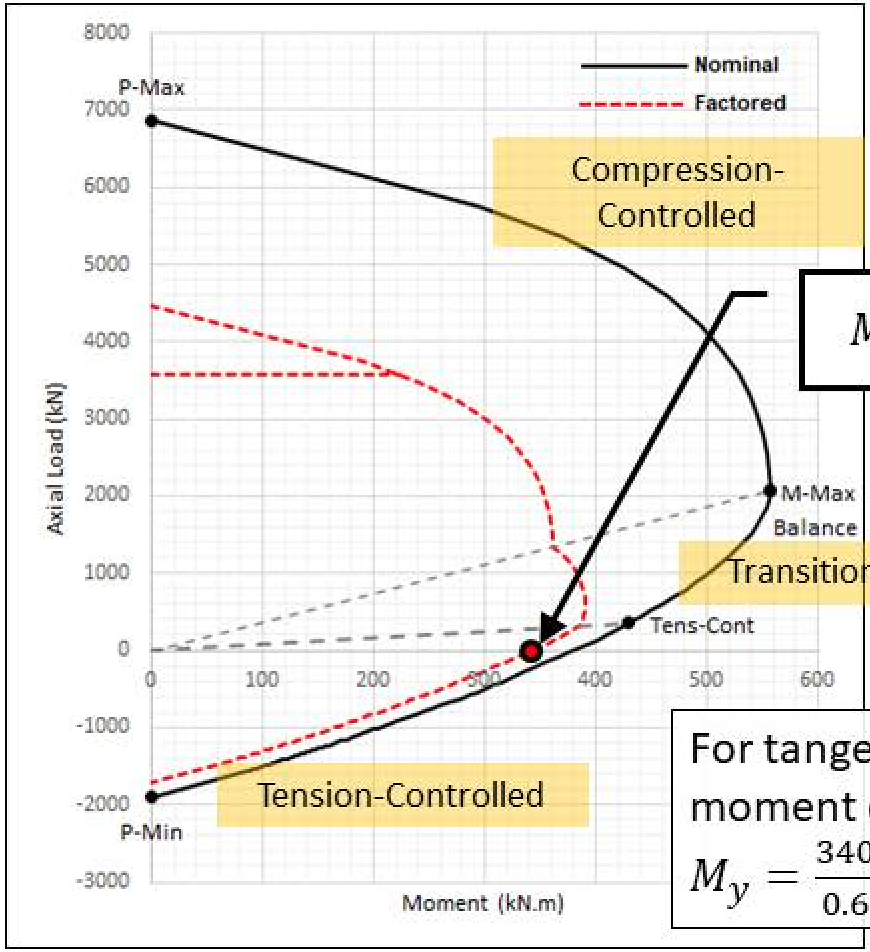
Clay Kz= 10^-8 cm/sec

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*.



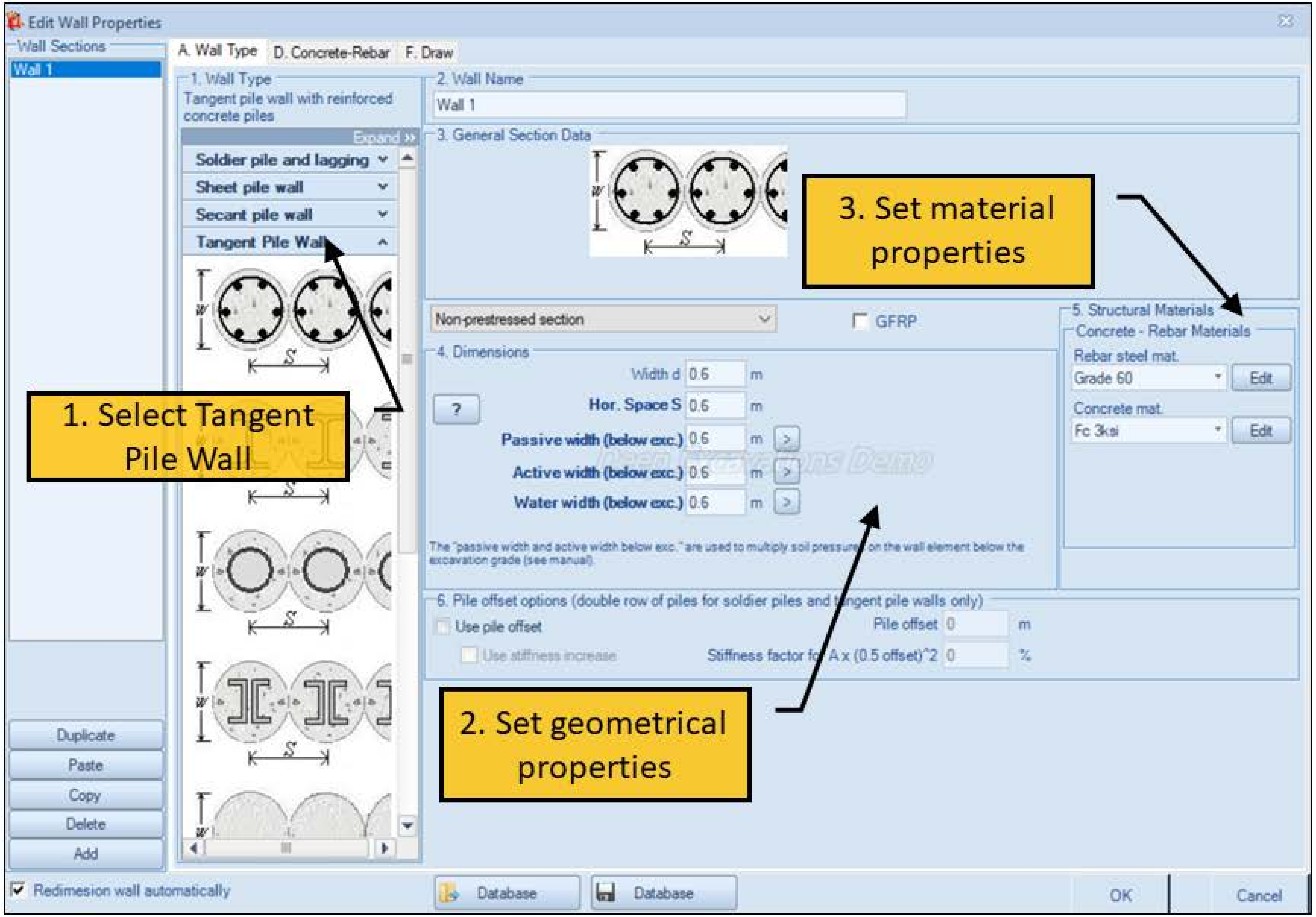
$M_y \approx 340$ kN-m

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

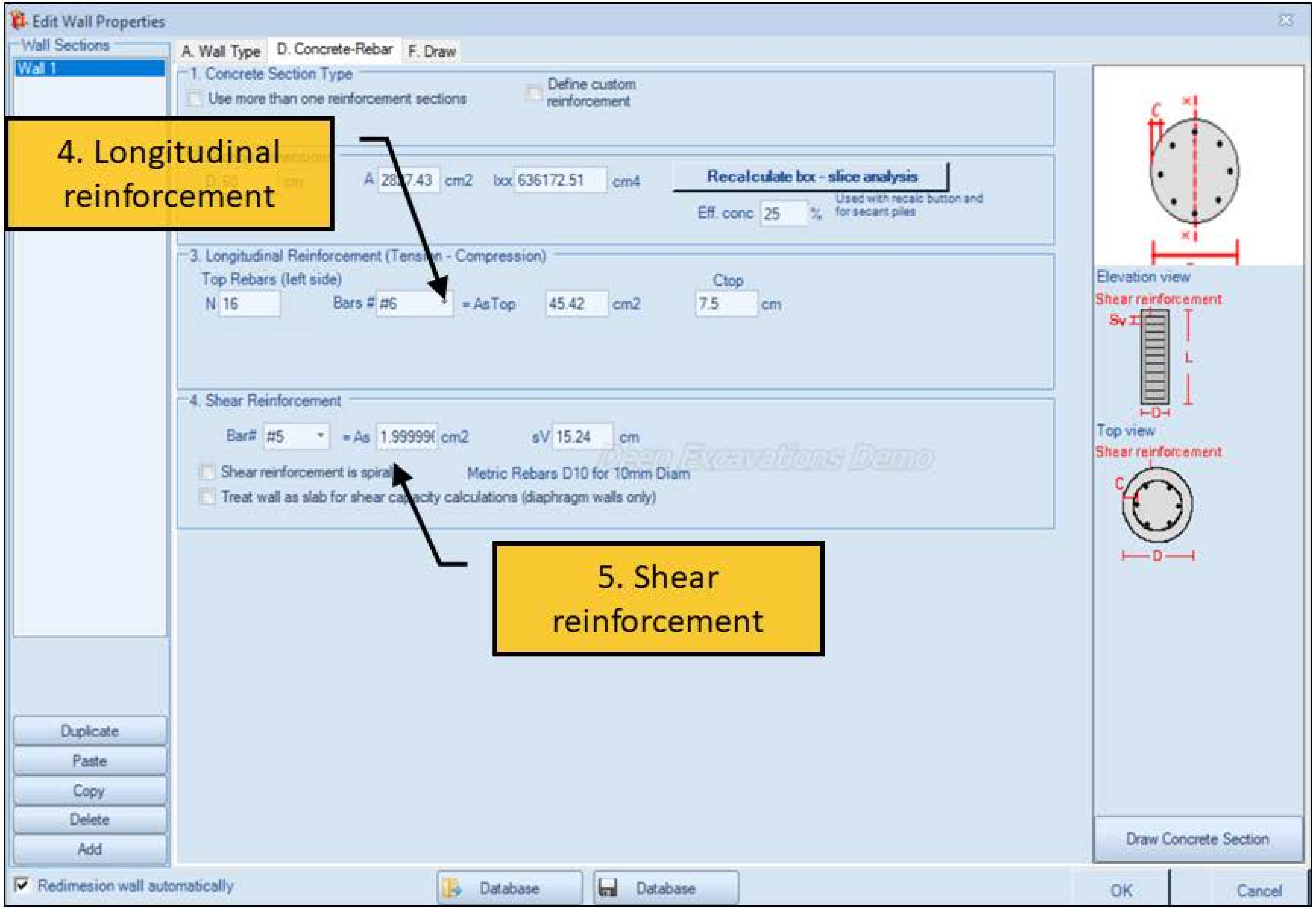
$$M_y = \frac{340}{0.6} = 566.67 \text{ kN-m/m}$$

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

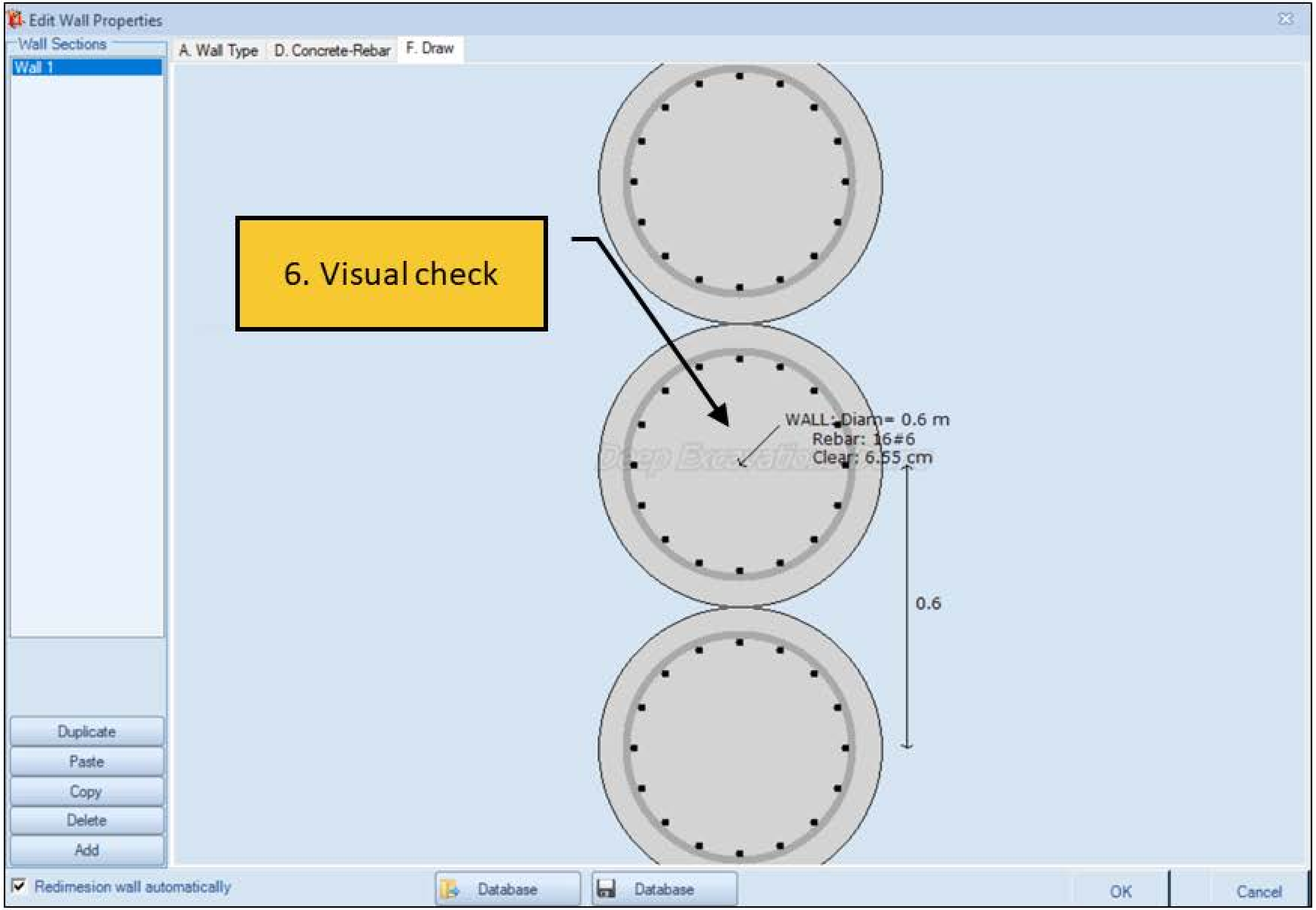
Wall: Concrete Tangent Pile (2/5)



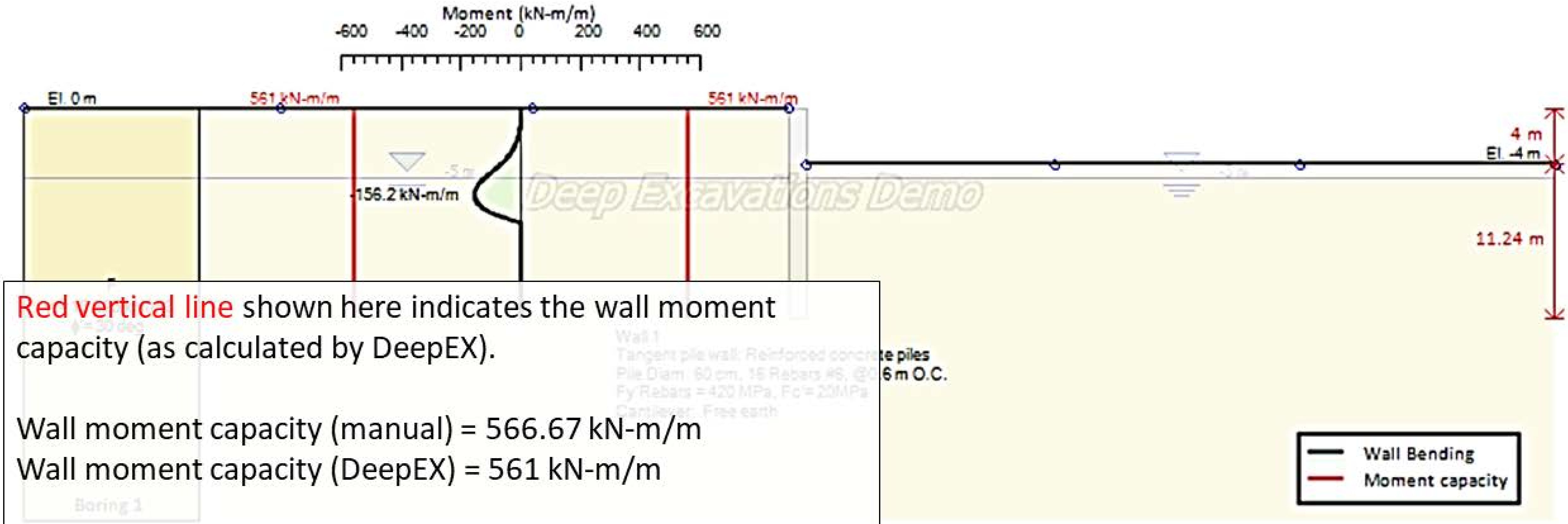
Wall: Concrete Tangent Pile (3/5)



Wall: Concrete Tangent Pile (4/5)



Wall: Concrete Tangent Pile (5/5)



Red vertical line shown here indicates the wall moment capacity (as calculated by DeepEX).

Wall moment capacity (manual) = 566.67 kN-m/m
Wall moment capacity (DeepEX) = 561 kN-m/m

Note: By default DeepEX uses Wall SF = 1.6; it is set to 1.0 in this example (for illustration purpose).

Result are in good agreement !! → Eliminate design loop with structural engineer (=save time).

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).

$$Z_x = \frac{I_{xx}}{y} = \frac{50700}{44.7/2} = 2268.46 \text{ cm3/m}$$

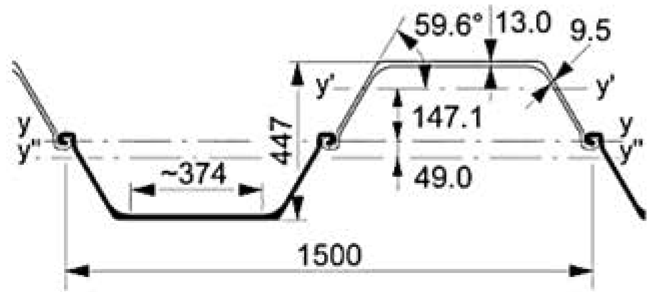
2. Calculate nominal capacity:

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

3. Calculate factored capacity

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

- Note: Ω_b is the safety factor for flexure.



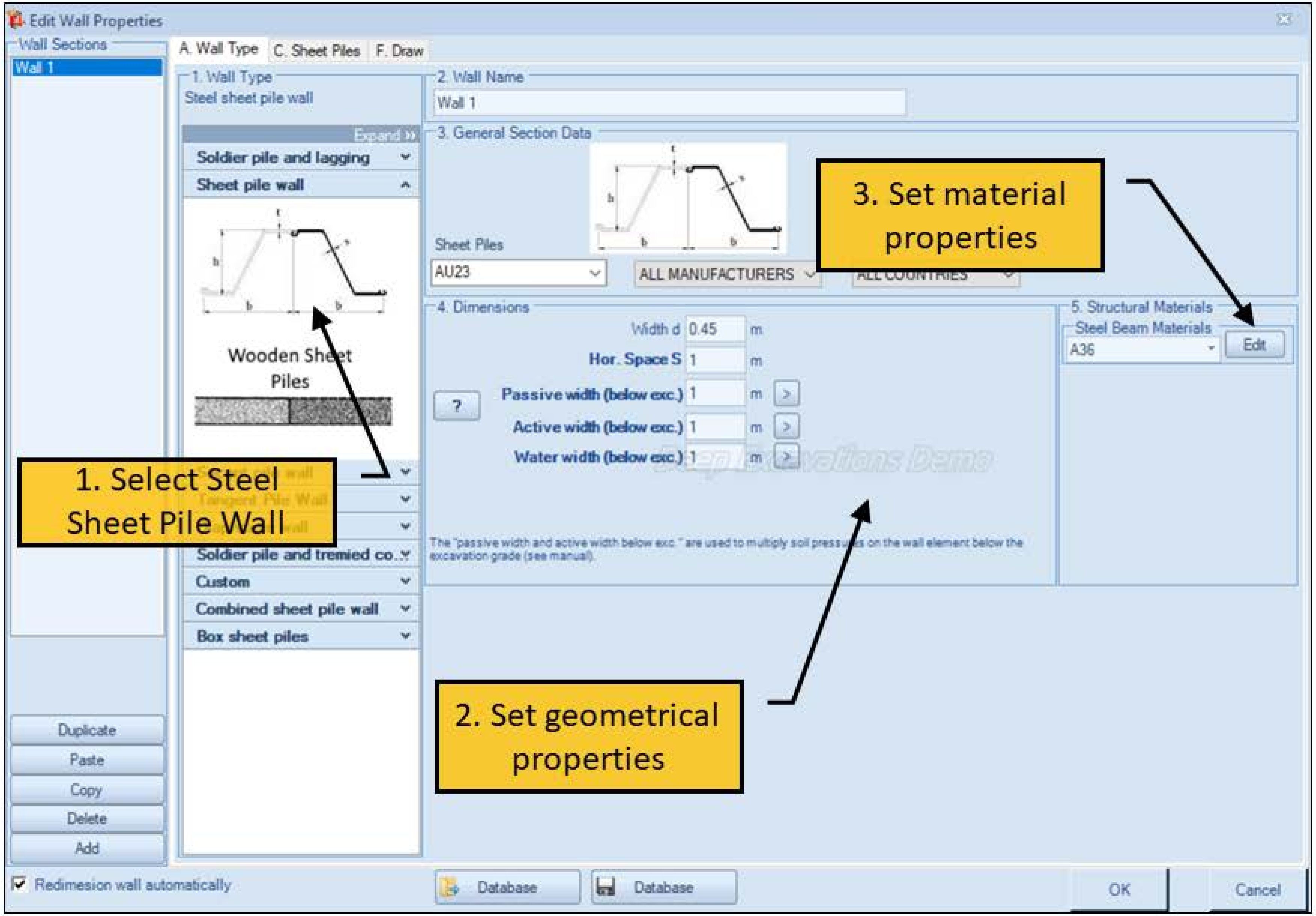
AU 23

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

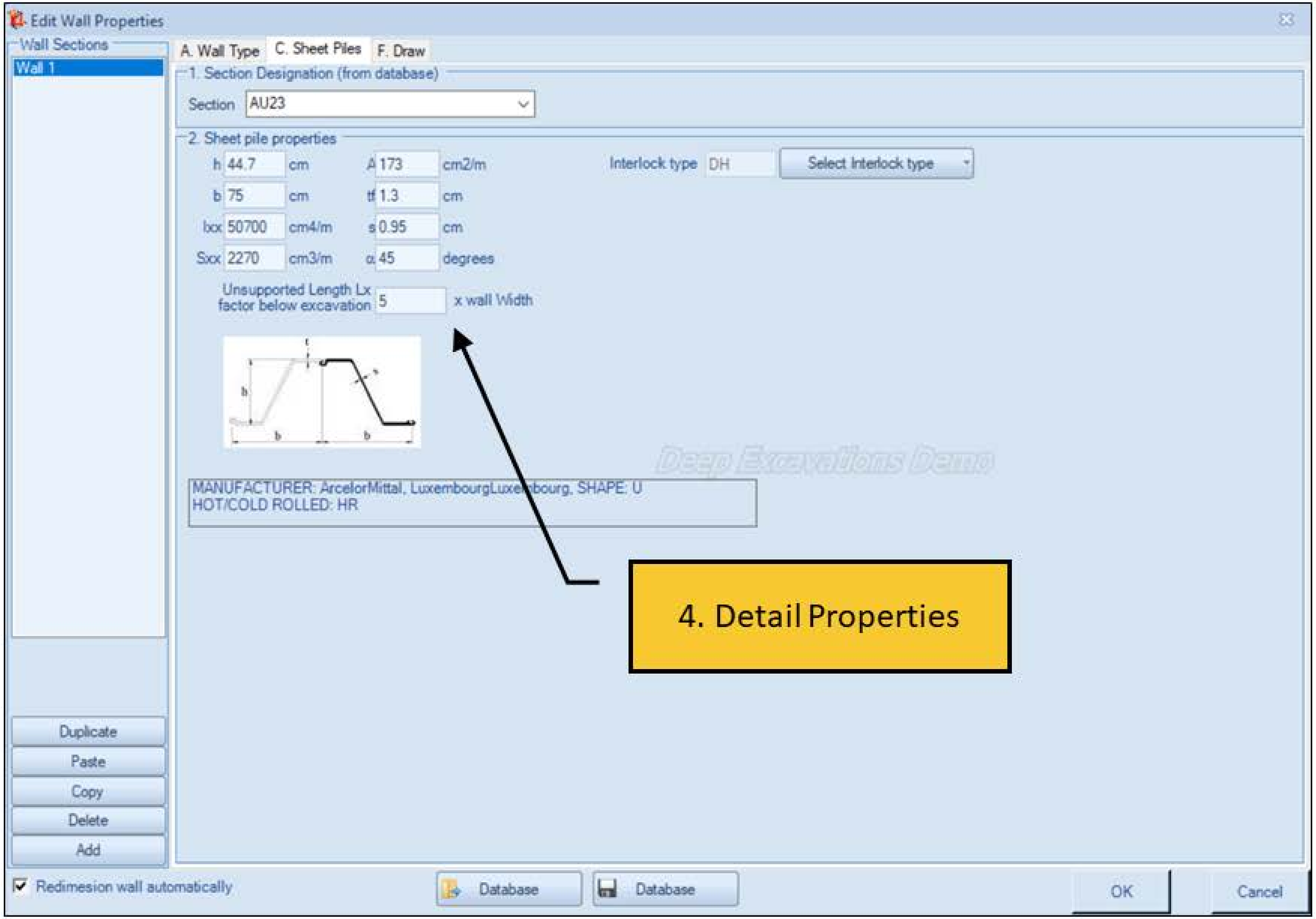
A	Sectional area
G	Mass per meter
I_y	Moment of inertia about the main neutral axis y-y
$W_{el,y}$	Elastic section modulus
r_g	Radius of gyration about the y-y axis
A_L	Coating area. One side, excludes inside of interlocks
S	Single pile: considered neutral axis y'-y'
D	Double pile, wall: considered neutral 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)



Wall: Steel Sheet Pile (3/5)



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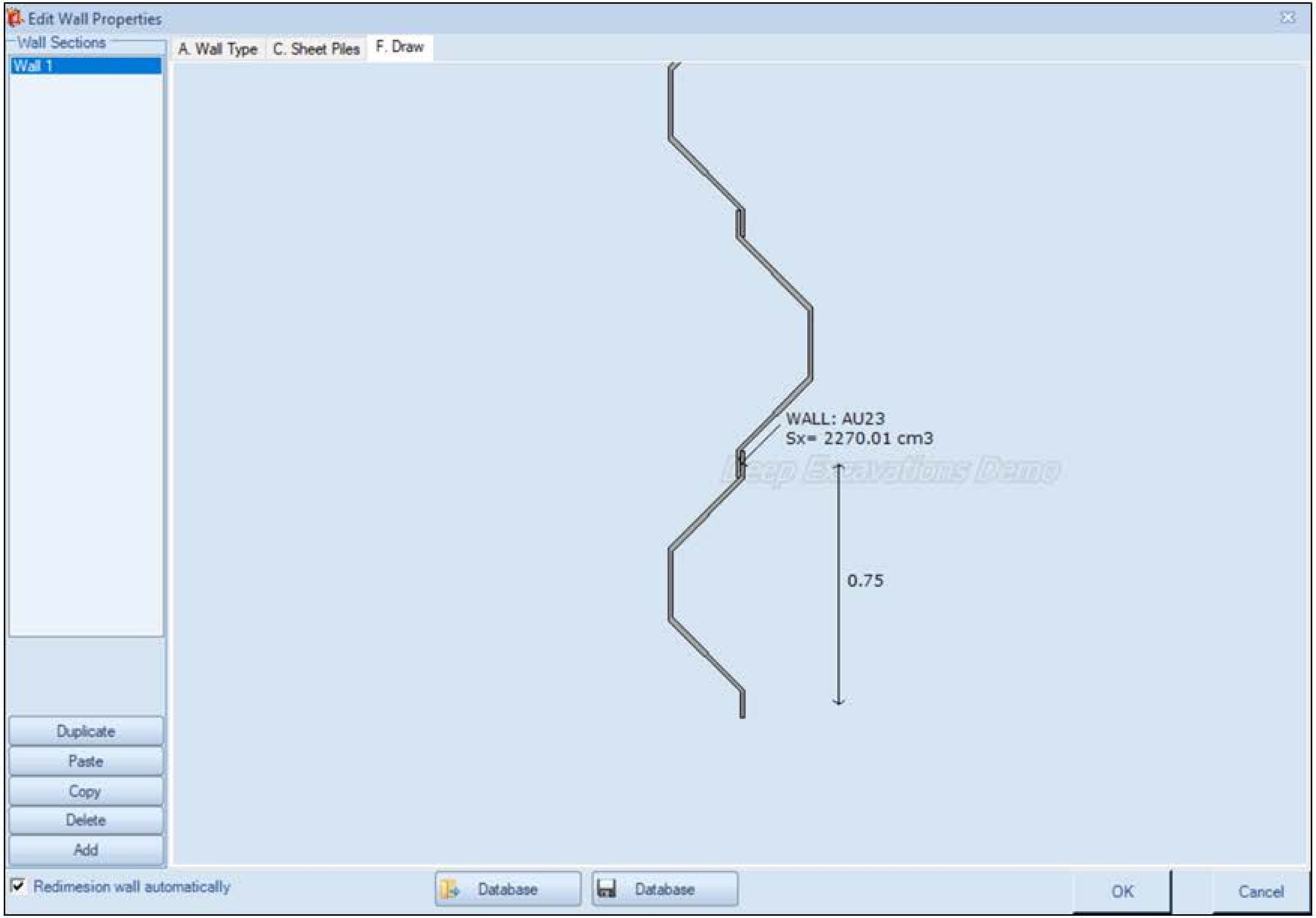
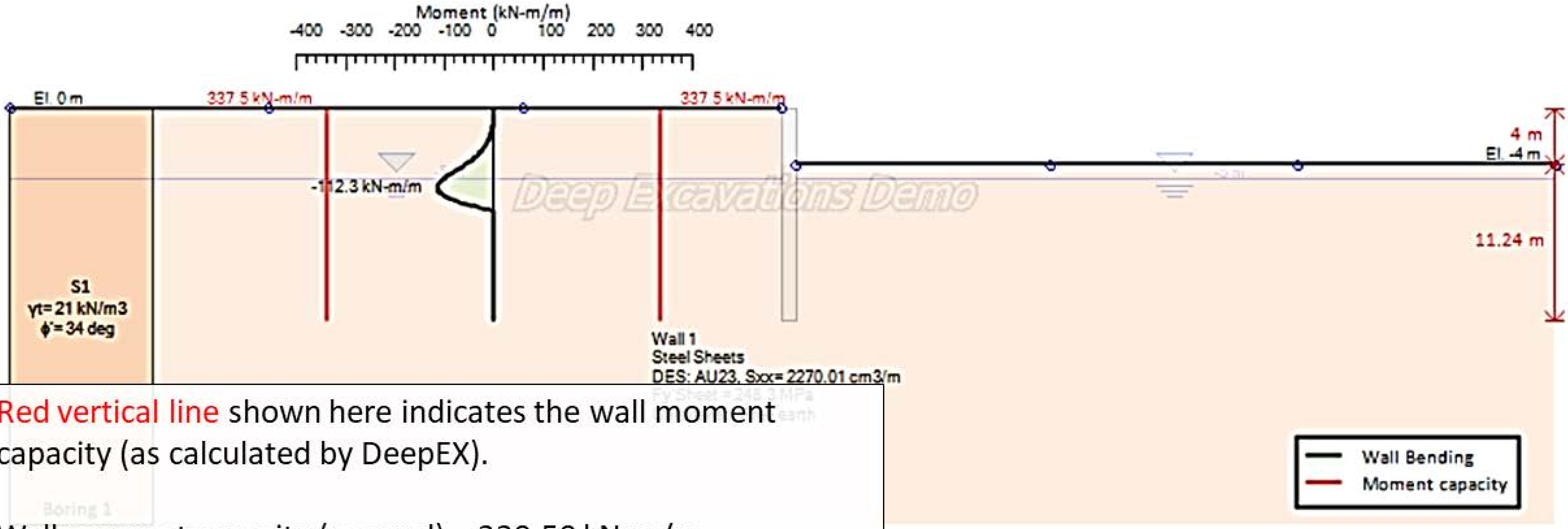
Wall: Steel Sheet Pile (4/5)



Wall: Steel Sheet Pile (5/5)

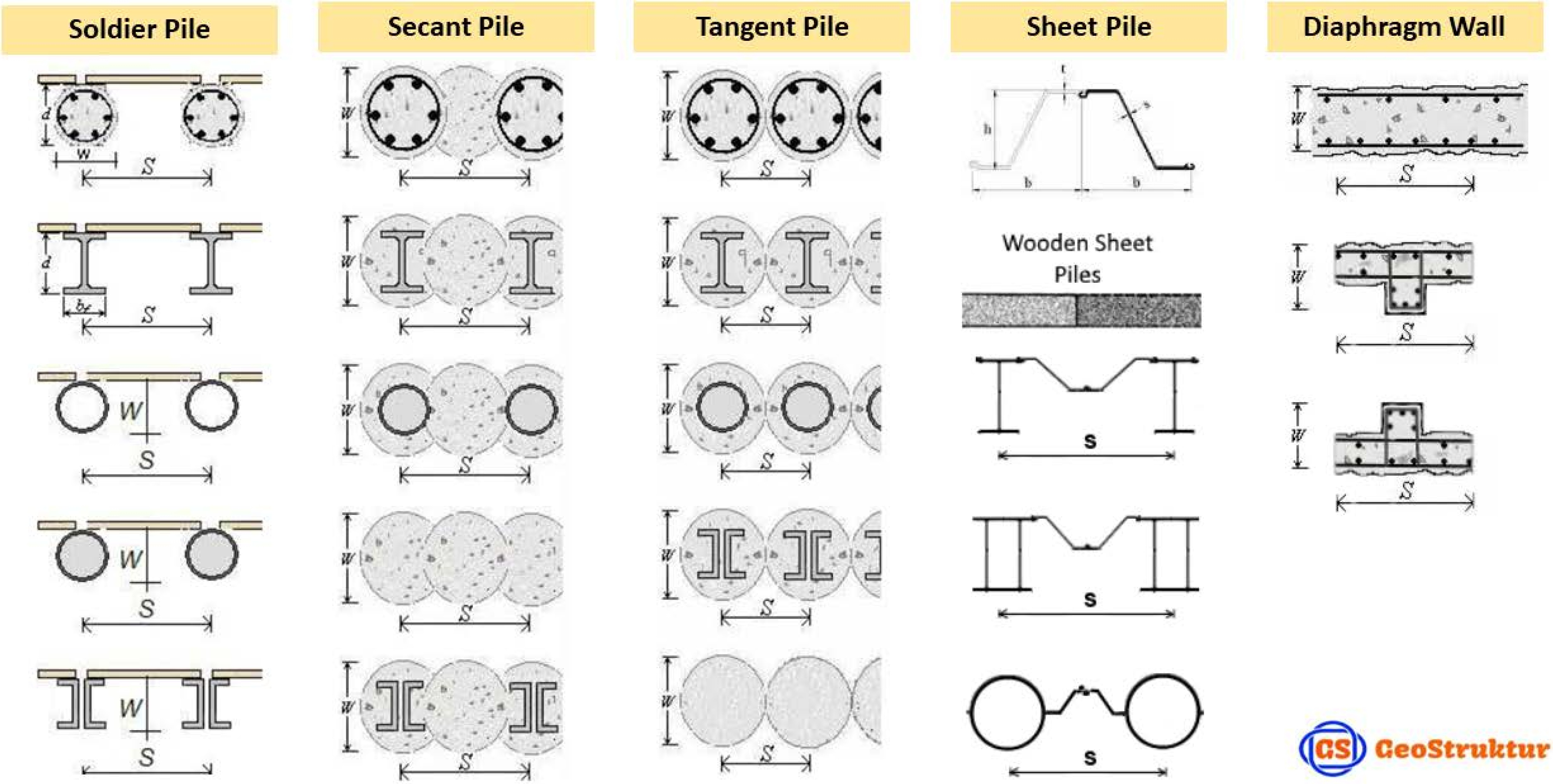


Red vertical line shown here indicates the wall moment capacity (as calculated by DeepEX).

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

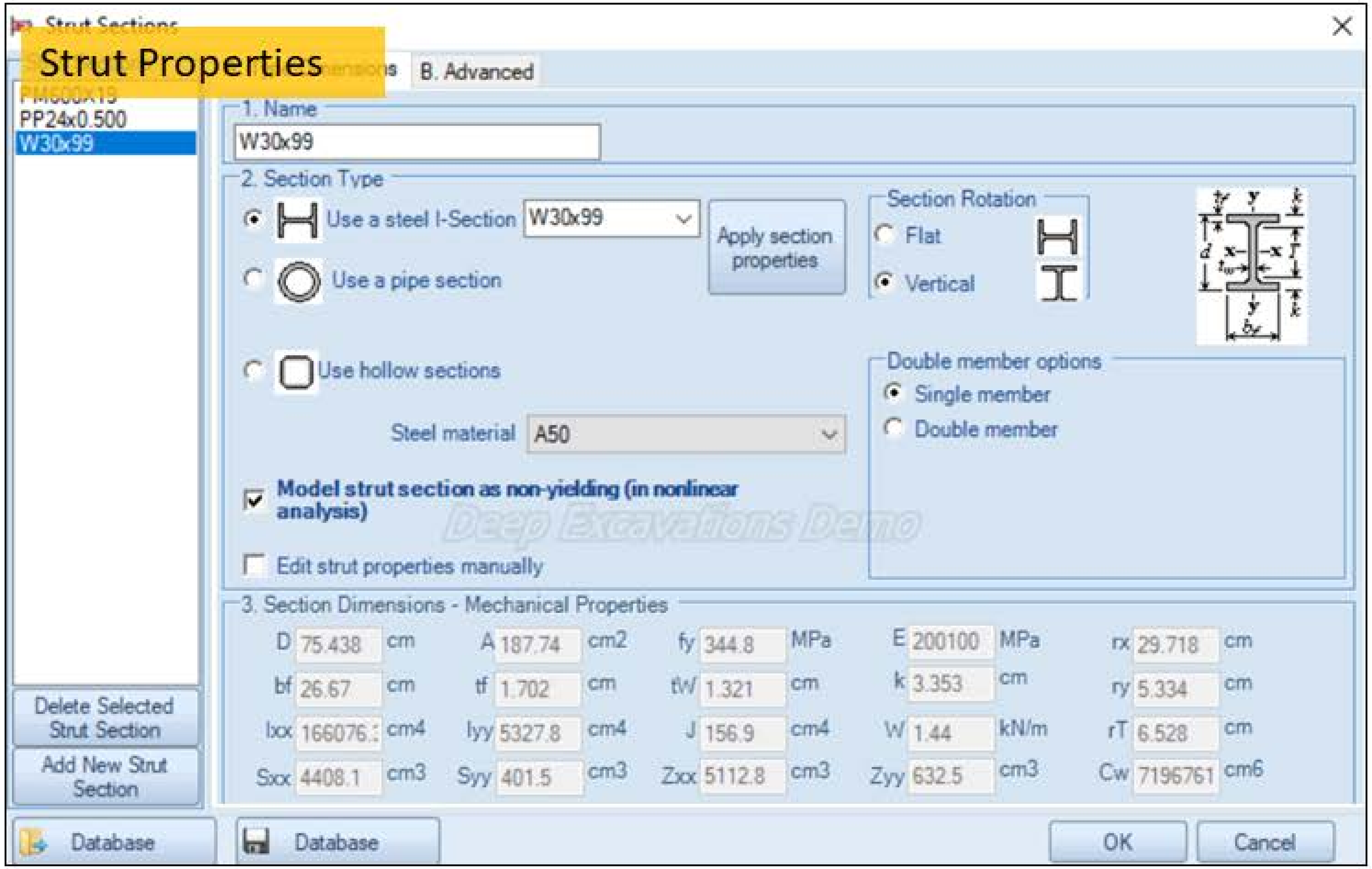


Support: Strut (1/5)

- **Support Type:** Steel Strut.

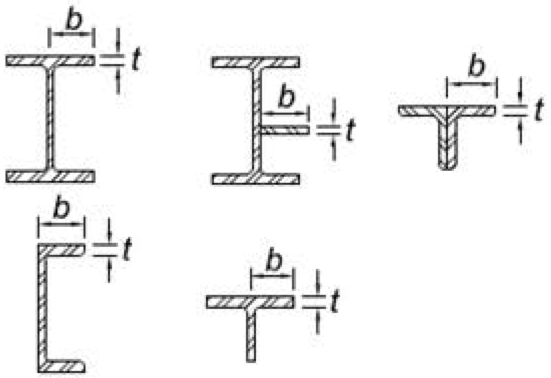
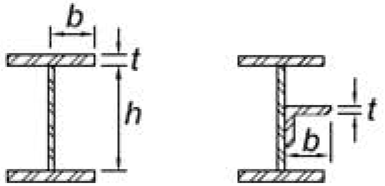
- **Properties:**
  - Geometry, as shown (W30x99).
  - Steel Grade A50, f_y = 344.74 MPa.
  - Unbraced length ≈ 15m.
  - Horizontal spacing = 5m.

- **Conventional Way:** Manual calculation as per referred standard (e.g. AISC 360).



Support: Strut (2/5)

TABLE B4.1a
Width-to-Thickness Ratios: Compression Elements
Members Subject to Axial Compression

	Case	Description of Element	Width-to-Thickness Ratio	Limiting Width-to-Thickness Ratio λ_r (nonslender/slender)	Examples
iffened 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:

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

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

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

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

where

A_g = gross cross-sectional area of member, in.^{2} (mm^2)

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)

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

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:

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

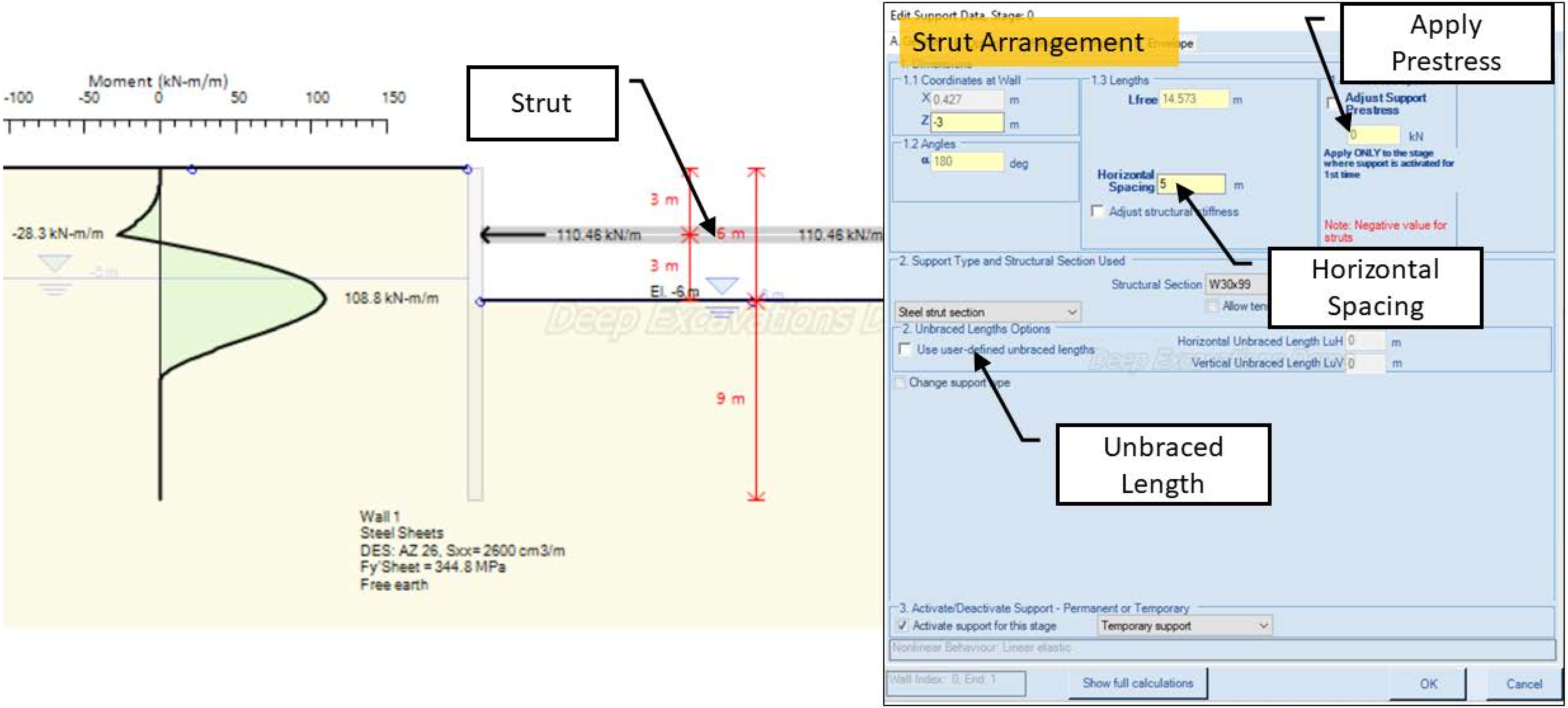
The critical stress, F_{cr}, shall be determined according to Equation E3-2 or E3-3, using the torsional or flexural-torsional elastic buckling stress, F_e, determined as follows:

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

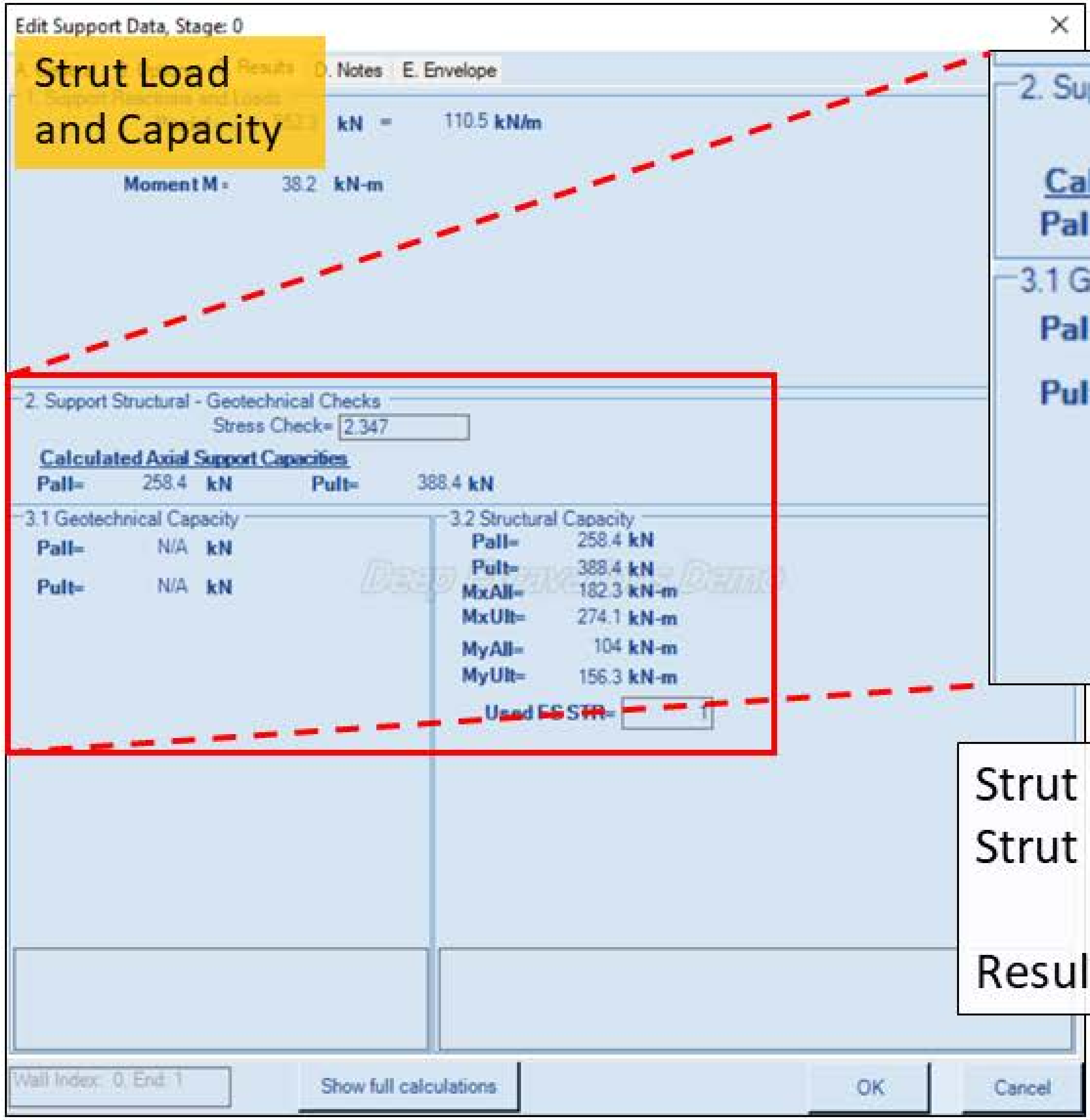
$$F_e = \left(\frac{\pi^2 E C_w}{L_{cz}^2} + GJ\right)\frac{1}{I_x + I_y} \quad \text{(E4-2)}$$

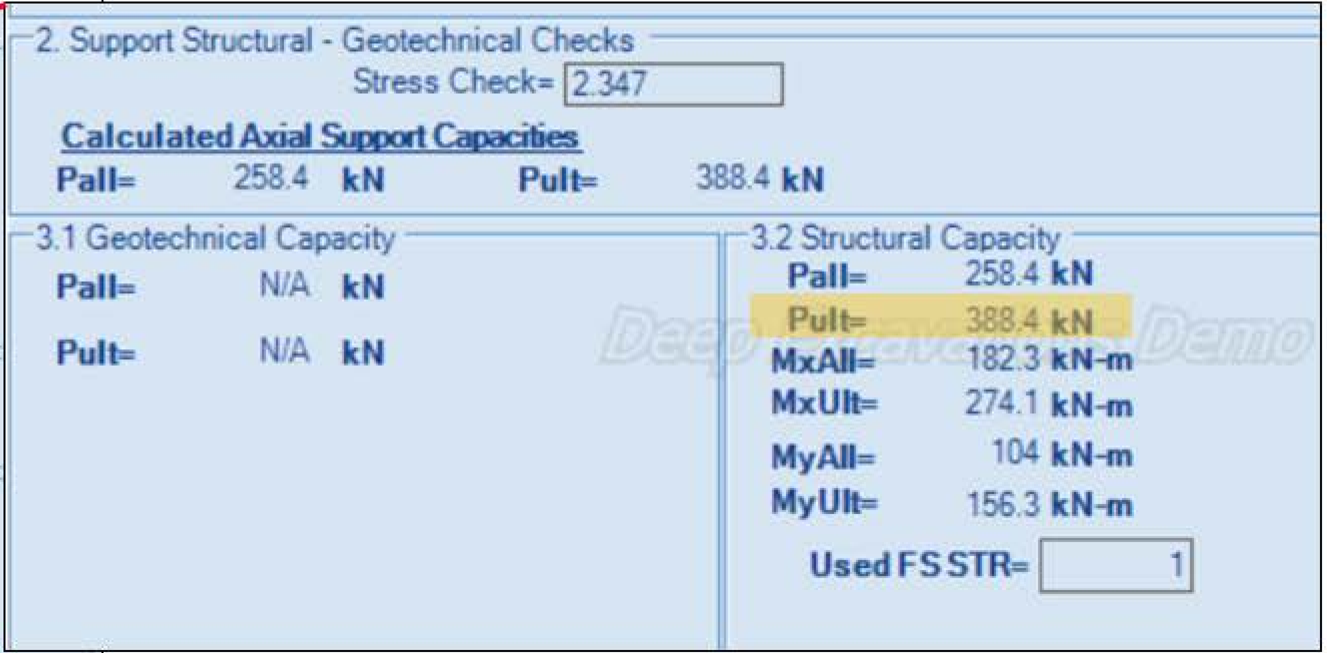
Source: AISC 360-16.

Support: Strut (4/5)



Support: Strut (5/5)





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).

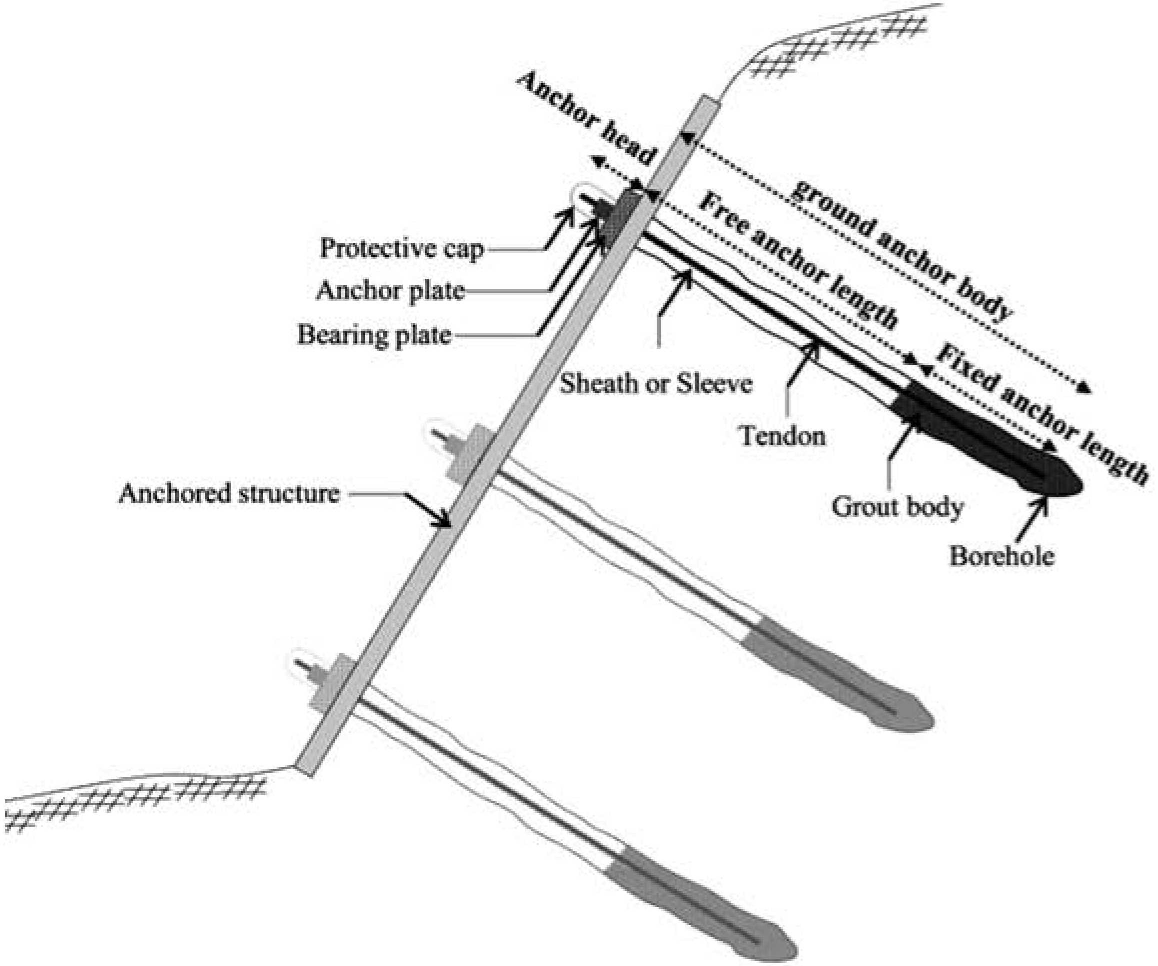


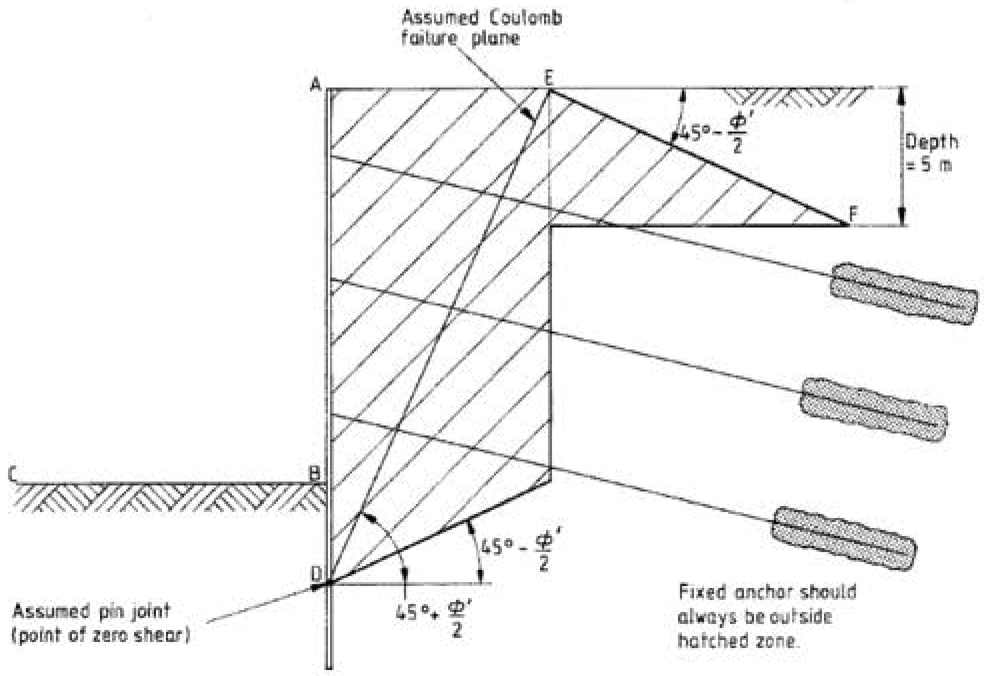
Illustration of Ground Anchors

Support: Ground Anchor (2/6)

- Fixed length requirements:
  - At least 5m below the ground.
  - Located outside the failure surface.
  - Embedded in N-SPT ≥ 25 (non-cohesive) and N-SPT ≥ 20 (cohesive).
- Geometry recommendations:
  - Spacing ≥1.5m for anchor with D ≤ 20 cm (to avoid group effect).
  - Anchor angle between 30°-45°.
- 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

Refer to SNI 8460 Section 10.6 for details.



Location of anchor fixed length (BS-8081)

Support: Ground Anchor (3/6)

- Anchor capacity in cohesive soil:

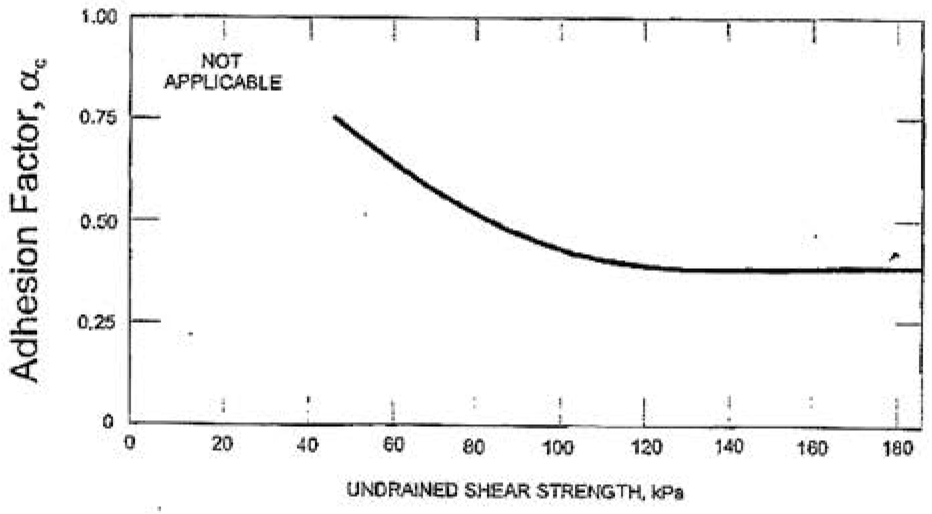
$$R_{ult} = \alpha A_s L_s S_{u,avg} = q_{ult} A_s L_s$$

- 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.
  - α = Adhesion factor.
  - σ_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.



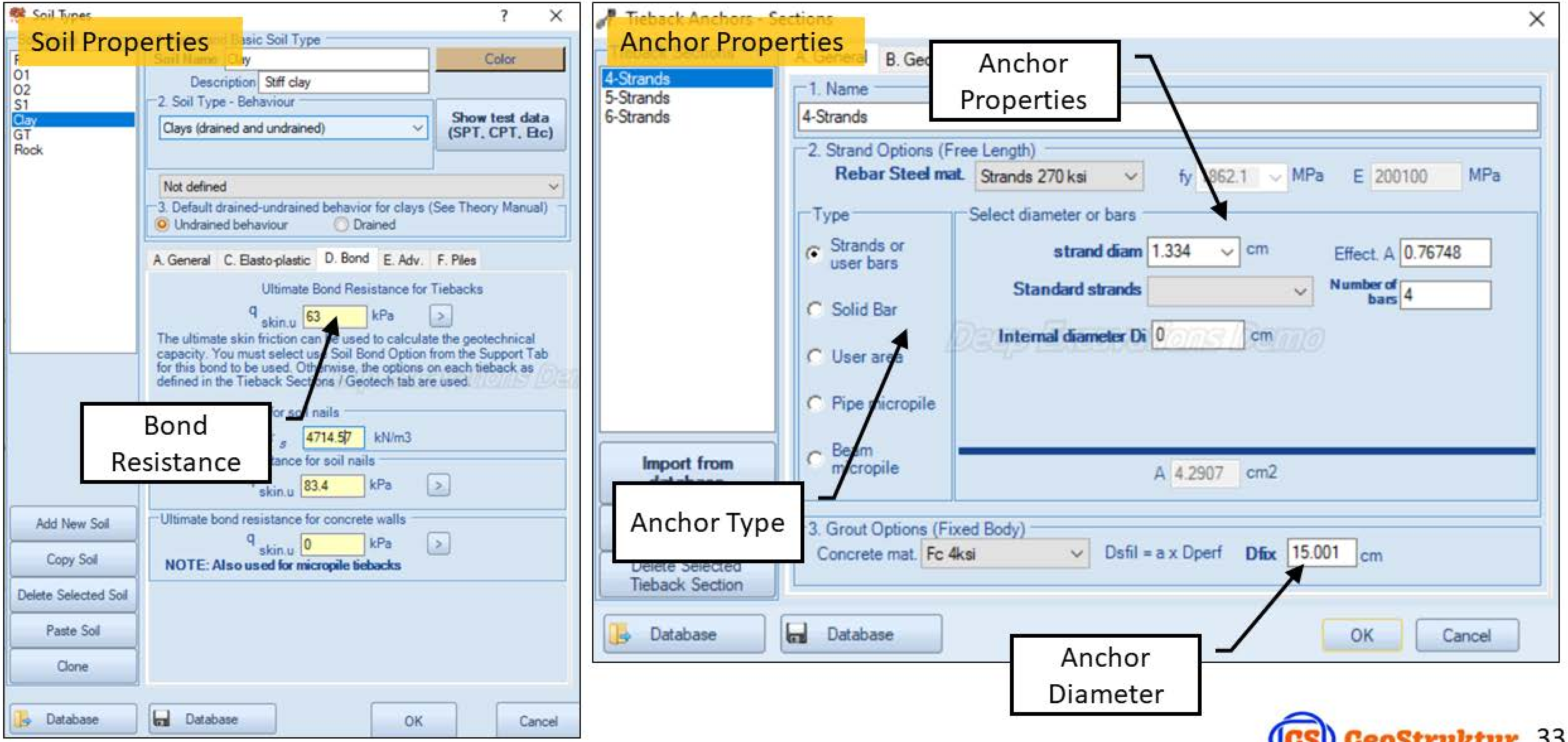
Adhesion Factor*

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

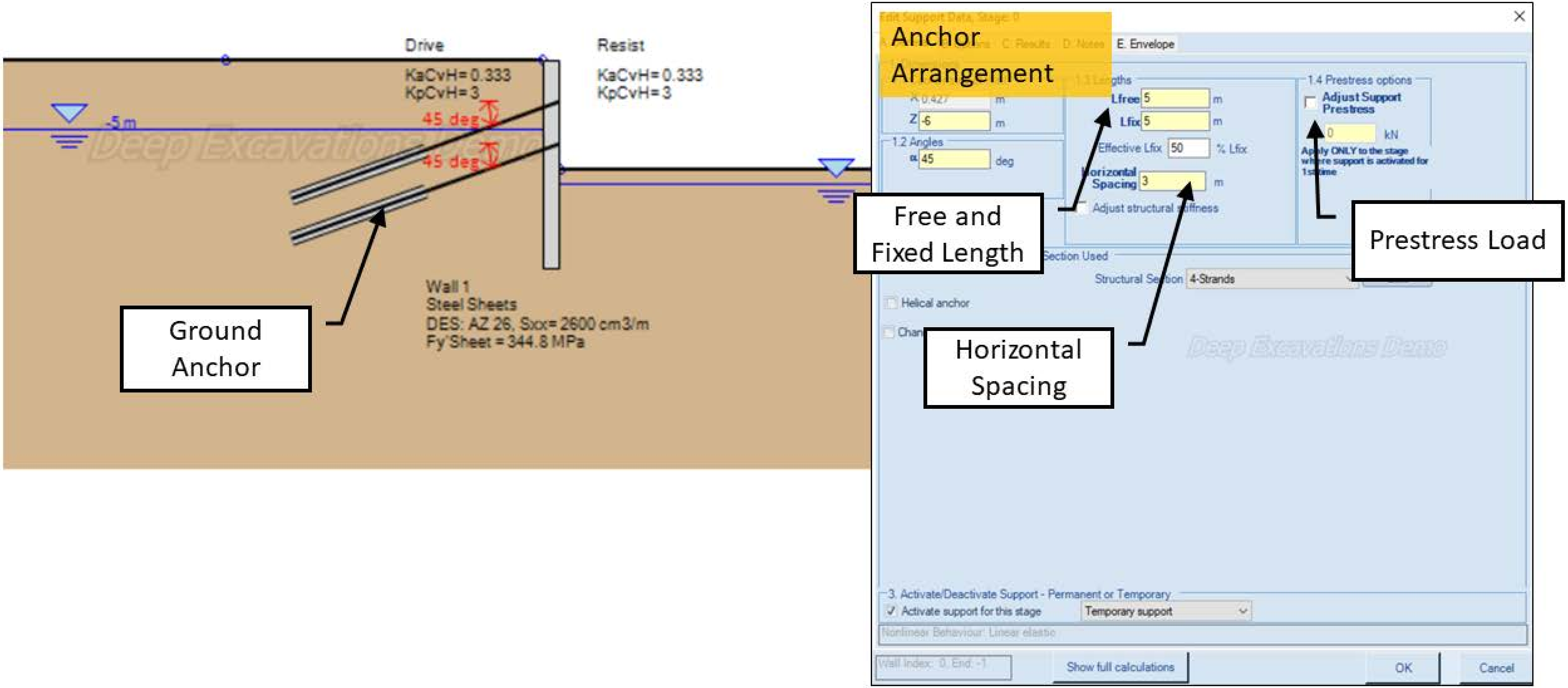
Anchor Coefficient

* Figure from Canadian Foundation Engineering Manual 4th Edition

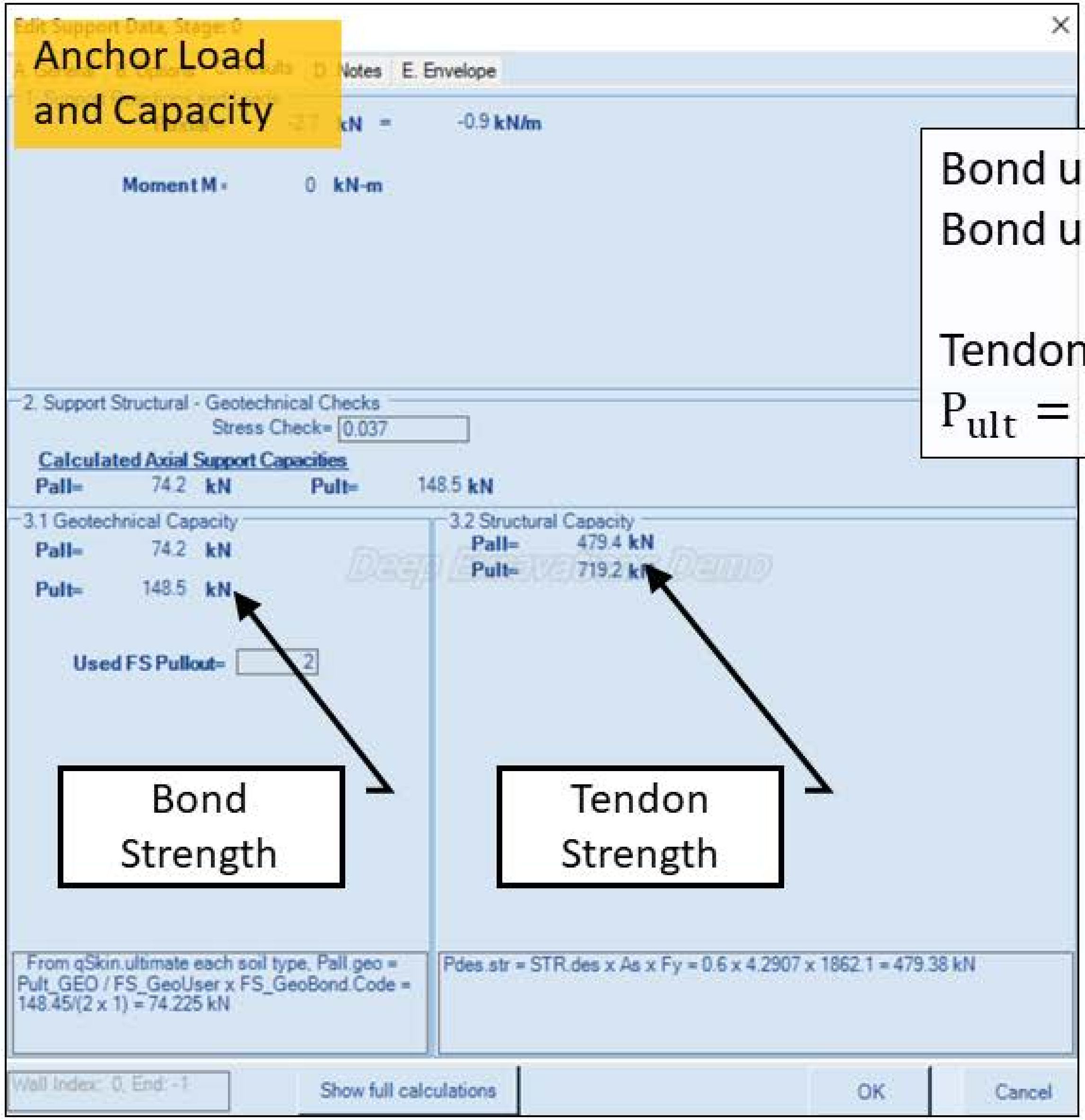
Support: Ground Anchor (4/6)



Support: Ground Anchor (5/6)



Support: Ground Anchor (6/6)



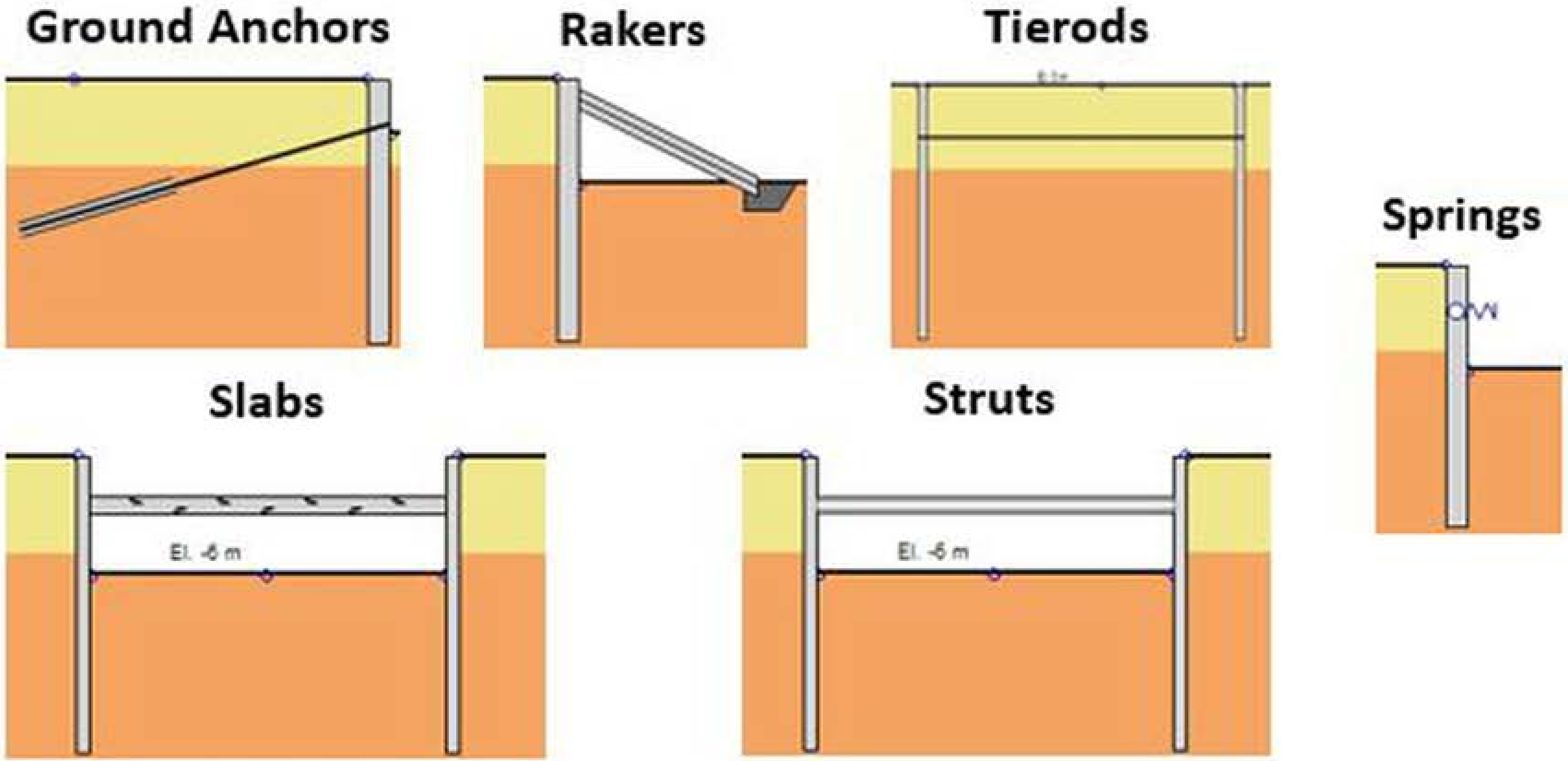
Bond ult. capacity (manual) = 63 kPa (πD) (5) = 148.4 kN

Bond ult. capacity (DeepEX) = 148.5

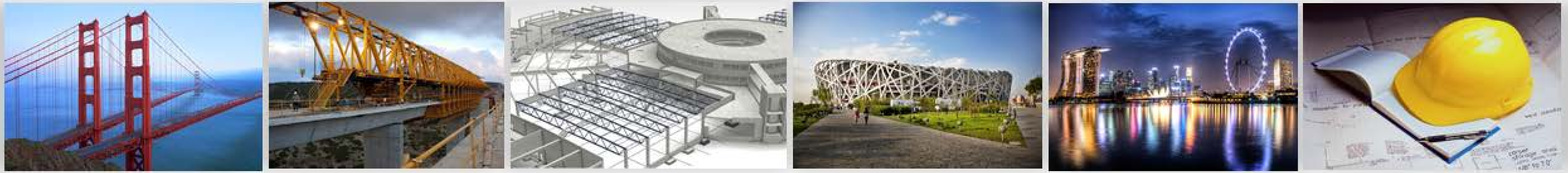
Tendon ult. capacity:

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

Other Support Types

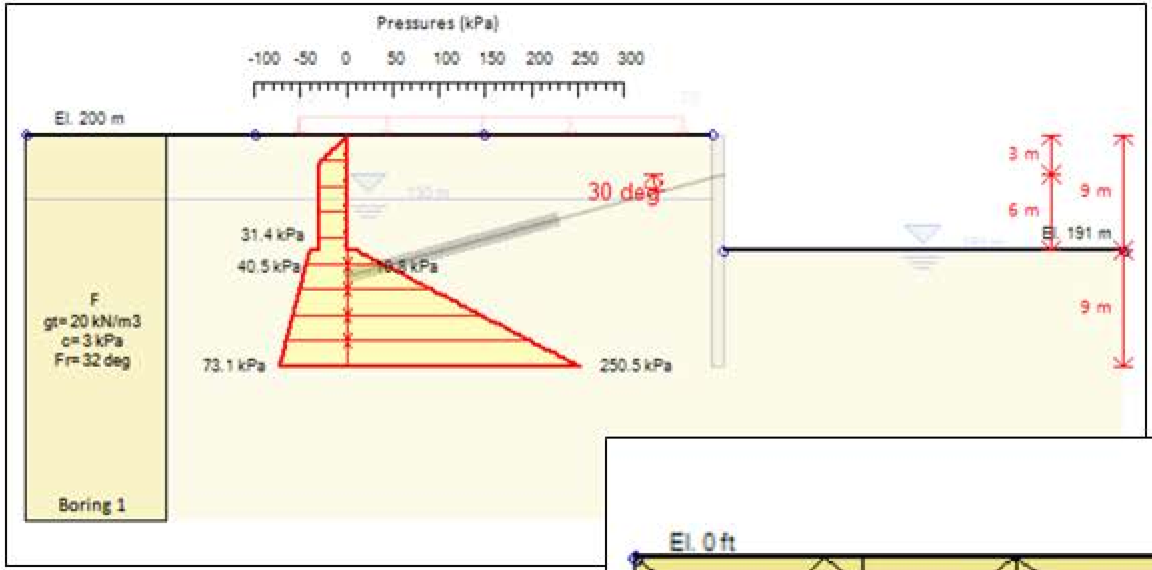


Effective Deep Excavation Analysis and Design

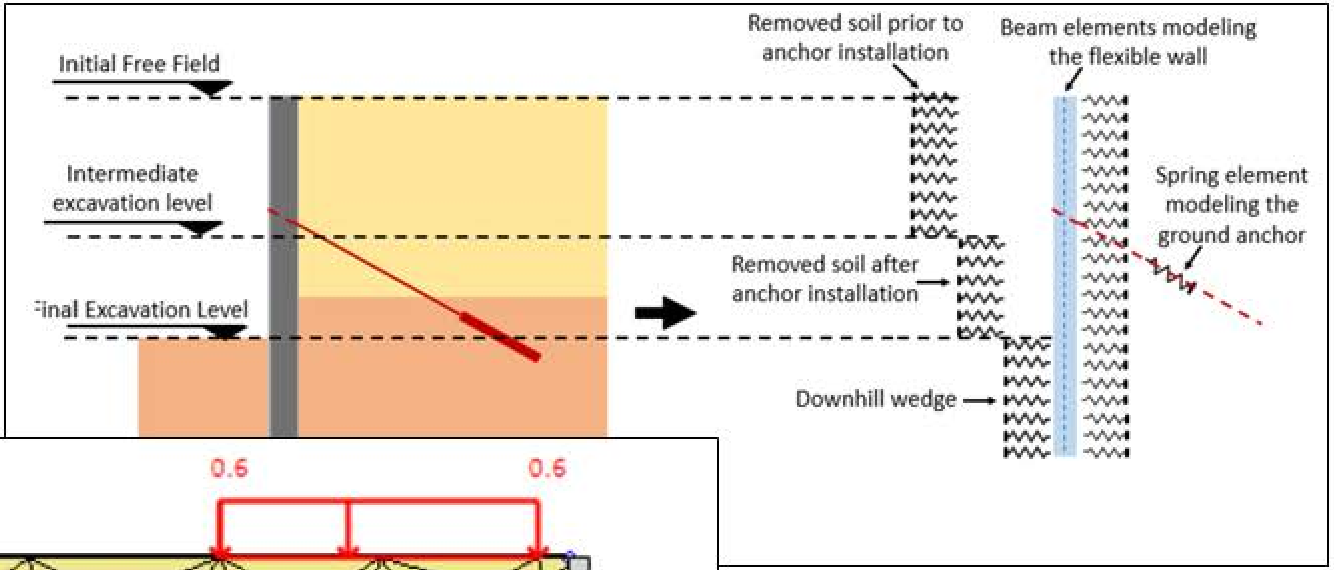


LEM Approaches and Design Check

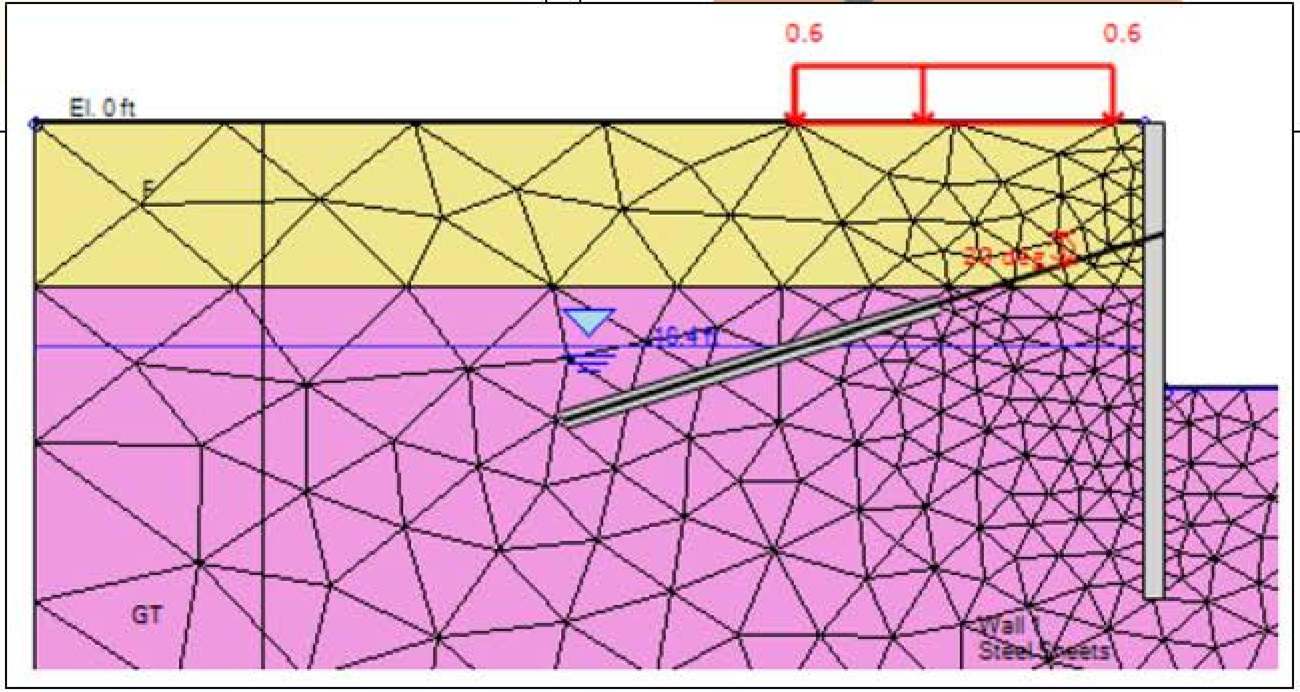
Modeling Approaches



Limit Equilibrium Method



Non-Linear Springs Method

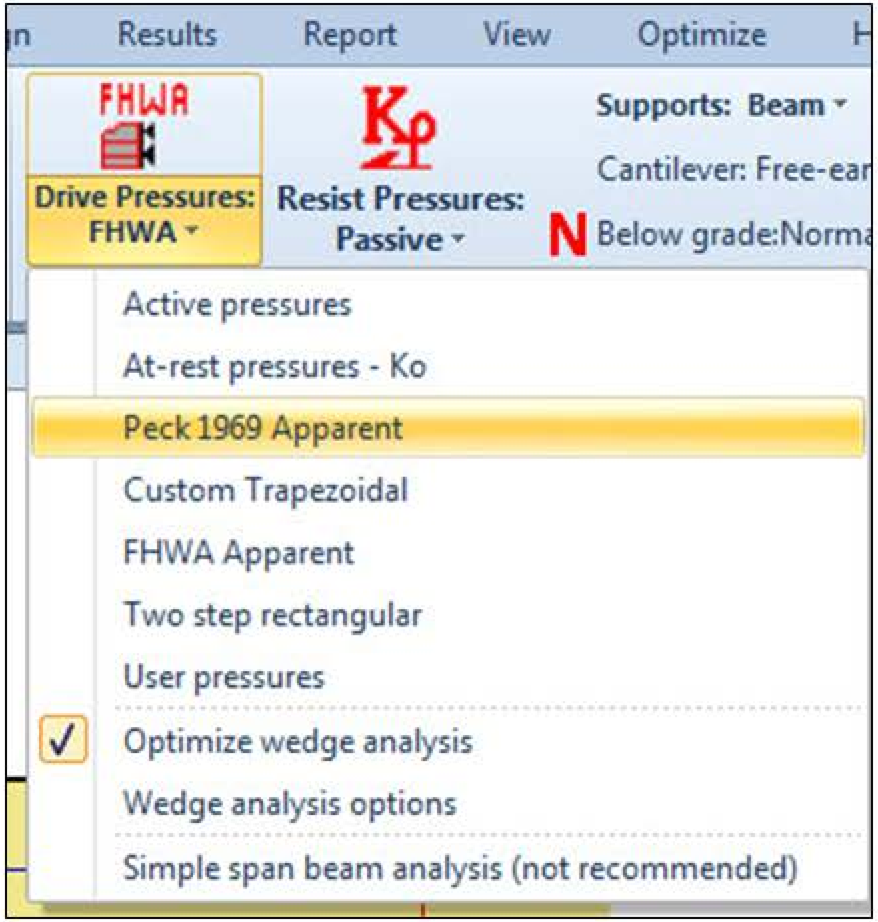


Finite Element Method

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.

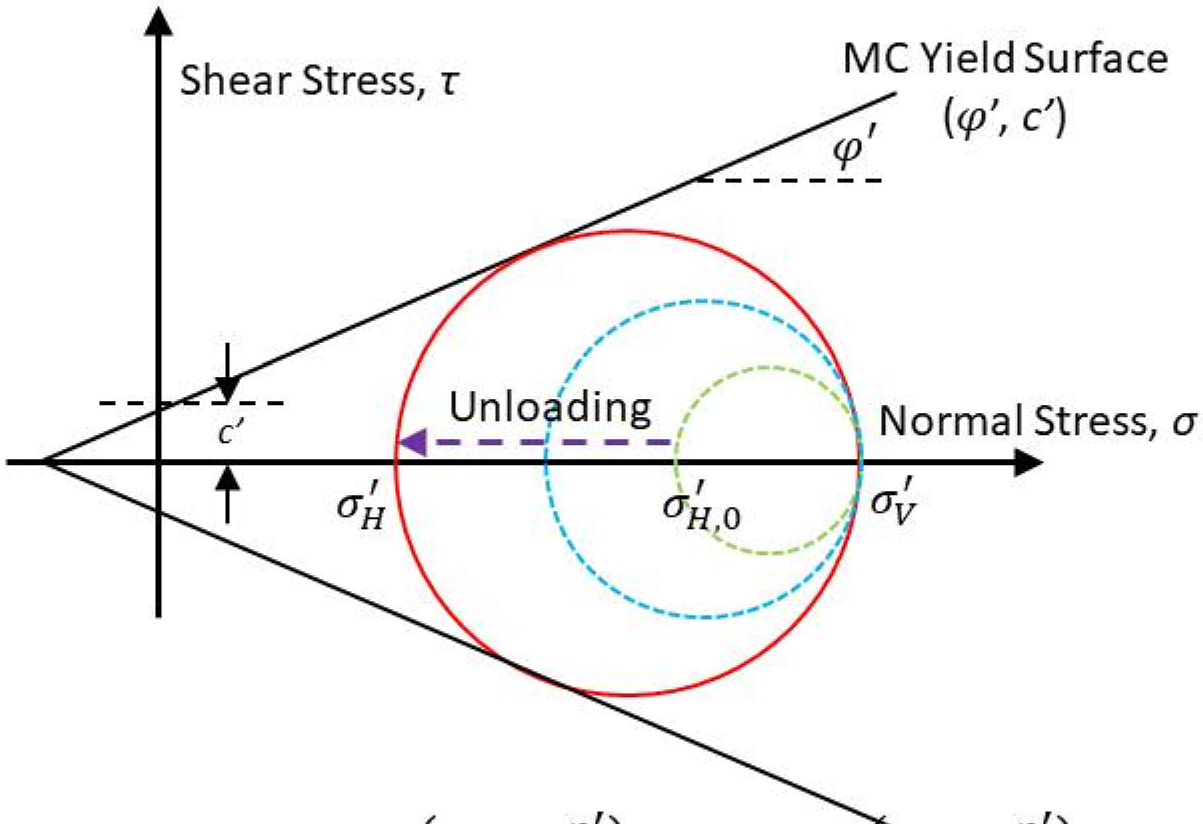
- Limitations:
  - Ignore stress path → Each stage is calculated independently.
  - Ignore strain-compatibility → Generally inaccurate displacement prediction.
  - Ignore soil-structure interaction.



Options for drive (active) pressures

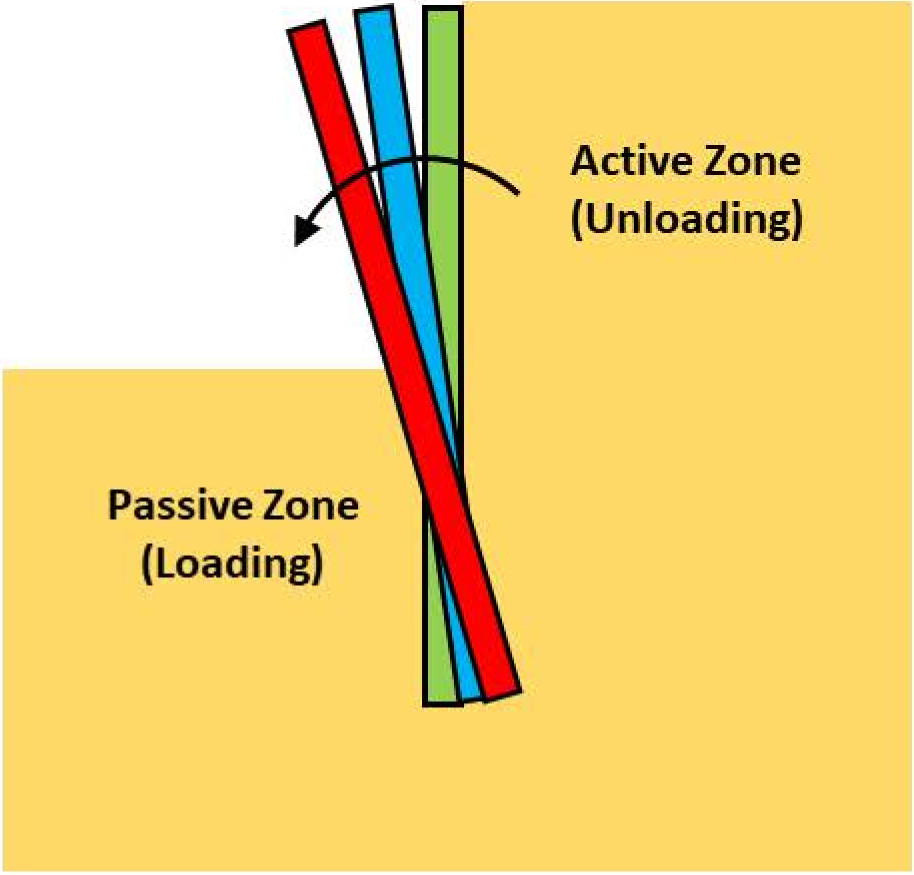
Rankine: Active Pressure

MC: $(\sigma_1' - \sigma_3') = 2c' \cos\varphi' + (\sigma_1' + \sigma_3') \sin\varphi'$



$$\sigma_H' = \sigma_V' \tan^2\left(45 - \frac{\varphi'}{2}\right) - 2c' \tan\left(45 - \frac{\varphi'}{2}\right)$$

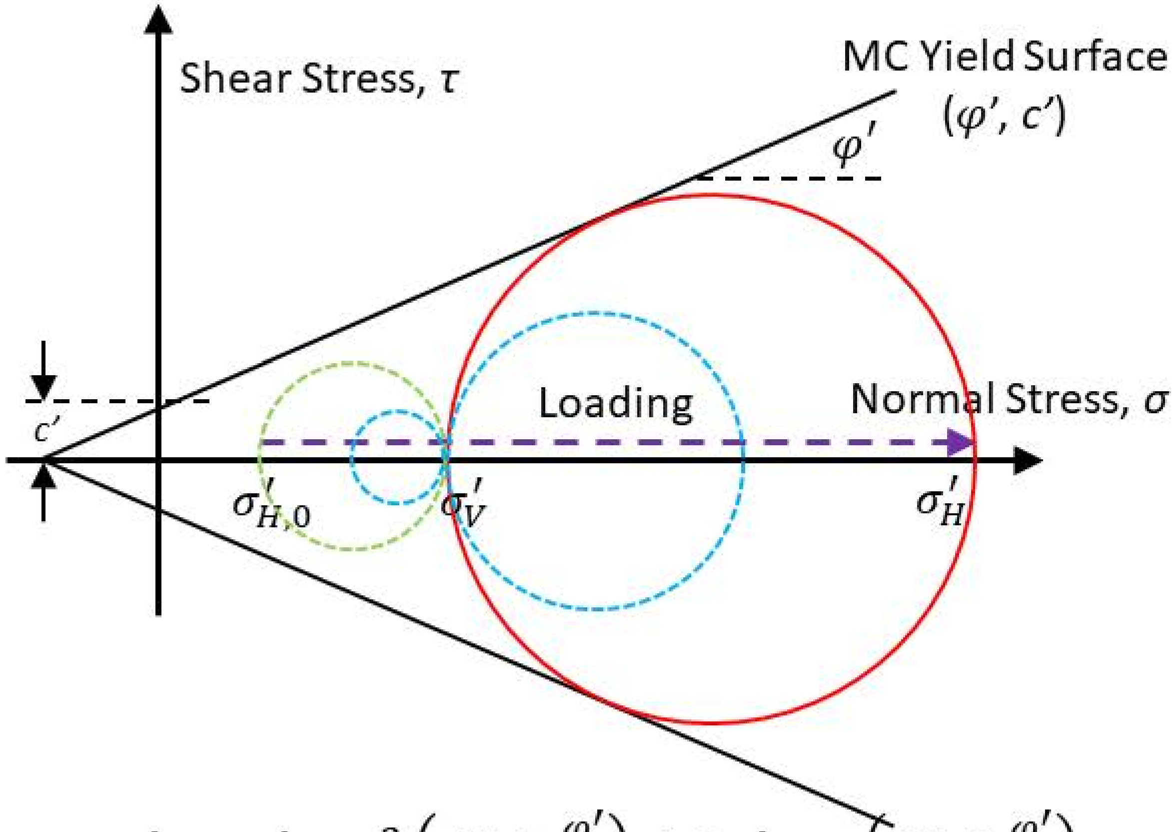
Note: $K_a = \tan^2\left(45 - \frac{\varphi'}{2}\right) = \frac{1-\sin(\varphi')}{1+\sin(\varphi')}$



Rotation of cantilever wall due to excavation

Rankine: Passive Pressure

MC: $(\sigma_1' - \sigma_3') = 2c' \cos\varphi' + (\sigma_1' + \sigma_3') \sin\varphi'$



$$\sigma_H' = \sigma_V' \tan^2\left(45 + \frac{\varphi'}{2}\right) + 2c' \tan\left(45 + \frac{\varphi'}{2}\right)$$

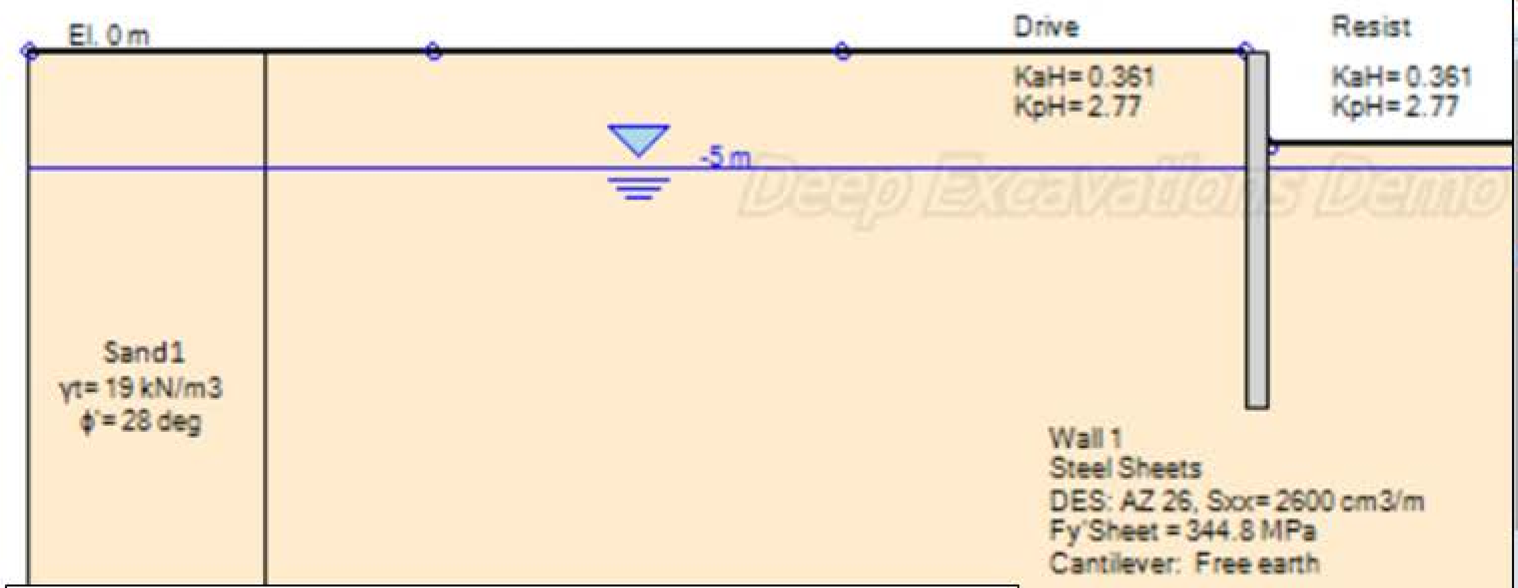
Note: $K_p = \tan^2\left(45 + \frac{\varphi'}{2}\right) = \frac{1+\sin(\varphi')}{1-\sin(\varphi')}$

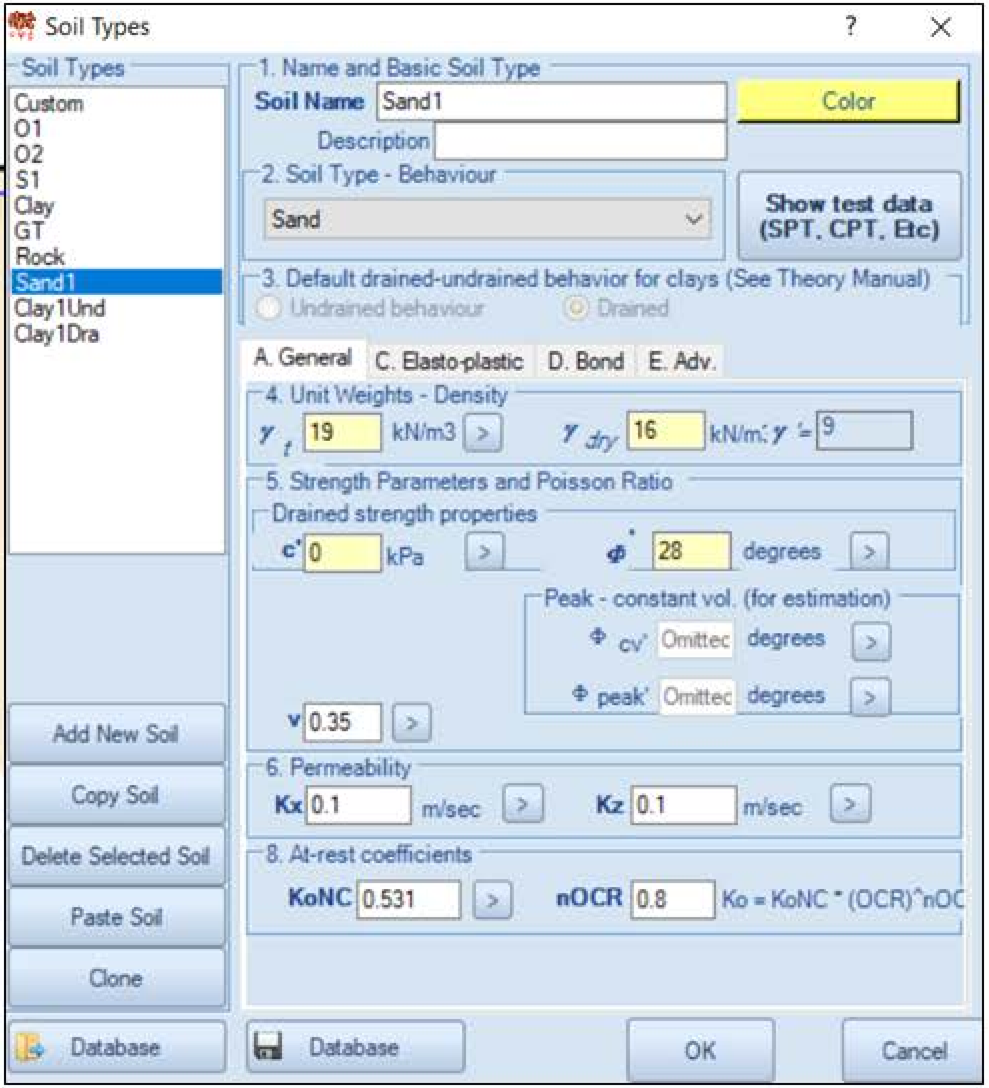
Limitations of Rankine's earth pressure:

- 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 !!

Earth Pres.: Flat Slope, No Wall Friction





Soil Slope : $\alpha = 0°$

Interface : $\delta' = 0°$

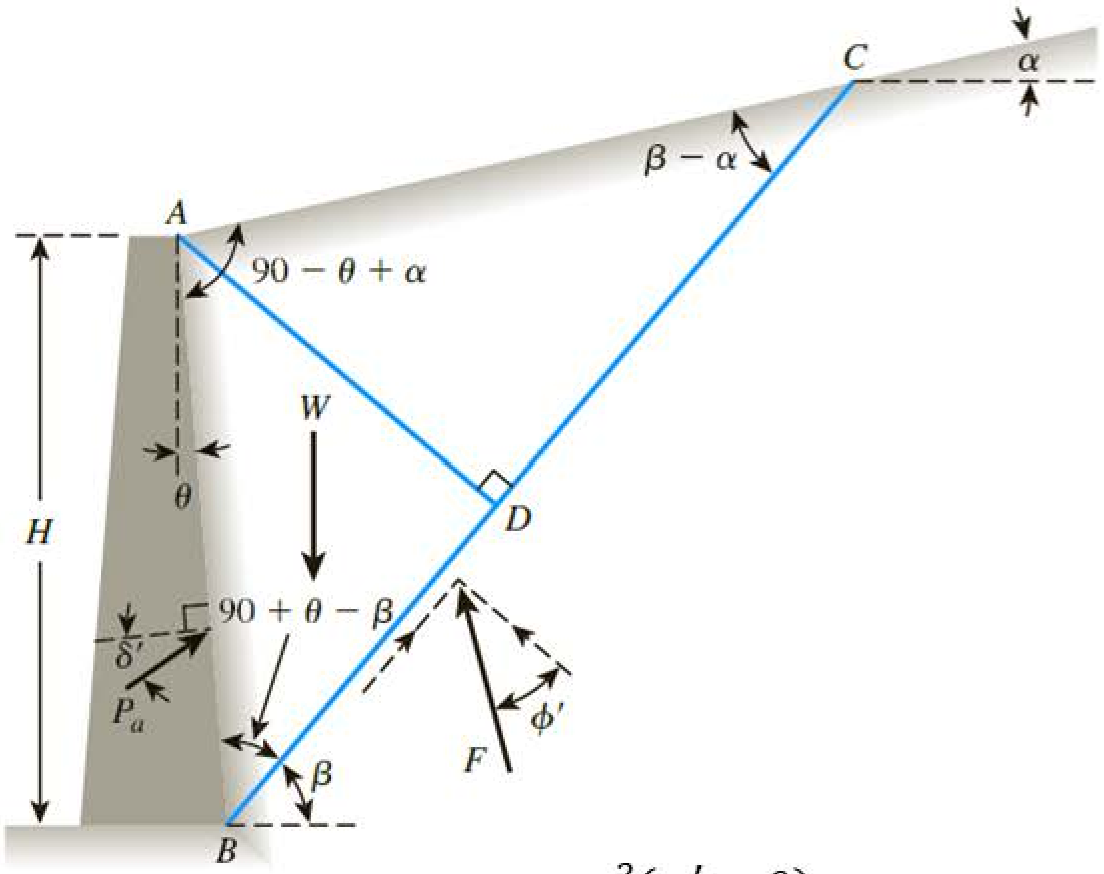
Wall Face : $\theta = 0°$

Rankine earth pressure coefficient:

$$K_a = \frac{1-\sin(\varphi')}{1+\sin(\varphi')} \rightarrow K_a(\varphi' = 28°) = 0.361$$

$$K_p = \frac{1+\sin(\varphi')}{1-\sin(\varphi')} \rightarrow K_p(\varphi' = 28°) = 2.77$$

Coulomb: Active Pressure



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

Coulomb's assumes soil failure wedge (ΔABC) → Active and passive earth pressure coefficients are calculated based on the static stability of this wedge.

Symbols:

φ' : Soil friction angle

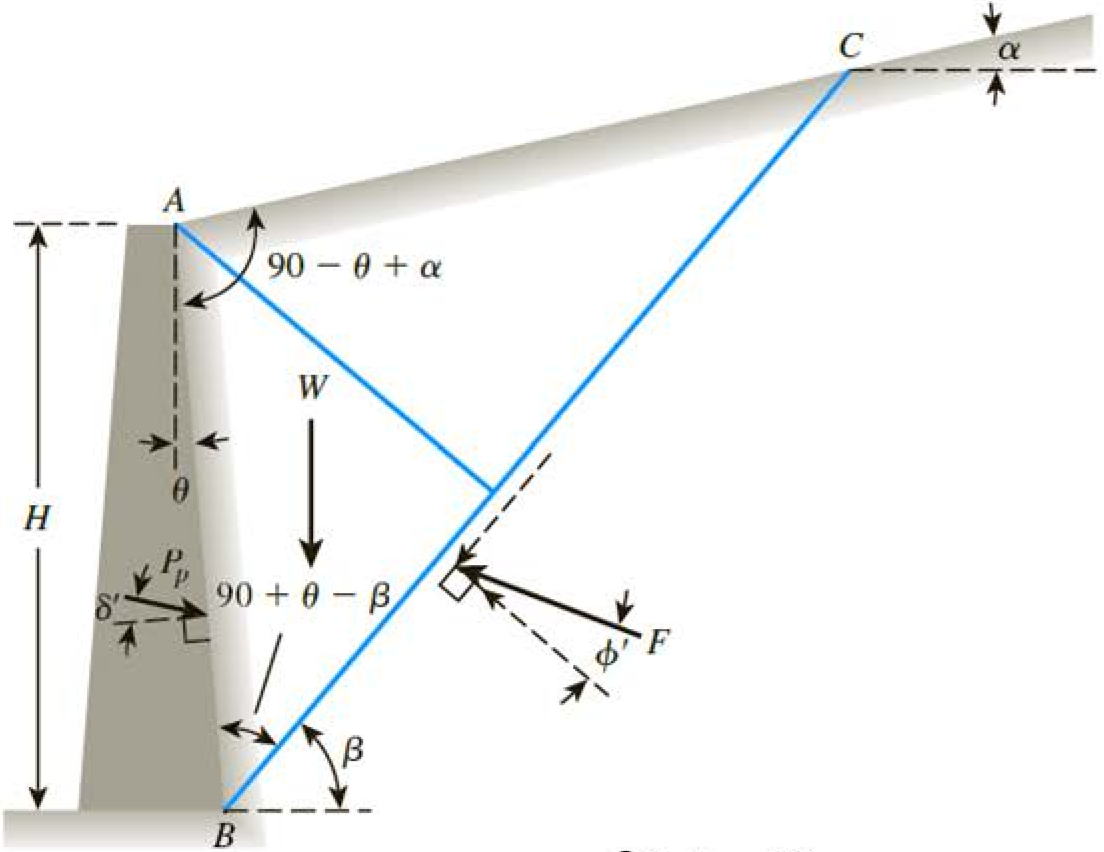
δ' : Soil-wall interface friction.

α : Soil slope angle.

θ : Inclination of wall upstream face.

Reference: [Das and Sobhan, 2018] Principles of geotechnical engineering, 9th edition.

Coulomb: Passive Pressure



Coulomb's earth pressure consider interface friction (δ'), non-horizontal soil slope (α), and non-vertical wall face (θ).

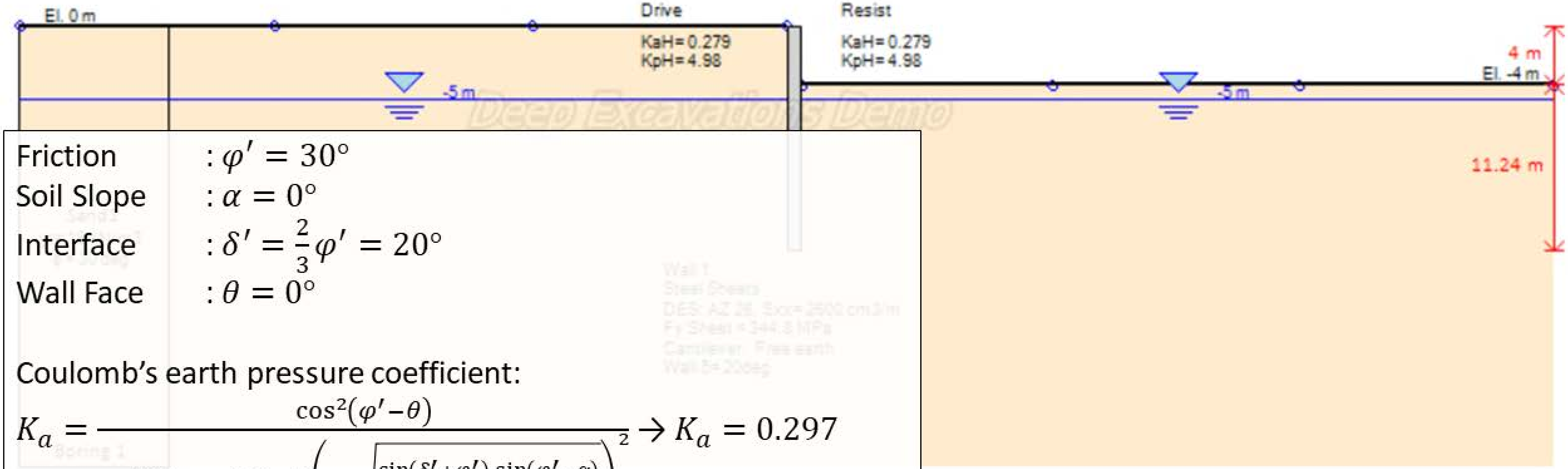
When plugging $\delta' = 0$, $\alpha = 0$, and $\theta = 0$ into Coulomb's formula, we will get Rankine's formula.

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

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

Reference: [Das and Sobhan, 2018] Principles of geotechnical engineering, 9th edition.

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



Friction : $\varphi' = 30°$
Soil Slope : $\alpha = 0°$
Interface : $\delta' = \frac{2}{3}\varphi' = 20°$
Wall Face : $\theta = 0°$

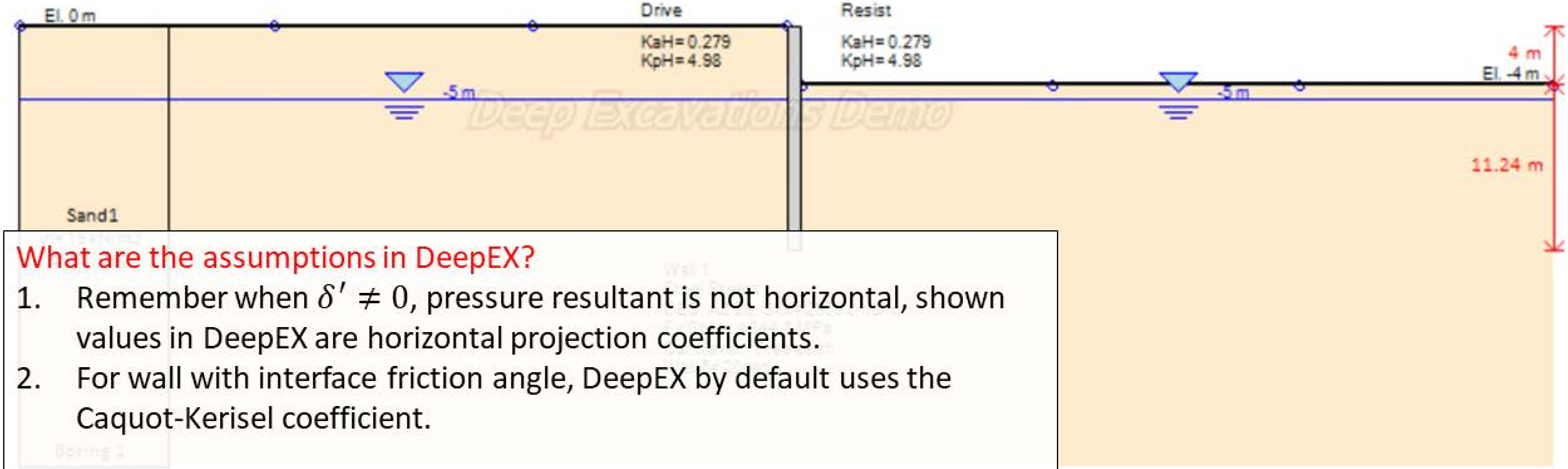
Coulomb's earth pressure coefficient:

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

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

Reference: [Das and Sobhan, 2018] Principles of geotechnical engineering, 9th edition.

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.

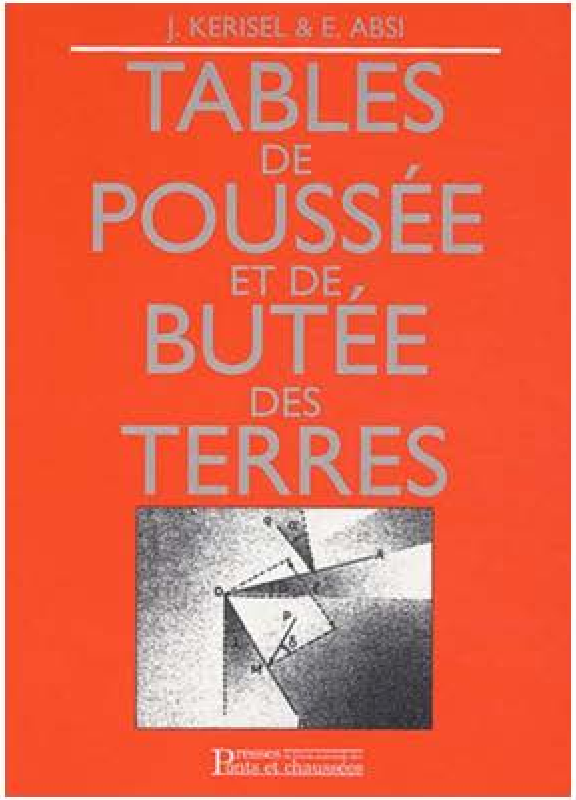
$$K_{ah}(Coulomb) = 0.297\cos(20) = 0.279$$
$$K_{ph}(Coulomb) = 6.105\cos(20) = 5.73$$

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

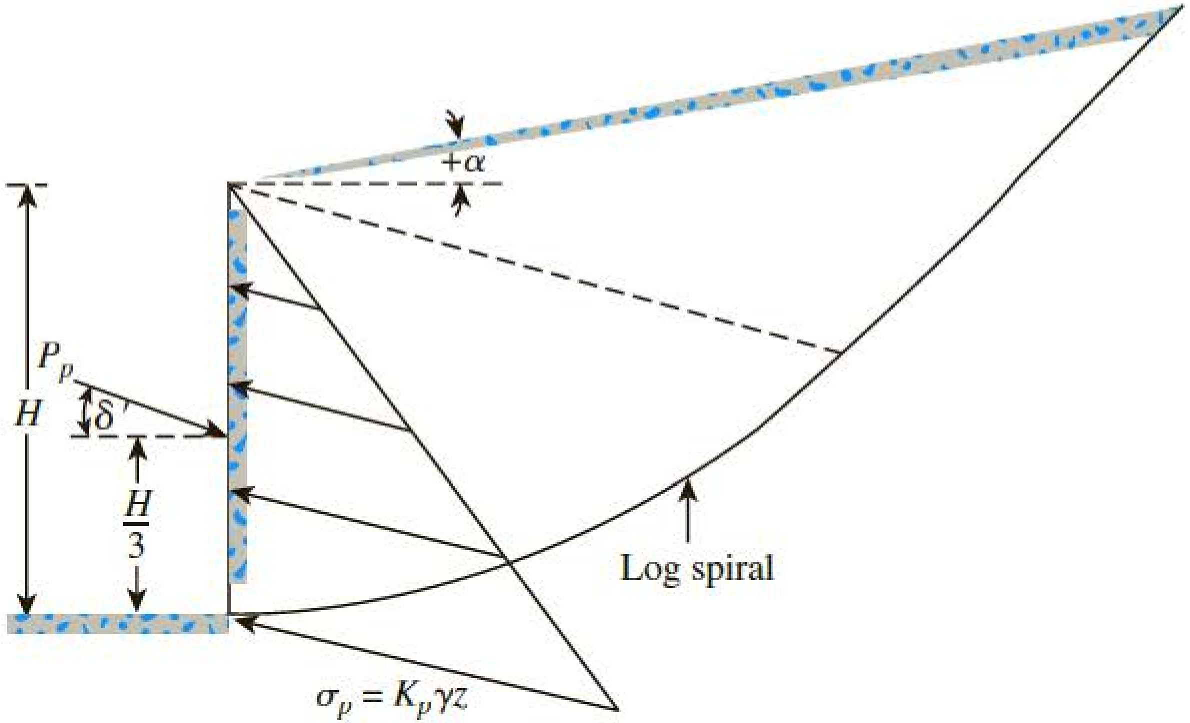
Note: CK (Caquot-Kerisel) coefficients can be obtained from table.

Reference: [Kerisel and Absi, 2003] p. 14.

Caquot-Kerisel: Passive Pressure



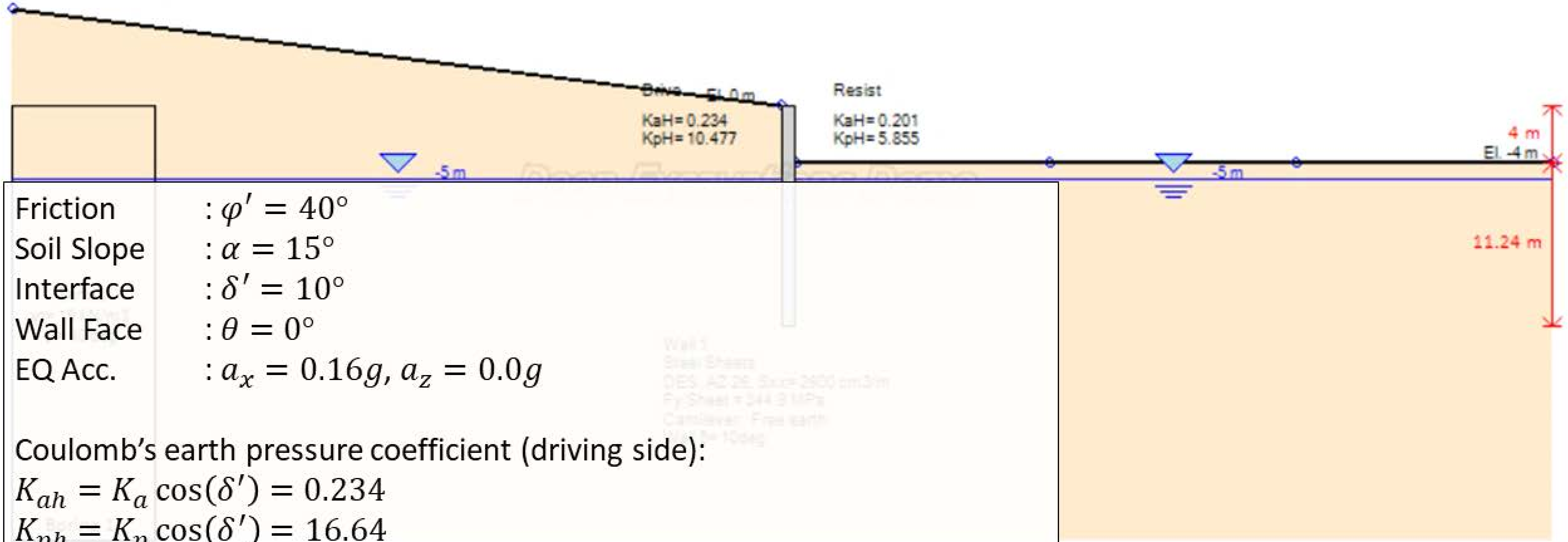
Active and passive earth pressure coefficient book (Caquot-Kerisel)



- 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).

[Das and Sobhan, 2018] and [Kerisel and Absi, 2003].

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



Friction	: $\varphi' = 40°$
Soil Slope	: $\alpha = 15°$
Interface	: $\delta' = 10°$
Wall Face	: $\theta = 0°$
EQ Acc.	: $a_x = 0.16g,\ a_z = 0.0g$

Coulomb's earth pressure coefficient (driving side):

$$K_{ah} = K_a \cos(\delta') = 0.234$$

$$K_{ph} = K_p \cos(\delta') = 16.64$$

Note: When seismic is active, seismic effects are added separately in the active side. The passive side, by default, will use Lancellota approach.

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

From prev. slide:
$\varphi' = 40°$
$\alpha = 15°$
$\delta' = 10°$
$\theta = 0°$
$a_x = 0.16g$
$a_z = 0.0g$

→

Using Lancellota:
$\beta = 9.09°$
$2\theta = 1.029$
$\gamma_1 = 1.013$
$K_{pe} = 10.401$
$K_{ph} = 10.477$

- 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.

[Lancellota, 2007] Lower-bound for seismic passive earth resistance.

Summary: Active & Passive Coefficients in DeepEX

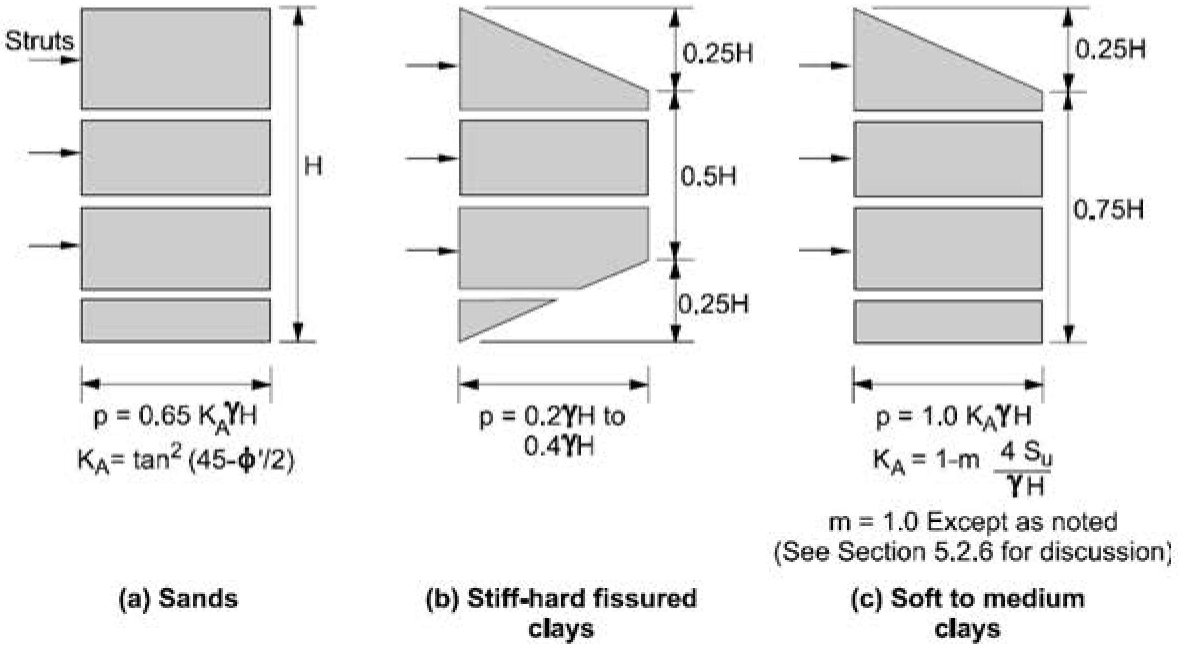
Method	Active				Passive			
	Available	**Soil Slope**	**Interface**	**EQ***	**Available**	**Soil Slope**	**Interface**	**EQ**
Rankine	Yes	No	No	No	Yes	No	No	No
Coulomb	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Caquot-Kerisel	No	-	-	-	Yes	Yes	Yes	No
Lancellota	No	-	-	-	Yes	Yes	Yes	Yes

* Seismic effects are added separately.

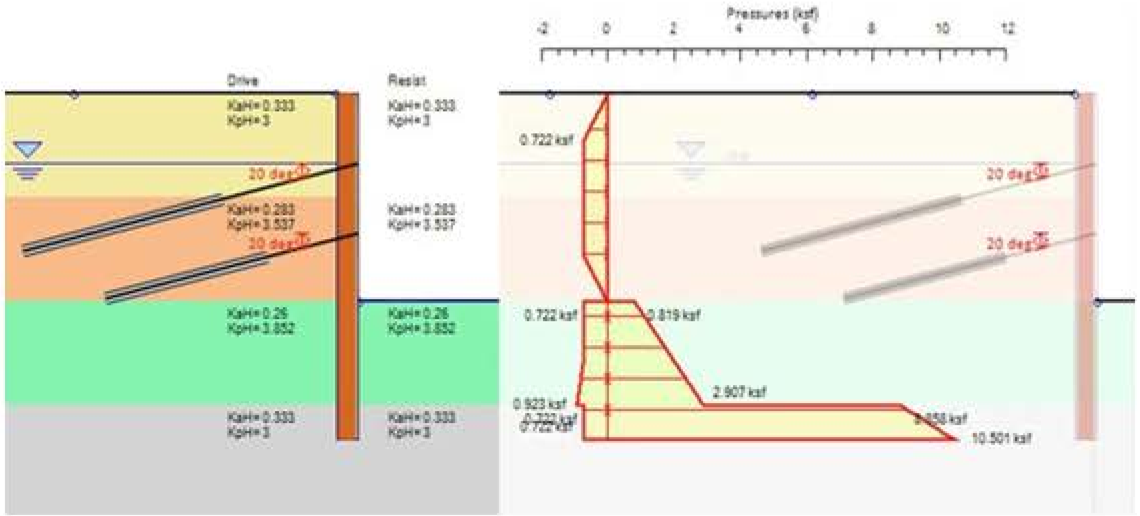
GeoStruktur

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*

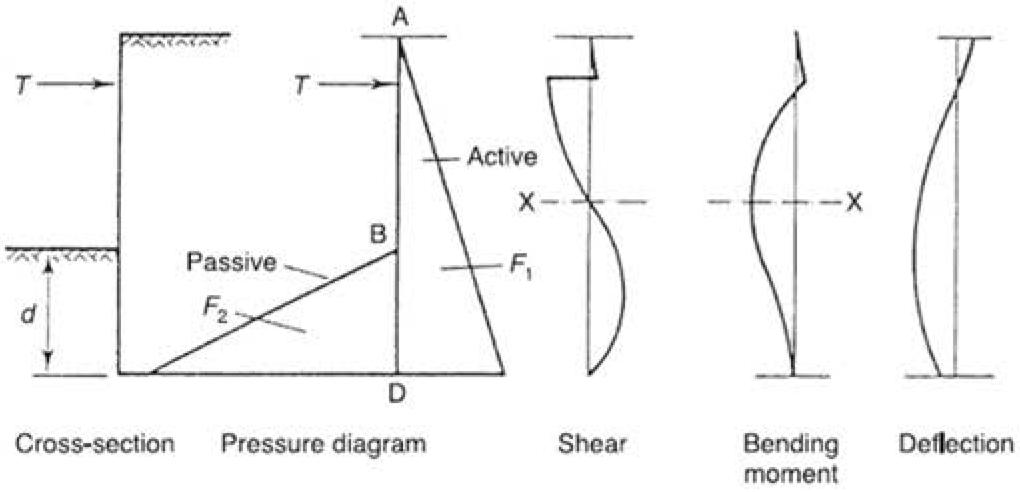


Peck Apparent Earth Pressure in DeepEX

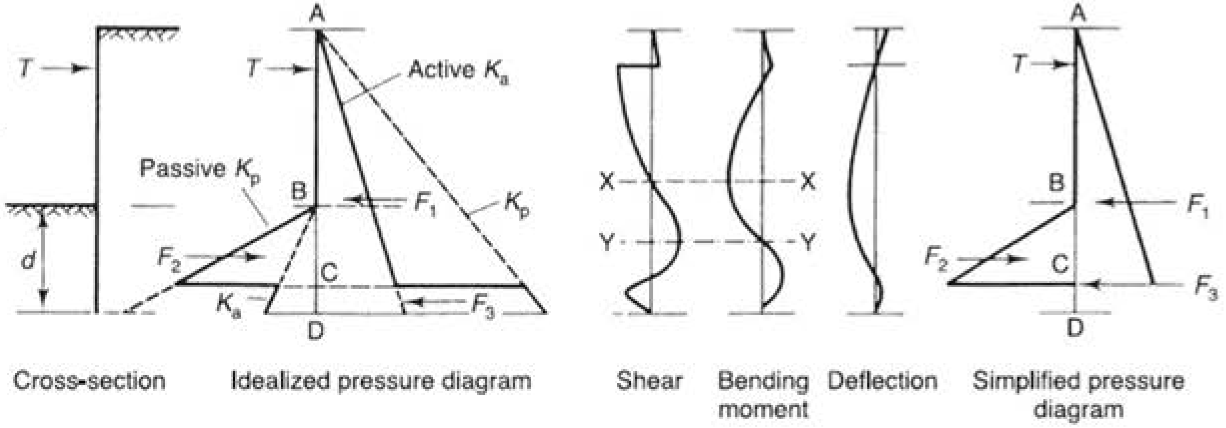
* FHWA-IF-99-015 Geotechnical Engineering Circular no 4.

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*



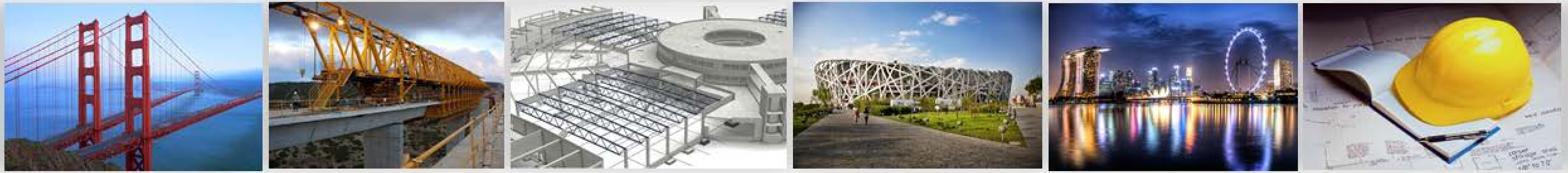
Fixed-Earth Support Method*

* [Puller, 2003] Deep Excavations: A Practical Manual 2nd 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, piping/sand boiling may occur (SF ≥ 1.25).
- If a confined aquifer is present, blow-in may happen during an excavation (SF ≥ 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.

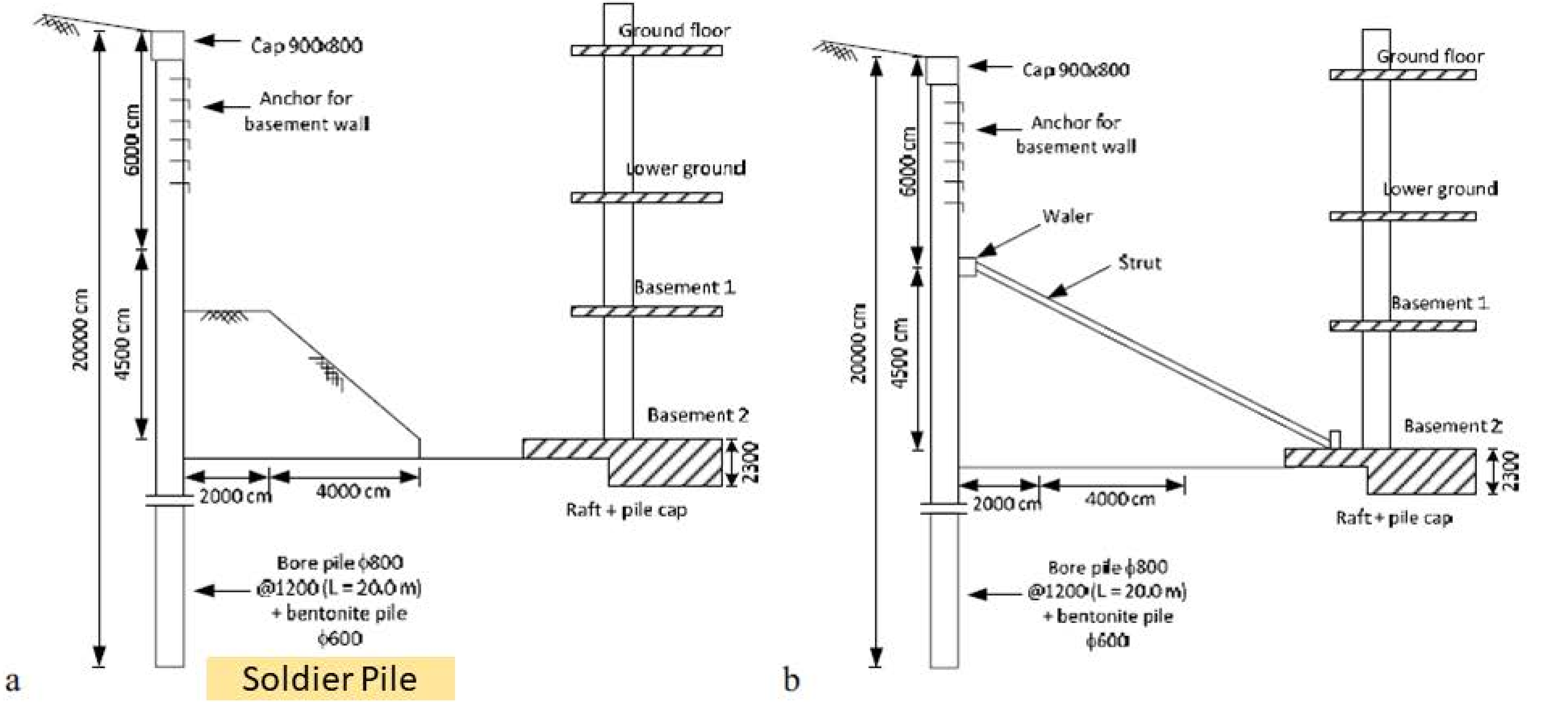


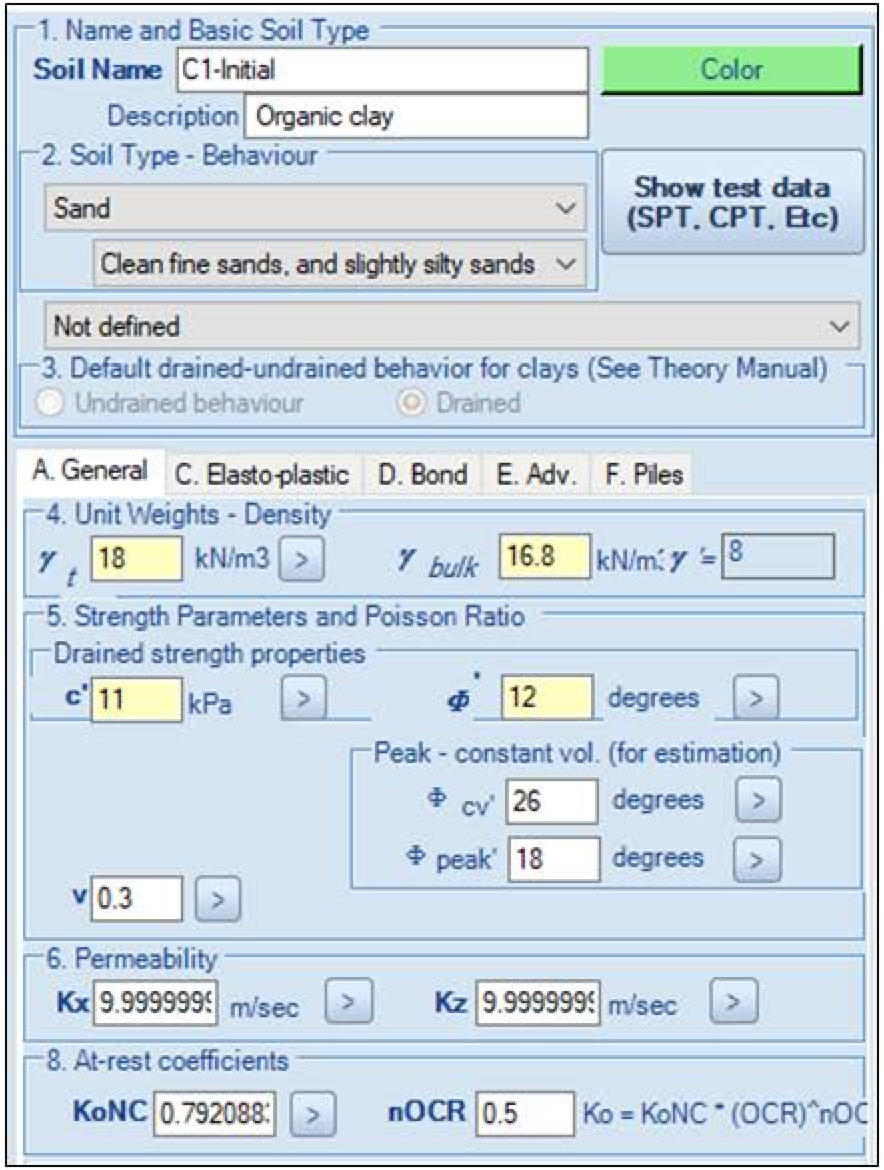
Figure and data from: [Ma'ruf dan Darjanto, 2017] Back calculation of excessive deformation on deep excavation

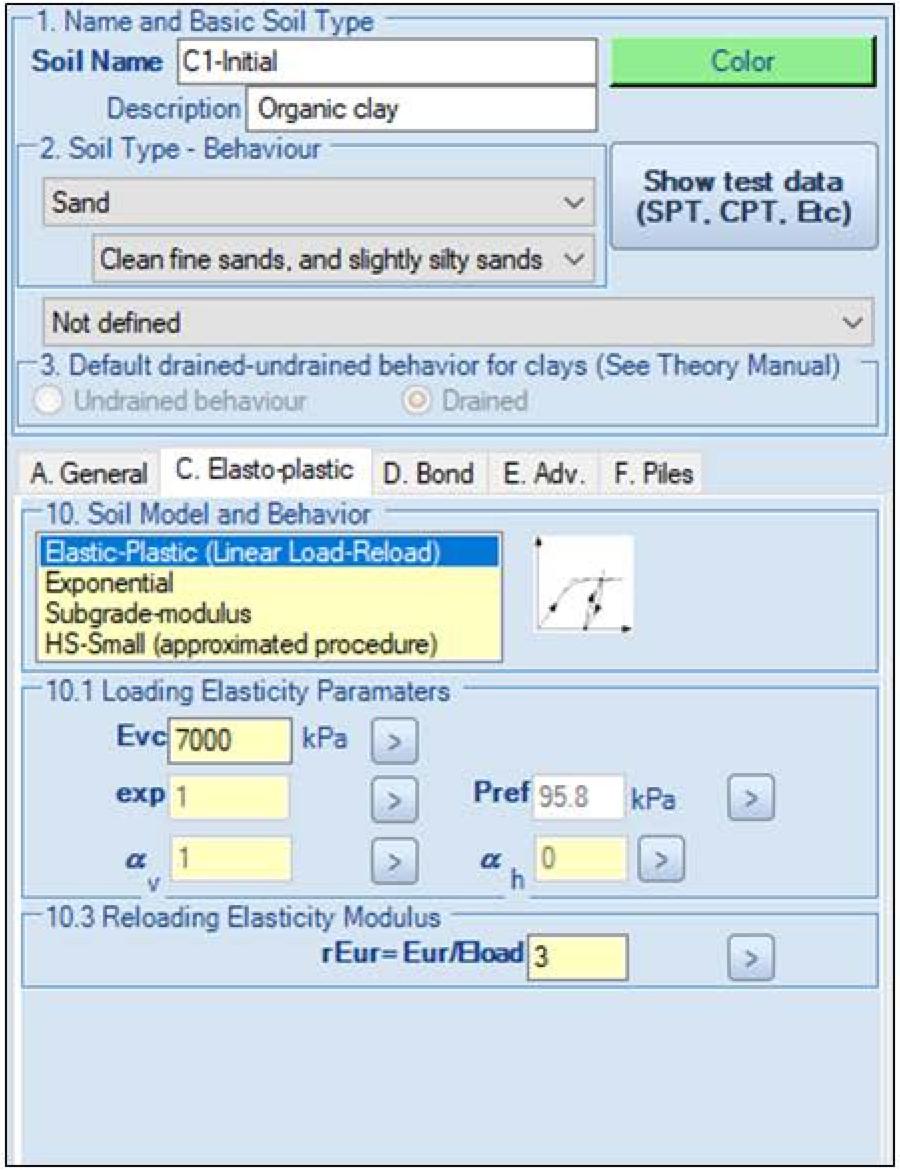
Case Study: Soil Data

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^3)	γ_{unsat}	16	16.8	17.2
Saturated unit weight (kN/m^3)	γ_{sat}	17	18	18
Stiffness modulus (kN/m^2)	E	7E3	9E3	12E3
Poisson ratio	υ	0.3	0.35	0.35
Cohesion (kN/m^2)	c	11	21	20
Friction angel (°)	ϕ	12	13	17

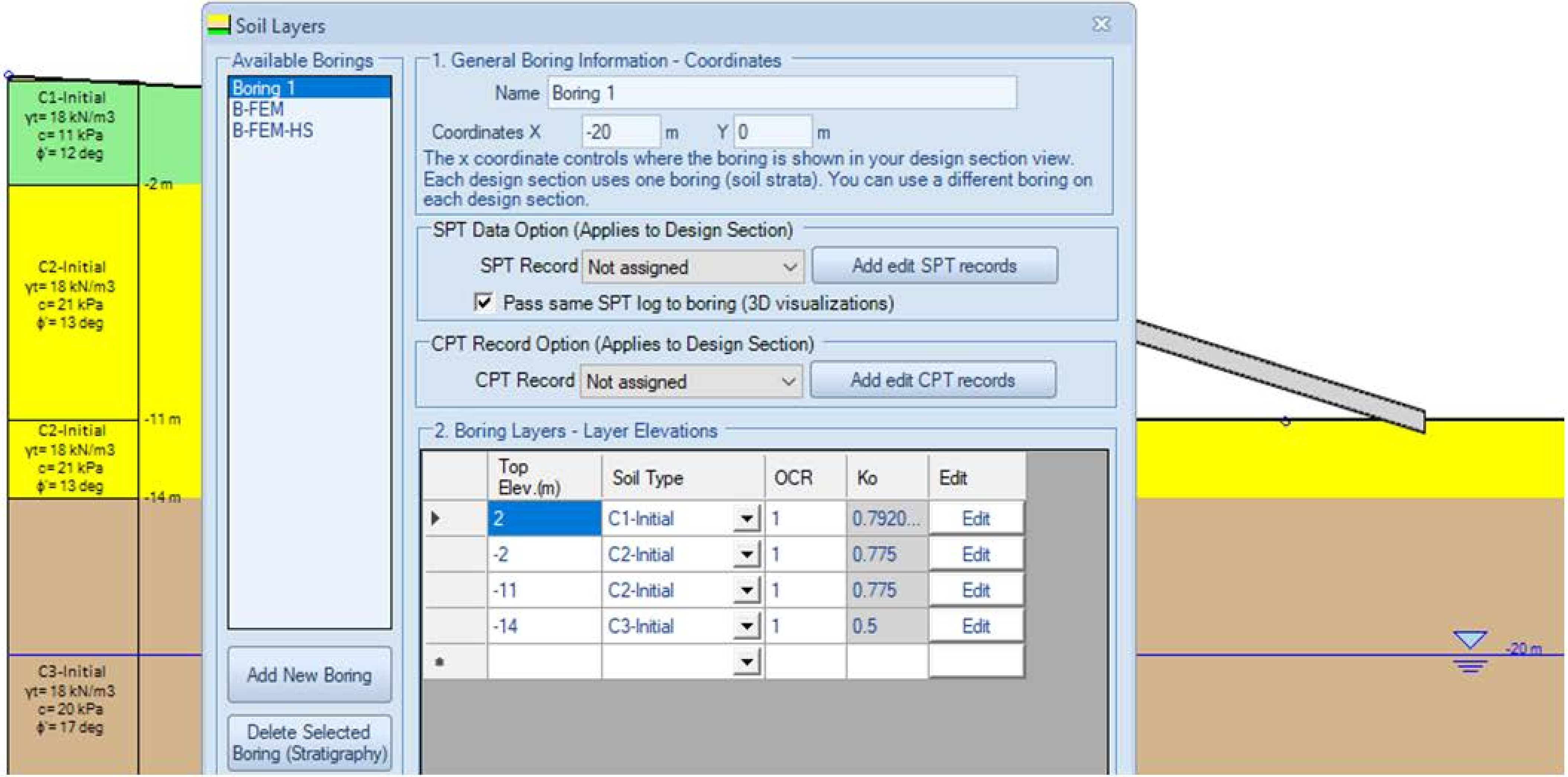
Figure and data from: [Ma'ruf dan Darjanto, 2017] Back calculation of excessive deformation on deep excavation

Modeling: Input Soil Data (Top Layer)

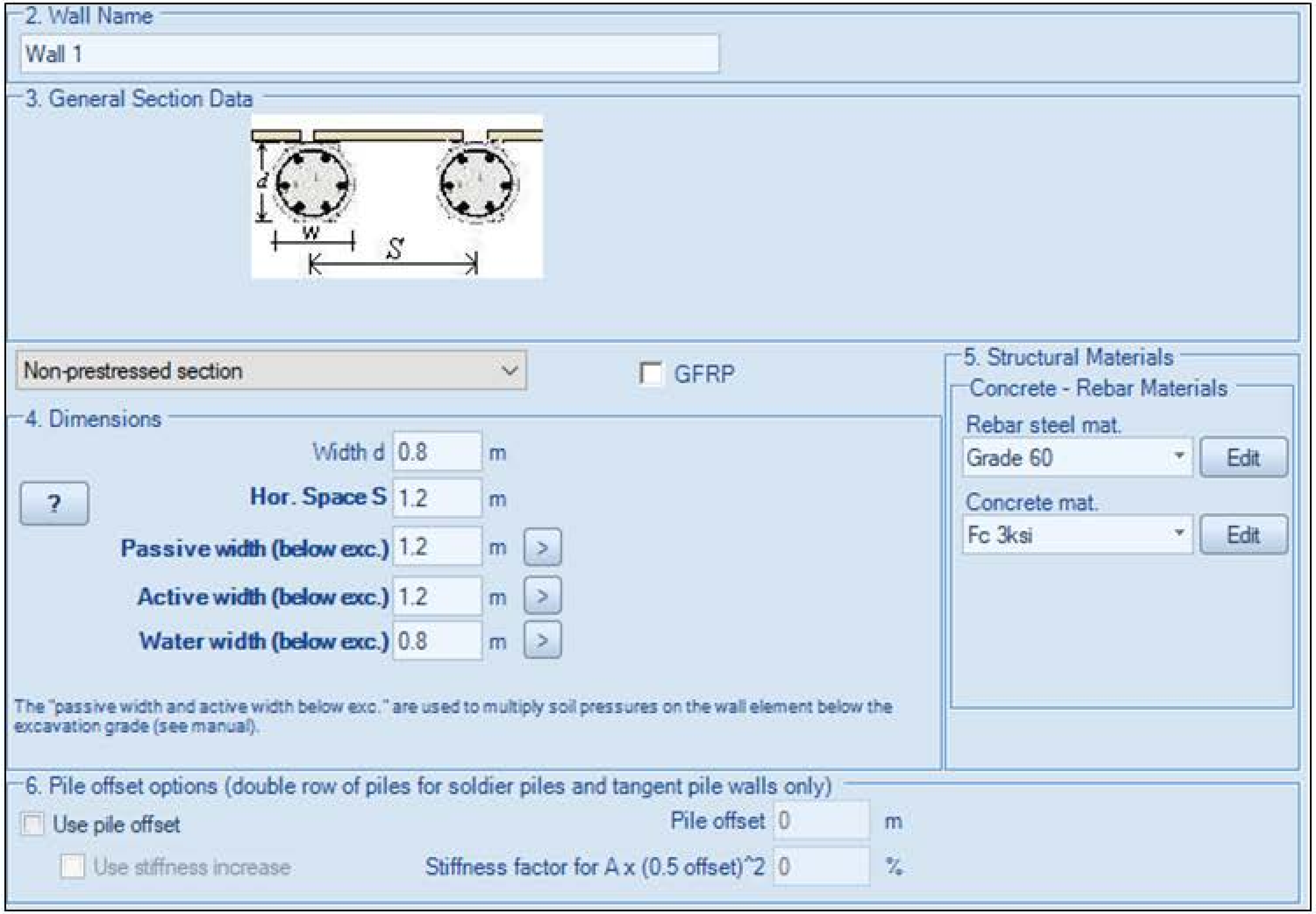


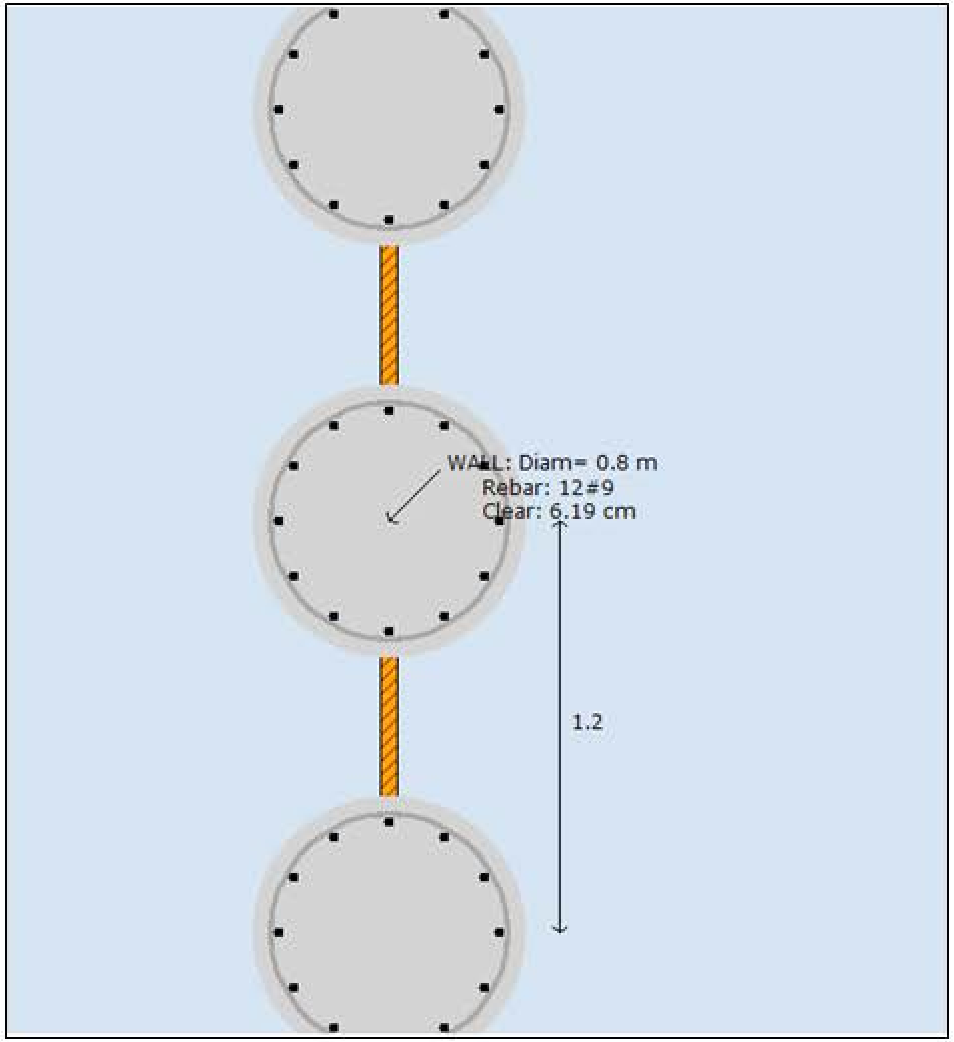


Modeling: Assign Soil Data

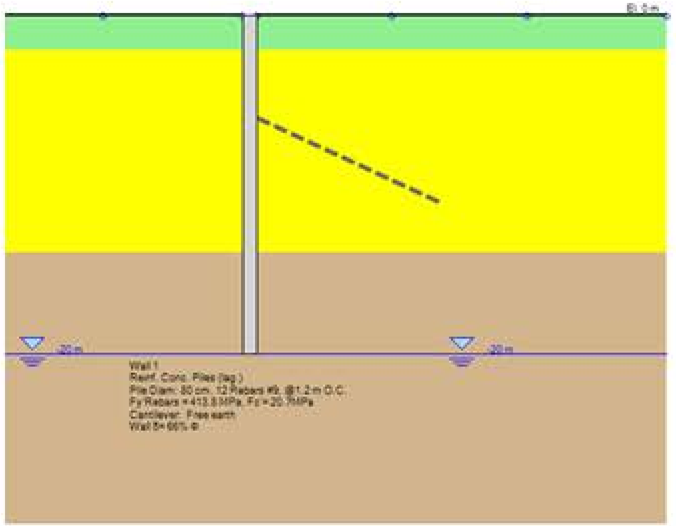


Modeling: Input Wall Data

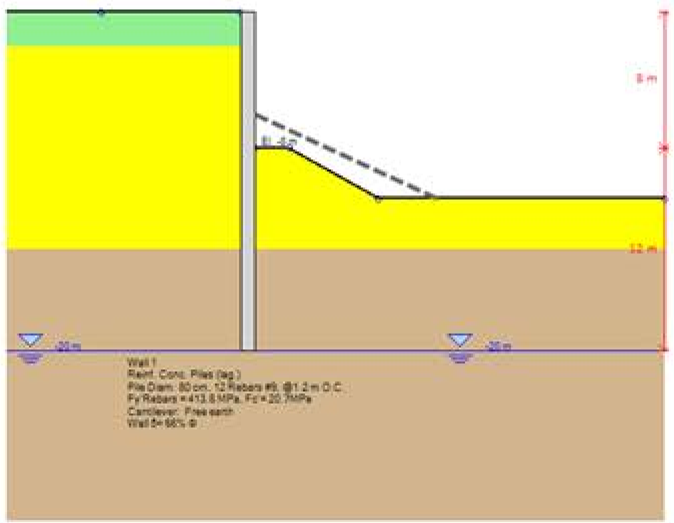




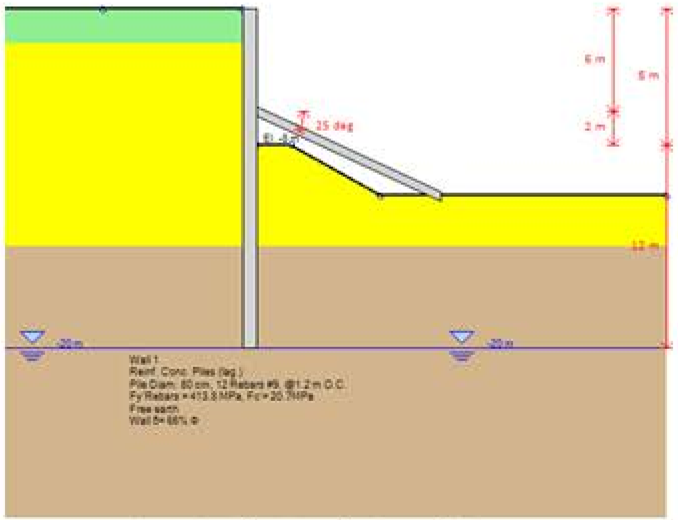
Modeling: Staged-Construction



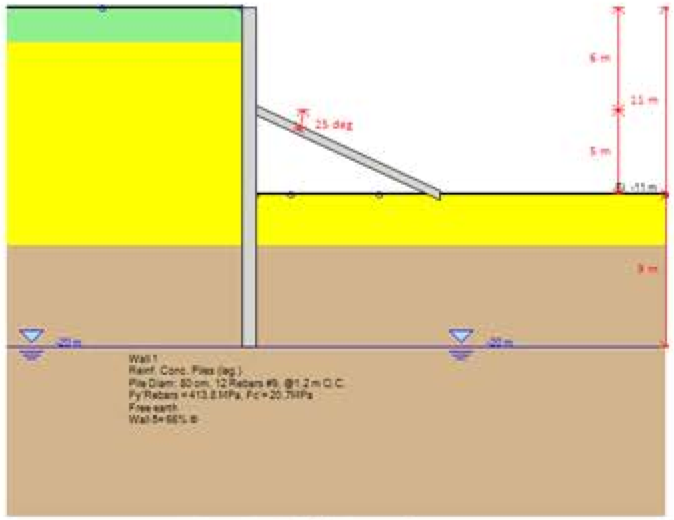
Stage 0: Initial Conditions - No Excavation



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



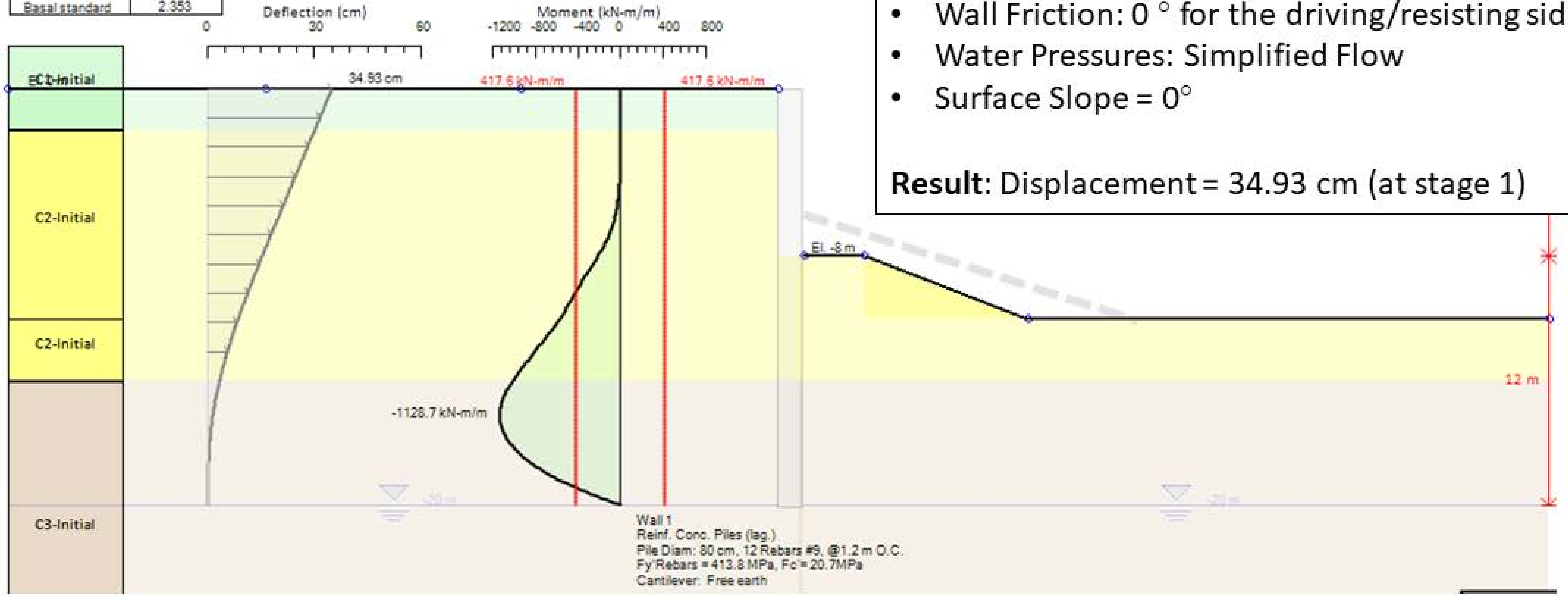
Stage 2: Raker Installation at El: -6m



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



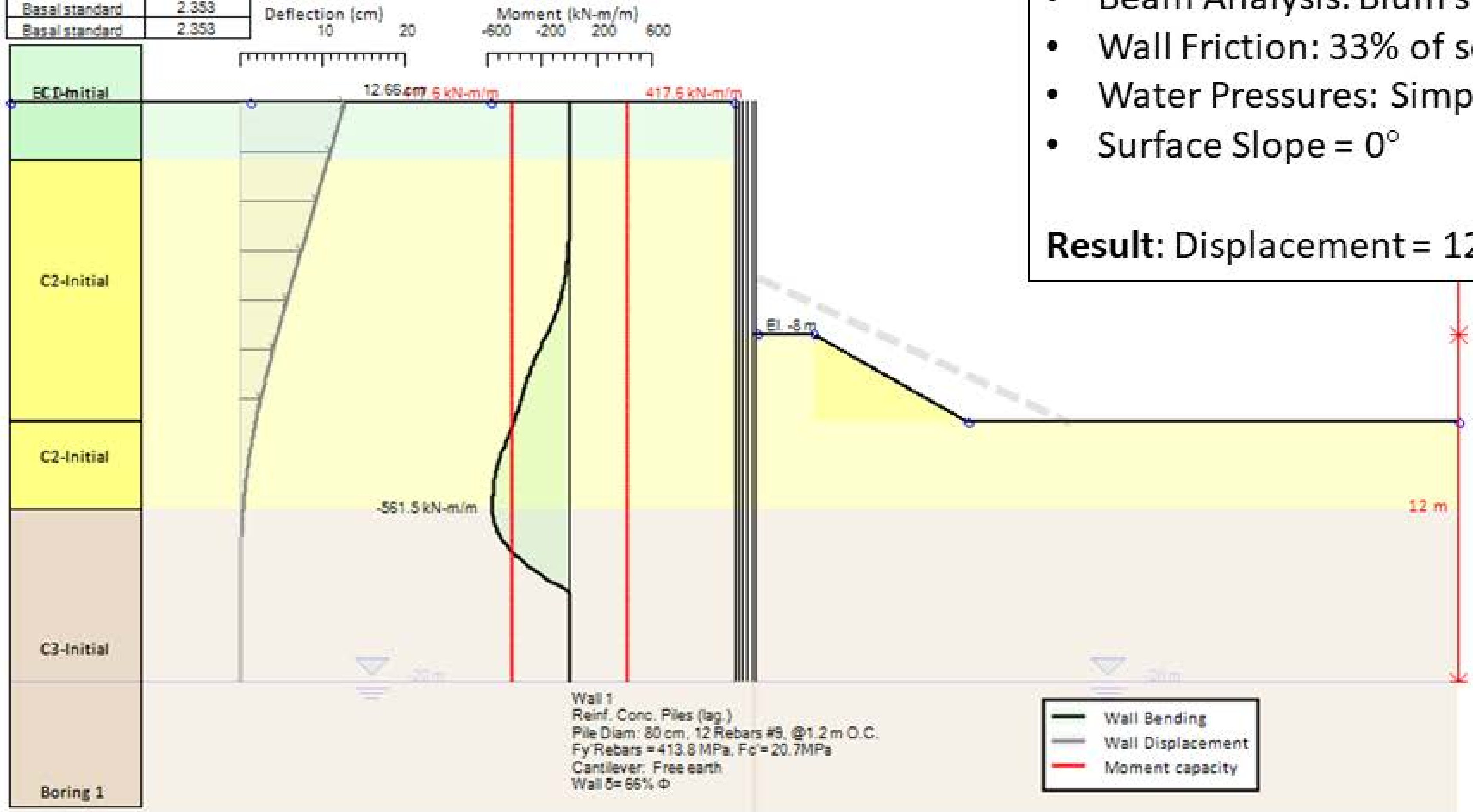
Settings:

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

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



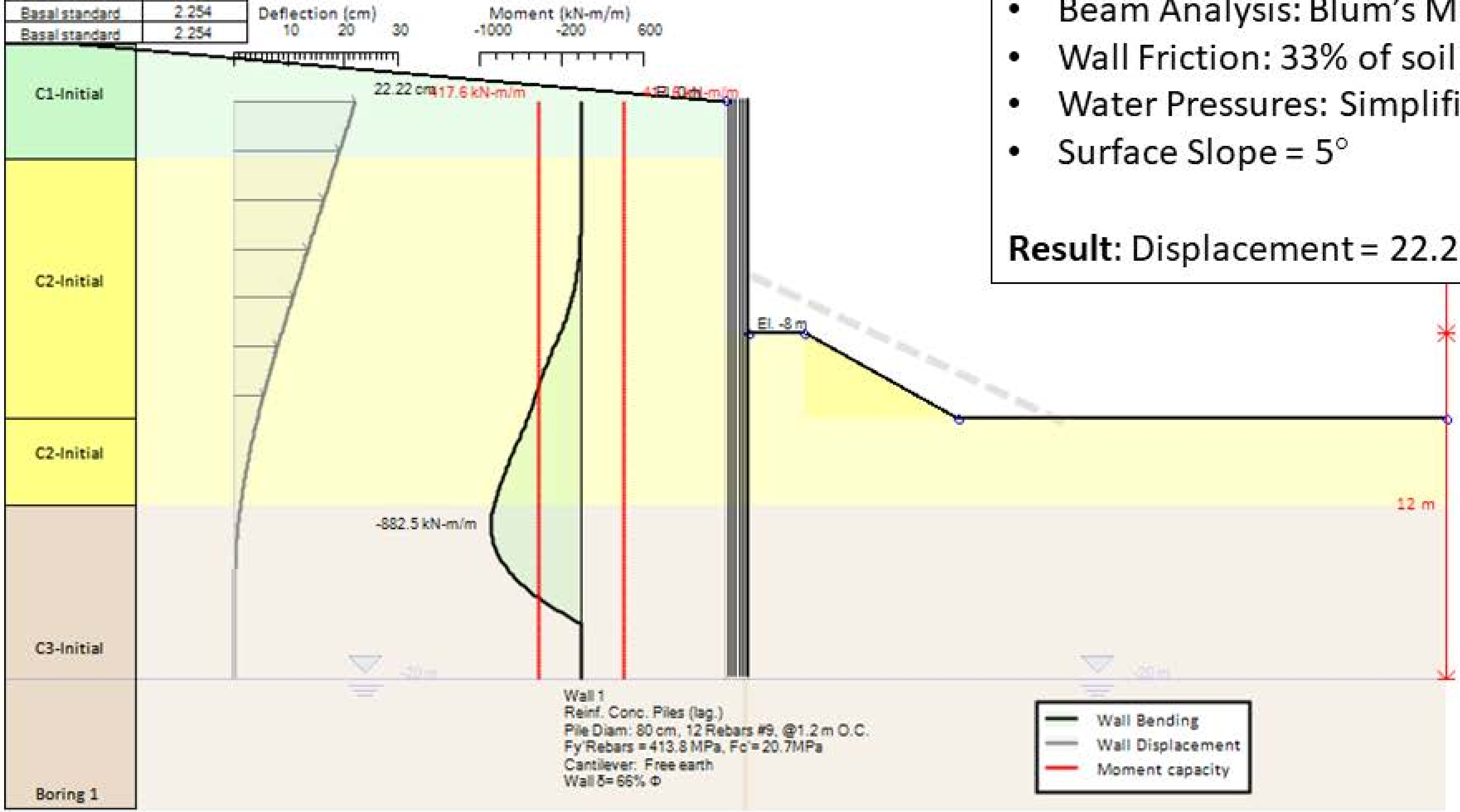
Settings:

- 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



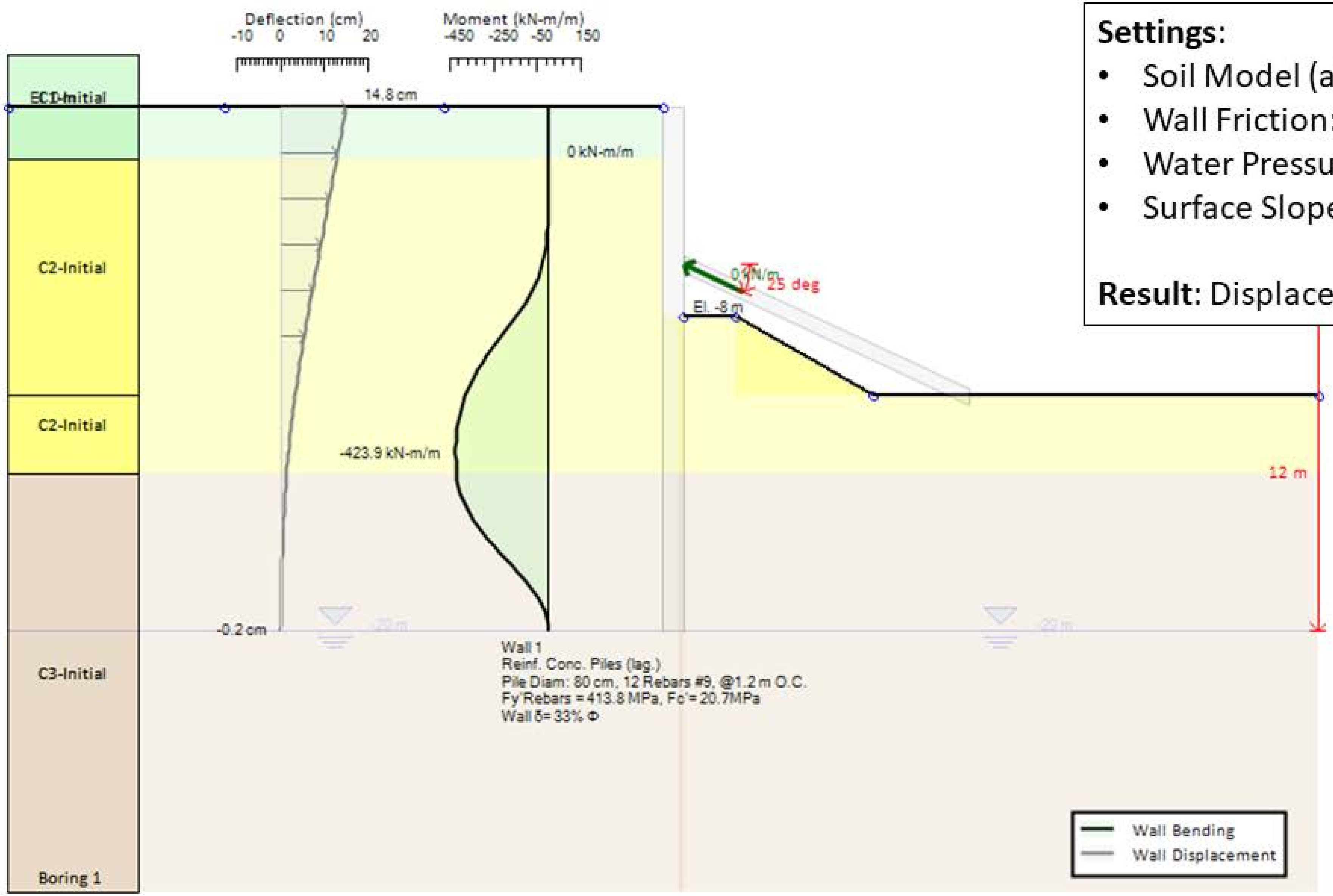
Settings:

- 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)

GeoStruktur

Result: NL, Flat Slope, With Wall Friction



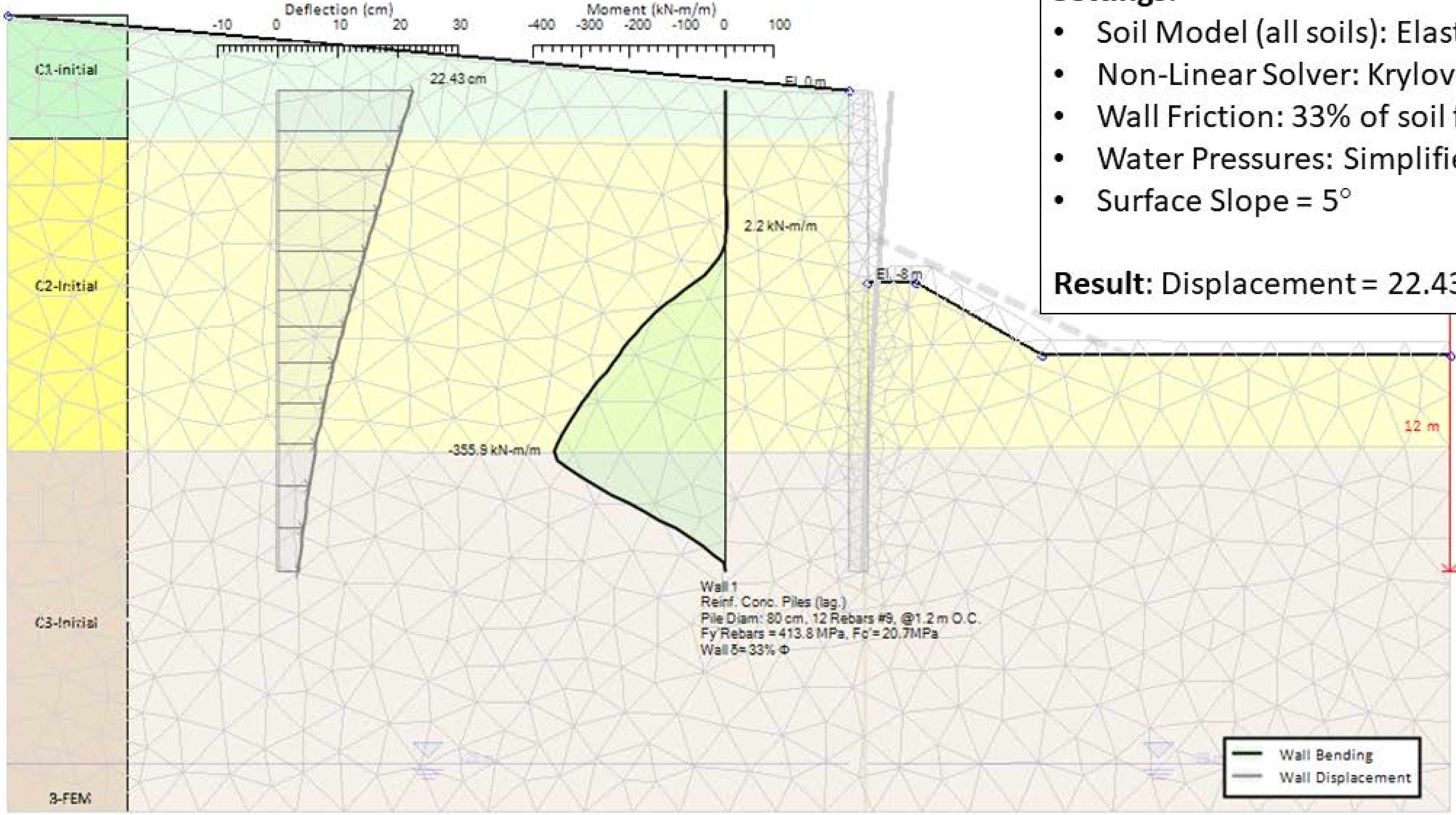
Settings:

- Soil Model (all soils): Elastic-Plastic.
- Wall Friction: 33% of soil friction.
- Water Pressures: Simplified Flow
- Surface Slope = 0°

Result: Displacement = 14.8 cm (at stage 1)

GeoStruktur

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



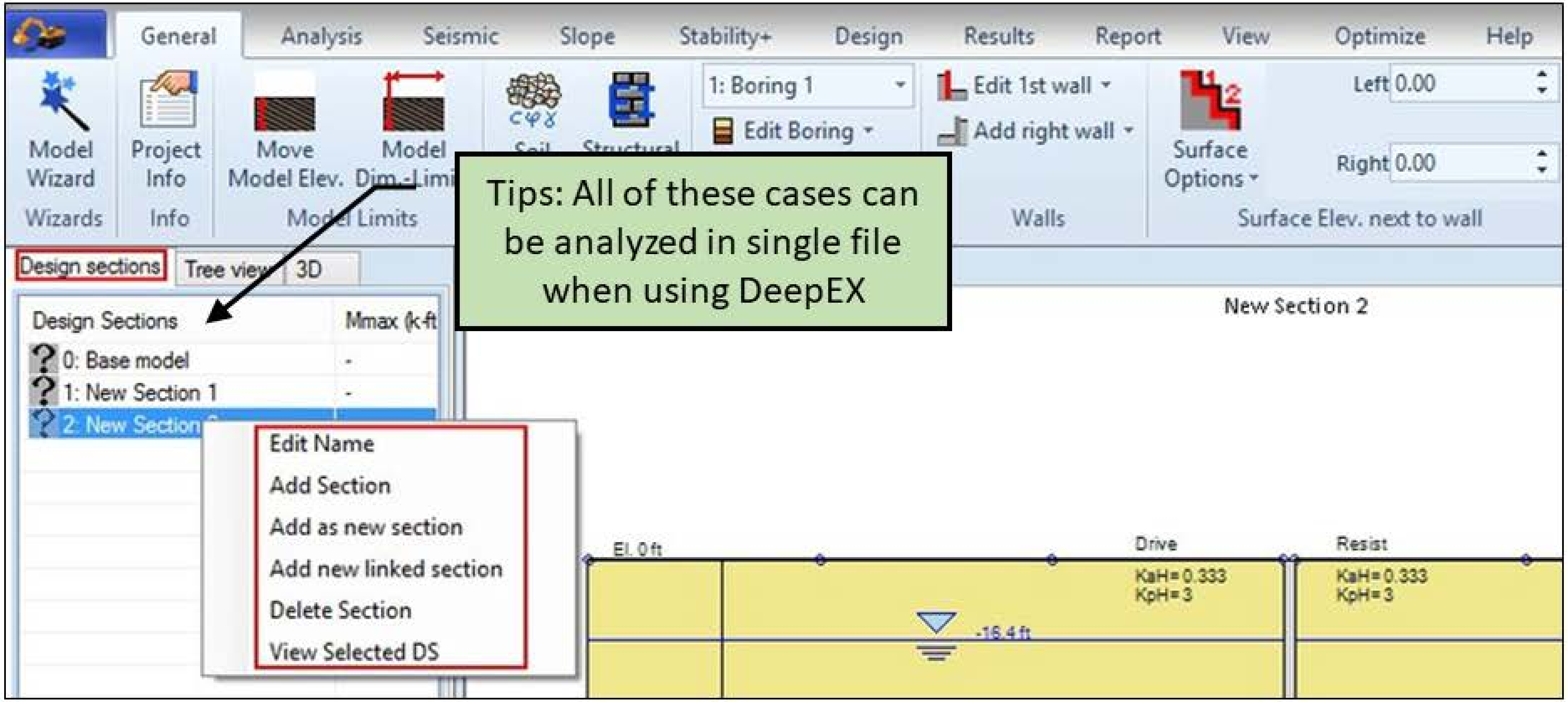
Settings:

- Soil Model (all soils): Elastic-Plastic.
- Non-Linear Solver: Krylov-Newton Method
- Wall Friction: 33% of soil friction.
- Water Pressures: Simplified Flow
- Surface Slope = 5°

Result: Displacement = 22.43 cm (at stage 1)

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).



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.

Usually, these parts take most of our time

- Essential design aspects & case study.
  - Sensitivity analyses.
  - LEM vs NL vs FEM comparison.

Important part to obtain a robust design

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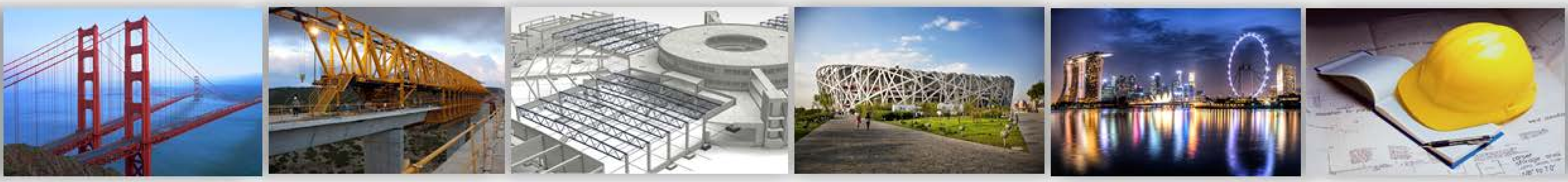

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www.geostruktur.biz
Email: general@geostruktur.com
WA: +62 812 6075 200

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