Anchored Sheet pile walls

Rekayasa Pondasi II

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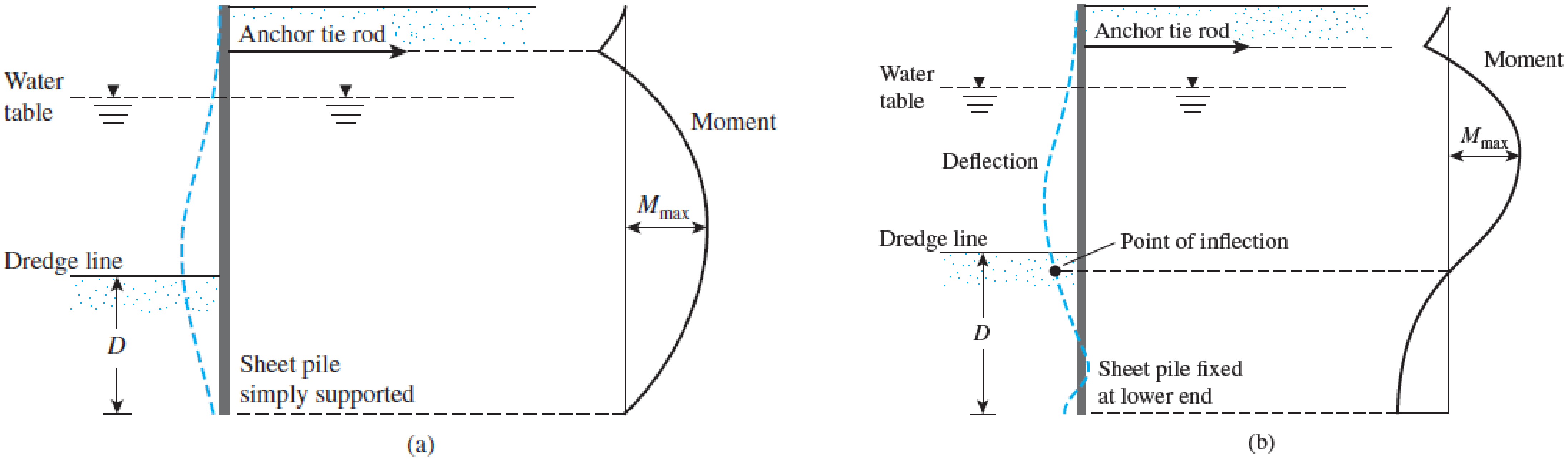
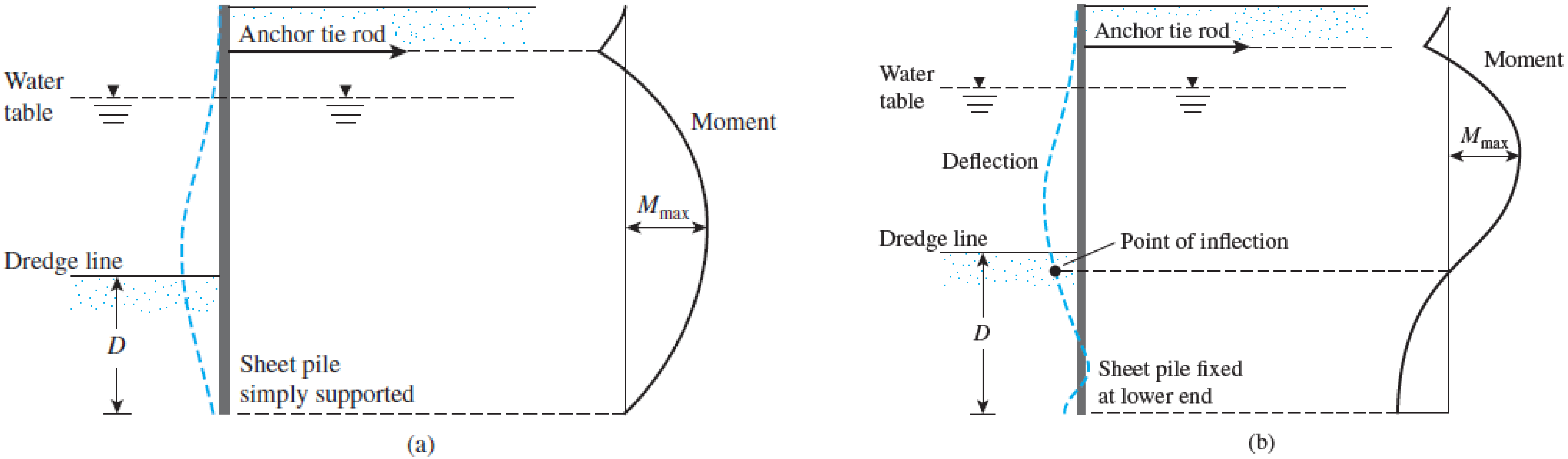
Anchored Sheet Pile wall



If the height of backfill material behind the cantilever sheet-pile exceeds 6m, using anchored becomes more economical.
Anchored sheet pile walls **minimize** the depth of penetration required by sheet piles and also **reduce** the cross-sectional area and weight of sheet piles needed for construction. However. The tie rods and Anchors must be carefully design.

Anchored Sheet Pile wall



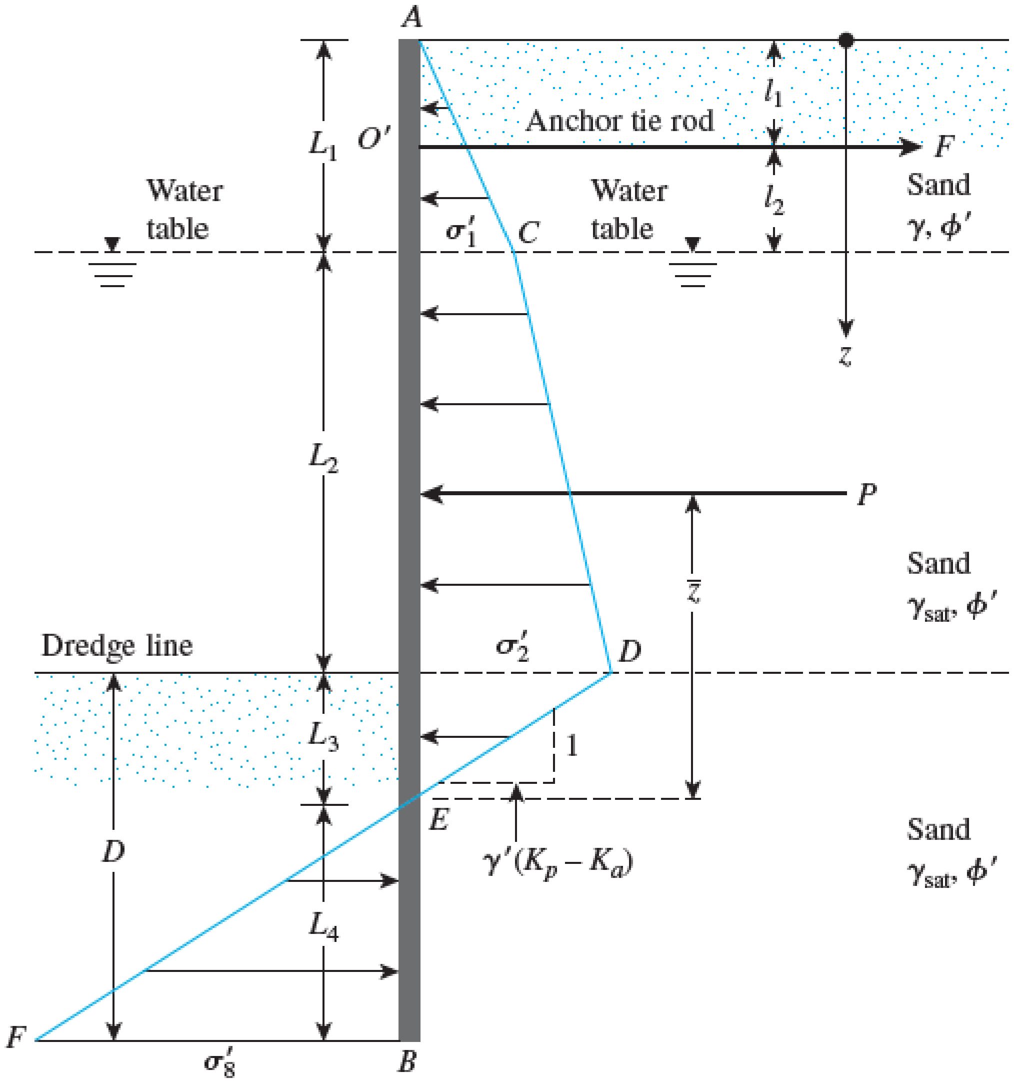
The two basic method of designing anchored sheet pile walls :

(a). The free earth support method

(b). The fixed earth support method

Note that : D free earth < D fixed earth

Free Earth Support Method for Penetrating of Sandy Soils



The intensity of the active pressure at a depth z = L_1

$$\sigma'_1 = \gamma.\ L_1.\ K_a$$

The active pressure at a depth of z = $L_1 + L_2$

$$\sigma'_2 = (\gamma L_1 + \gamma' L_2) K_a$$

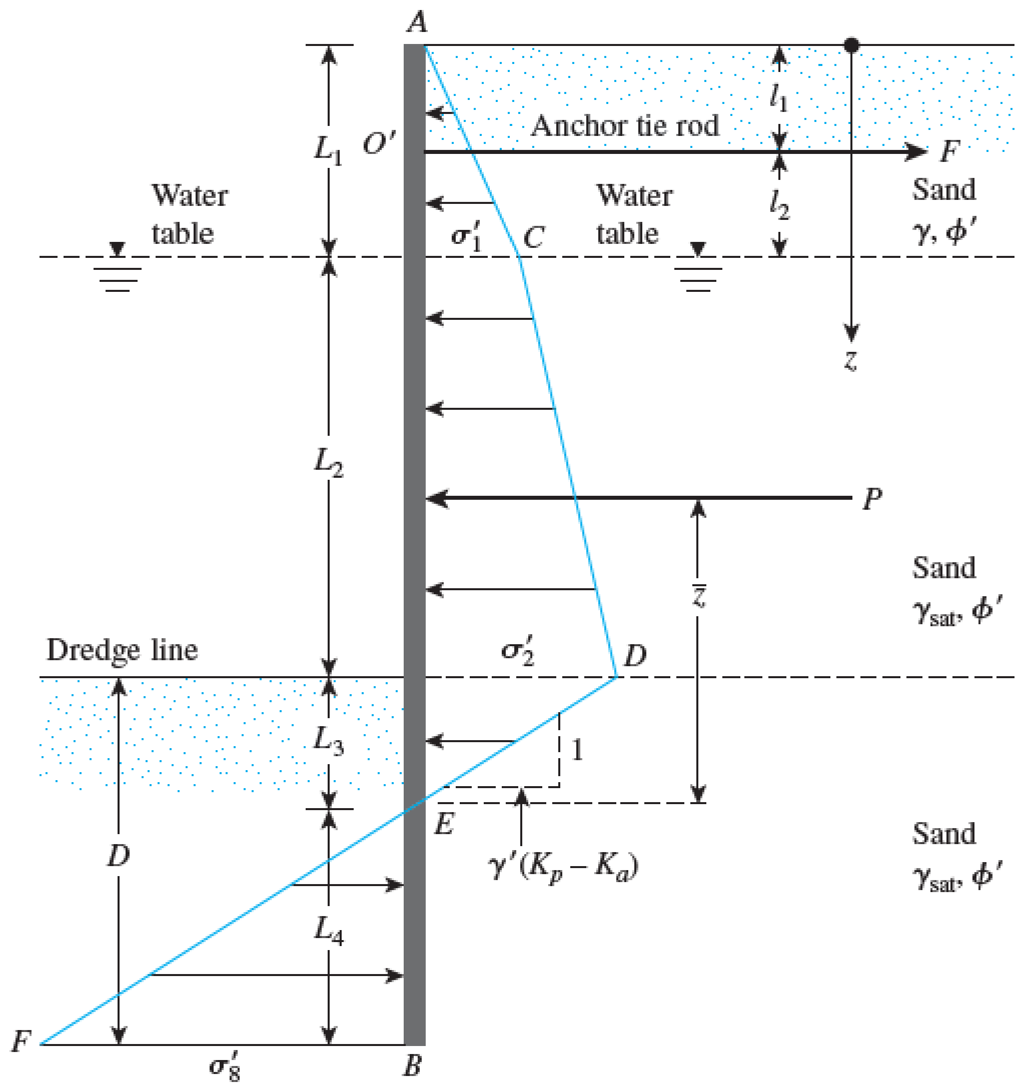
Below the dredge line, the net pressure will be zero at z = $L_1 + L_2 + L_3$, so: $L_3 = \dfrac{\sigma'_2}{\gamma'(K_p - K_a)}$

at z = $L_1 + L_2 + L_3 + L_4$, the net pressure is given by :

$$\sigma'_8 = \gamma'(K_p - K_a)L_4$$

Note that the slope of the line DEF is 1 vertical to γ'(Kp-Ka) horizontal

Free Earth Support Method for Penetrating of Sandy Soils



For equilibrium of the sheet pile, $\Sigma F_H = 0$, And $\Sigma M_O = 0$. Summing the forces in the horizontal direction gives :

Area of the pressure diagram ACDE- area EBF – F = 0

Where F = tension in the tie rod/unit length of the wall, or

$$P - \tfrac{1}{2}\sigma'_8 L_4 - F = 0 \qquad \text{or} \qquad F = P - \tfrac{1}{2}[\gamma'(K_p - K_a)]L_4^2$$

Where P = Area of the pressure diagram ACDE

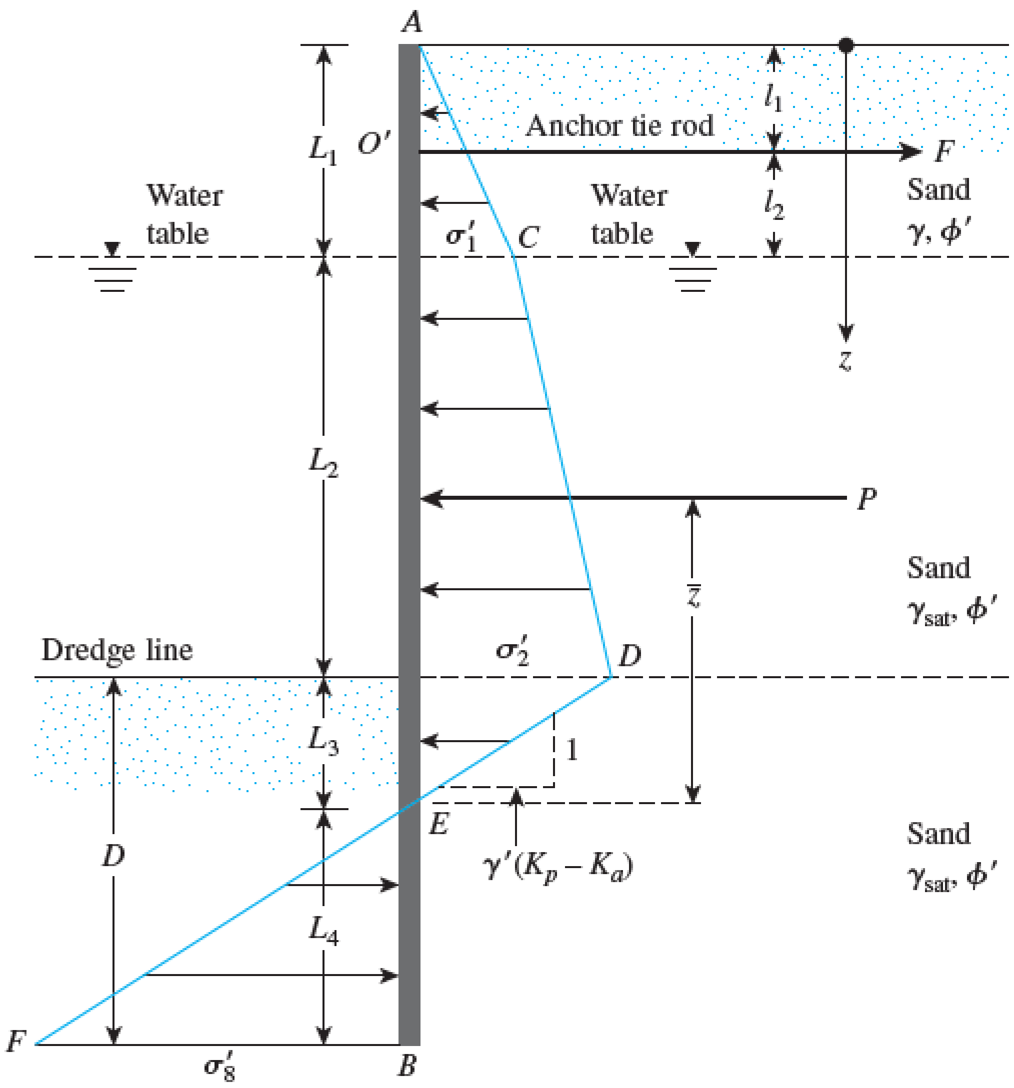
Taking the moment about point O' gives :

$$-P[(L_1 + L_2 + L_3) - (\bar{z} + l_1)] + \tfrac{1}{2}[\gamma'(K_p - K_a)]L_4^2(l_2 + L_2 + L_3 + \tfrac{2}{3}L_4) = 0$$

or

$$L_4^3 + 1.5L_4^2(l_2 + L_2 + L_3) - \frac{3P[(L_1 + L_2 + L_3) - (\bar{z} + l_1)]}{\gamma'(K_p - K_a)} = 0$$

Free Earth Support Method for Penetrating of Sandy Soils



Equation above may be solved by trial and error to determine the theoretical depth, L_4 :

$$D_{theoretical} = L_3 + L_4$$

The theoretical depth is increased by about 30 to 40% for actual construction, or

$$D_{actual} = 1.3 \text{ to } 1.4\, D_{theoretical}$$

Maximum moment (M_{max}) will be subjected occurs at a depth between depth z = L_1 and z = L_1 + L_2 . The depth z for zero shear and hence maximum moment may be evaluated from :

$$\tfrac{1}{2}\sigma'_1 L_1 - F + \sigma'_1(z - L_1) + \tfrac{1}{2}K_a\gamma'(z - L_1)^2 = 0$$

Free Earth Support Method for Penetrating of Sandy Soils

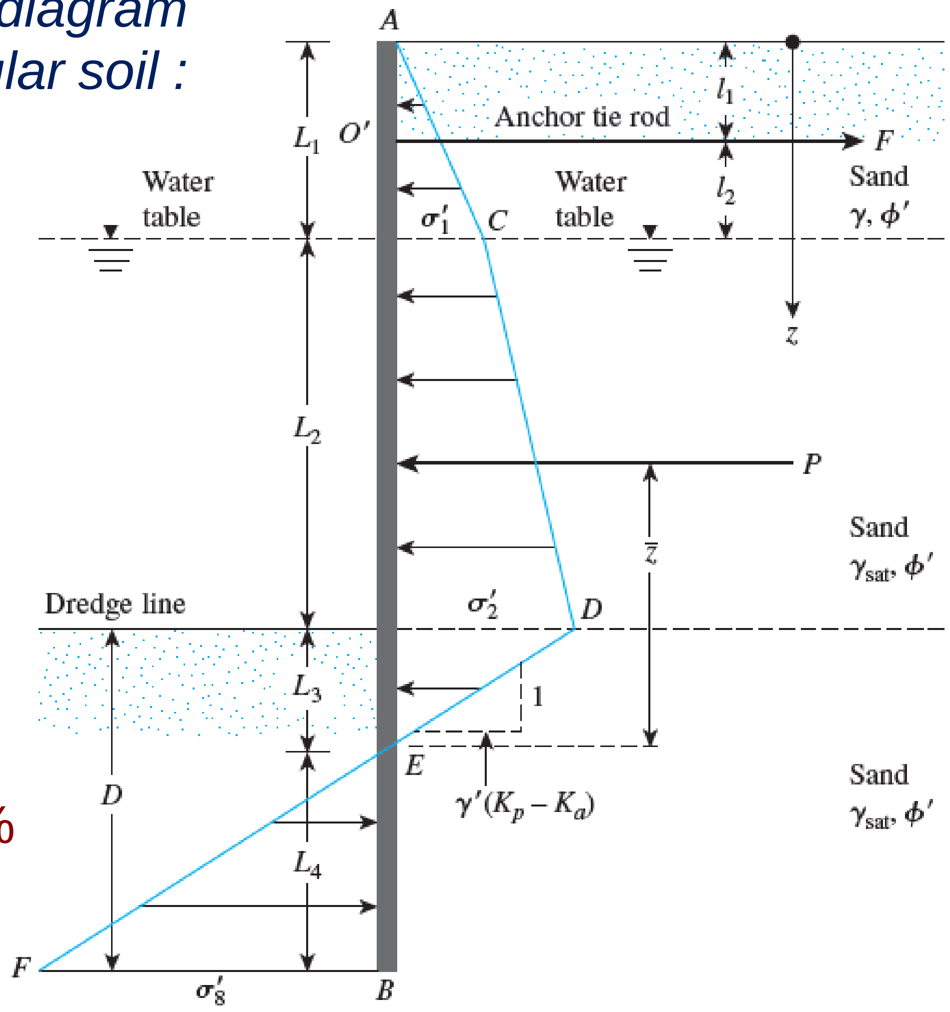
Step by step procedure to obtaining the pressure diagram for a cantilever sheet pile wall penetrating a granular soil :

1. Calculate K_a and K_p
2. Calculate σ'_1 and σ'_2 (L_1 and L_2 will be given)
3. Calculate L_3
4. Calculate P
5. Calculate $\hat{z}$ (the center of pressure for area ACDE, by taking moment about E)
6. Solve trial and error to determine L_4 and F
7. Draw pressure distribution diagram
8. The theoretical depth of penetration is:

$$D_{\text{theoretical}} = L_3 + L_4$$

The theoretical depth is increased about 30% to 40% for actual construction, or

$$D_{\text{actual}} = 1.3 \text{ to } 1.4\, D_{\text{theoretical}}$$



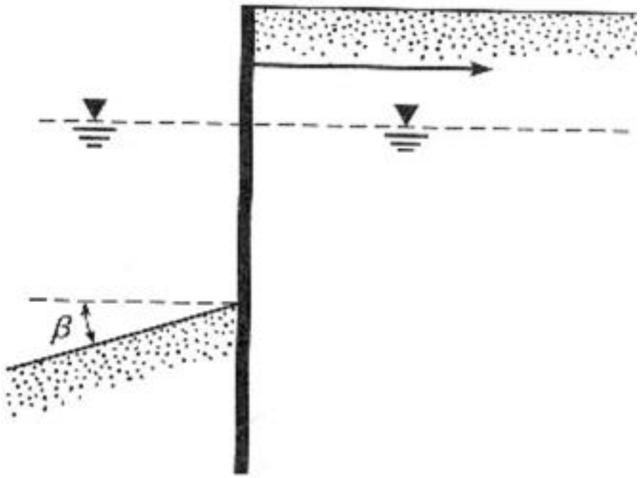
Free Earth Support Method for Penetrating of Sandy Soils

Calculation of maximum bending moment:

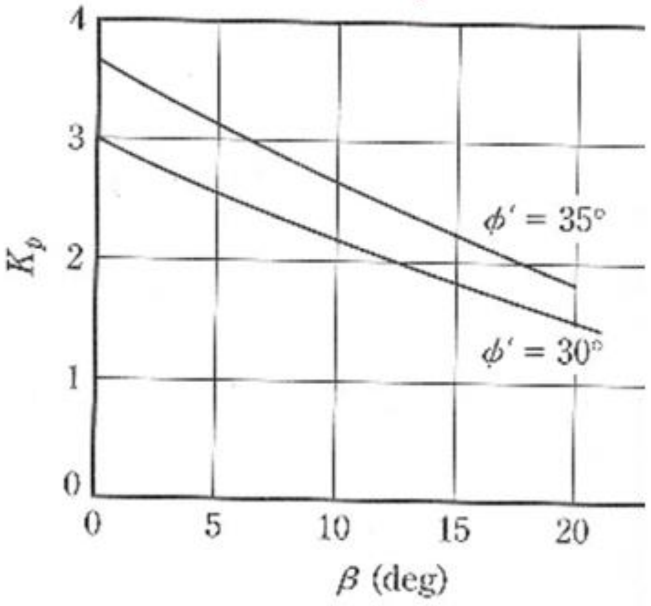
The maximum theoretical moment to which the sheet pile wall be subjected occurs at a depth between $z = L_1$ and $z = L_1 + L_2$. The depth z for zero shear and hence maximum moment may be evaluated from :

$$\frac{1}{2}\sigma_1' L_1 - F + \sigma_1'(z - L_1) + \frac{1}{2}K_a\gamma'(z - L_1)^2 = 0$$

Sometimes, the dredge line slopes at an angle B with respect to the horizontal :



Variation K_p:



Free Earth Support Method for Penetrating of Sandy Soils

Moment Reduction for Anchored Sheet Pile

Rowe (1952, 1957) suggested a procedure for reducing the maximum design moment on the sheet-pile walls obtained from the free earth support method.

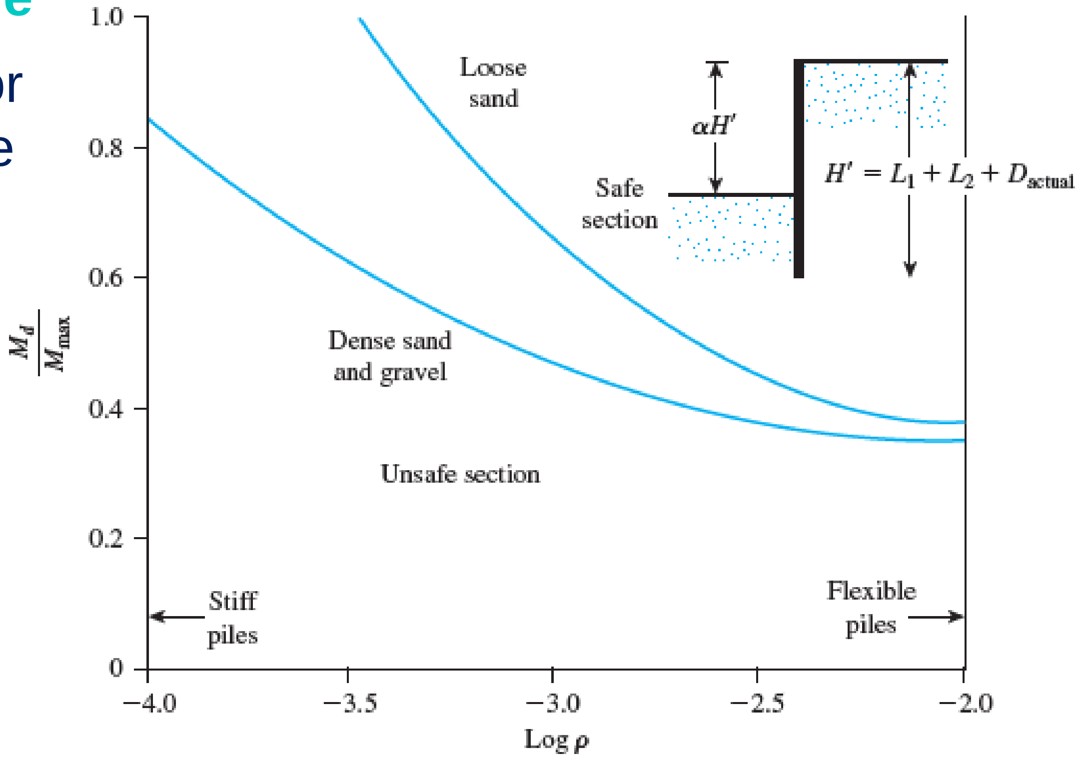
1. H' = total height of pile driven (i.e., $L_1 + L_2 + D_{actual}$)
2. Relative flexibility of pile:

$$\rho = 10.91 \times 10^{-7}\left(\frac{H'^4}{EI}\right)$$

where

H' is in meters
E = modulus of elasticity of the pile material (MN/m^2)
I = moment of inertia of the pile section per meter of the wall (m^4/m of wall)

3. M_d = design Moment
4. M_{max} = maximum theoretical moment



Free Earth Support Method for Penetrating of Sandy Soils

The procedure for the use of the moment reduction diagram:

1. Choose a sheet pile section (for among those given in table 14.1)
2. Find the modulus S of the selected section
3. Determine the moment of inertia of the section.
4. Obtain H' and calculate ρ.
5. Find log ρ .
6. Find the moment capacity of the pile section chosen ($M_d = \sigma_{all}$ S).
7. Determine M_d / M_{max} (M_{max} is the maximum theoretical moment determined before)
8. Plot log ρ and M_d / M_{max} .
9. Repeat steps 1-8 for several sections. The points that fall above the curve are safe sections. The points that fall below the curve are unsafe sections. Note that the section chosen will have an $M_d < M_{max}$

Free Earth Support Method for Penetrating of Sandy Soils

Table 14.1 Properties of Some Commercially Available Sheet-Pile Sections (Based on Hammer and Steel, Inc., Hazelwood, Missouri, USA)

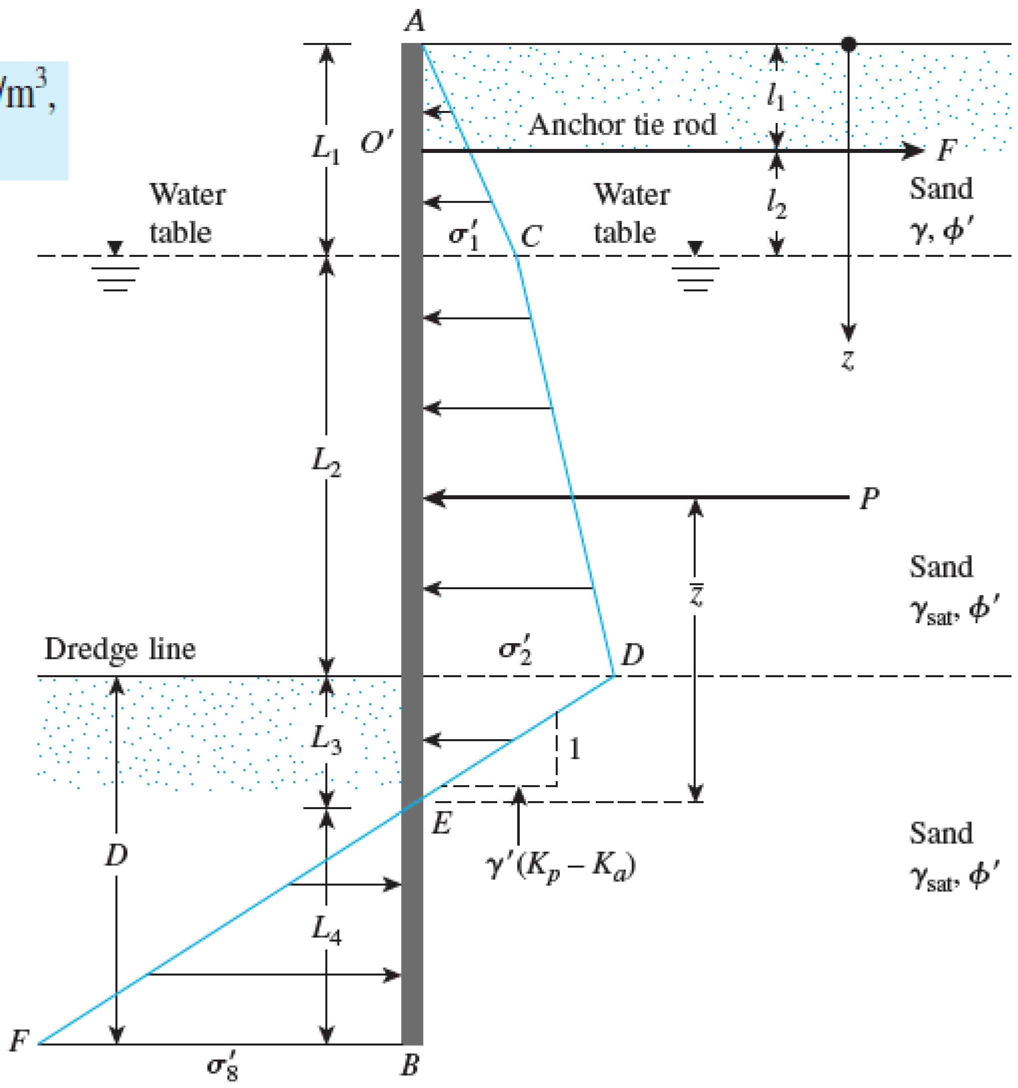
Section designation	*H* mm (in.)	*L* mm (in.)	*f* mm (in.)	*w* mm (in.)	Section modulus m^3/m of wall ($in.^3$/ft of wall)	Moment of inertia m^4/m of wall ($in.^4$/ft of wall)
PZC-12	318.0 (12.52)	708.2 (27.88)	8.51 (0.335)	8.51 (0.335)	120.42×10^{-5} (22.4)	192.06×10^{-6} (140.6)
PZC-13	319.0 (12.56)	708.2 (27.88)	9.53 (0.375)	9.53 (0.375)	130.1×10^{-5} (24.2)	207.63×10^{-6} (152.0)
PZC-14	320.0 (12.6)	708.2 (27.88)	10.67 (0.420)	10.67 (0.420)	139.78×10^{-5} (26.0)	225.12×10^{-6} (164.8)
PZC-17	386.3 (15.21)	635.0 (25.00)	8.51 (0.335)	8.51 (0.335)	166.67×10^{-5} (31.0)	322.38×10^{-6} (236.6)
PZC-18	387.4 (15.25)	635.0 (25.00)	9.53 (0.375)	9.53 (0.375)	180.1×10^{-5} (33.5)	349.01×10^{-6} (255.5)
PZC-19	388.6 (15.30)	635.0 (25.00)	10.67 (0.420)	10.67 (0.420)	194.07×10^{-5} (36.1)	377.97×10^{-6} (276.7)
PZC-26	449.6 (17.70)	708.2 (27.88)	15.24 (0.60)	13.34 (0.525)	260.2×10^{-5} (48.4)	584.78×10^{-6} (428.1)
PZ-22	235.0 (9.25)	558.8 (22.00)	9.53 (0.375)	9.53 (0.375)	98.92×10^{-5} (18.4)	116.2×10^{-6} (85.1)
PZ-27	307.3 (12.1)	457.2 (18.00)	9.53 (0.375)	9.53 (0.375)	166.66×10^{-5} (31.00)	255.9×10^{-6} (187.3)
PZ-35	383.5 (15.1)	575.1 (22.64)	15.37 (0.605)	12.7 (0.5)	262.9×10^{-5} (48.9)	504.6×10^{-6} (369.4)
PZ-40	416.6 (16.4)	499.1 (19.69)	15.24 (0.6)	12.7 (0.5)	329.5×10^{-5} (61.3)	686.7×10^{-6} (502.7)

Free Earth Support Method for Penetrating of Sandy Soils

EXAMPLE

Let $L_1 = 3.05$ m, $L_2 = 6.1$ m, $l_1 = 1.53$ m, $l_2 = 1.52$ m, $c' = 0$, $\phi' = 30°$, $\gamma = 16$ kN/m^3, $\gamma_{sat} = 19.5$ kN/m^3, and $E = 207 \times 10^3$ MN/m^2

a. Determine the theoretical and actual depths of penetrations (Note $D_{actual} = 1.3 D_{theory}$).
b. Find the anchor force per unit length of the wall.
c. Determine the maximum moment, M_{max}.
d. Use Rowe's moment reduction technique to appropriate sheet-pile section. For the sheet pile, use E= 207 x 103 MN/m^2 and σ_{all}=172500 kN/m^2)



Free Earth Support Method for Penetrating of Sandy Soils

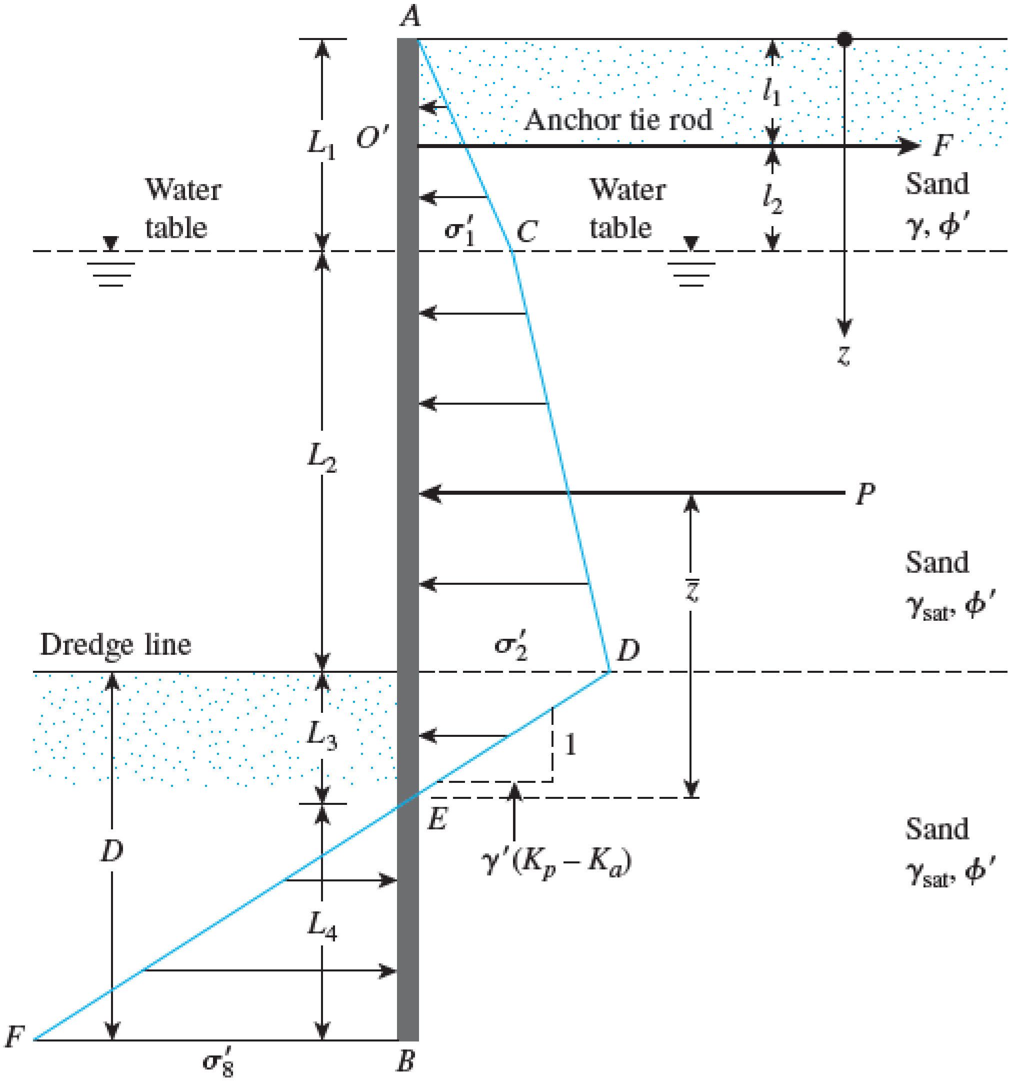
Part a : Determine the theoretical and actual depths of penetrations (Note D_{actual} =1.3 D_{theory}).

Part a

We use the following table.

Quantity required	Equation and calculation
K_a	$\tan^2\left(45 - \frac{\phi'}{2}\right) = \tan^2\left(45 - \frac{30}{2}\right) = \frac{1}{3}$
K_p	$\tan^2\left(45 + \frac{\phi'}{2}\right) = \tan^2\left(45 + \frac{30}{2}\right) = 3$
$K_p - K_a$	$3 - 0.333 = 2.667$
γ'	$\gamma_{sat} - \gamma_w = 19.5 - 9.81 = 9.69\ \text{kN/m}^3$
σ'_1	$\gamma L_1 K_a = (16)(3.05)(\frac{1}{3}) = 16.27\ \text{kN/m}^2$
σ'_2	$(\gamma L_1 + \gamma' L_2)K_a = [(16)(3.05) + (9.69)(6.1)]\frac{1}{3} = 35.97\ \text{kN/m}^2$
L_3	$\frac{\sigma'_2}{\gamma'(K_p - K_a)} = \frac{35.97}{(9.69)(2.667)} = 1.39\ \text{m}$
P	$P \quad \frac{1}{2}\sigma'_1 L_1 + \sigma'_1 L_2 + \frac{1}{2}(\sigma'_2 - \sigma'_1)L_2 + \frac{1}{2}\sigma'_2 L_3$ $+ (16.27)(6.1) + (\frac{1}{2})(35.97 - 16.27)(6.1) + (\frac{1}{2})(35.97)(1.39)$ $= 24.81 + 99.25 + 60.01 + 25.0 = 209.07\ \text{kN/m}$
$\bar{z}$	$\frac{\Sigma M_E}{P} = \left[\begin{array}{l}(24.81)\left(1.39 + 6.1 + \frac{3.05}{3}\right) + (99.25)\left(1.39 + \frac{6.1}{2}\right) \\ + (60.01)\left(1.39 + \frac{6.1}{3}\right) + (25.0)\left(\frac{2 \times 1.39}{3}\right)\end{array}\right]\frac{1}{209.07}$ $= 4.21\ \text{m}$

(Continued)



Free Earth Support Method for Penetrating of Sandy Soils

Part a : ***continue***

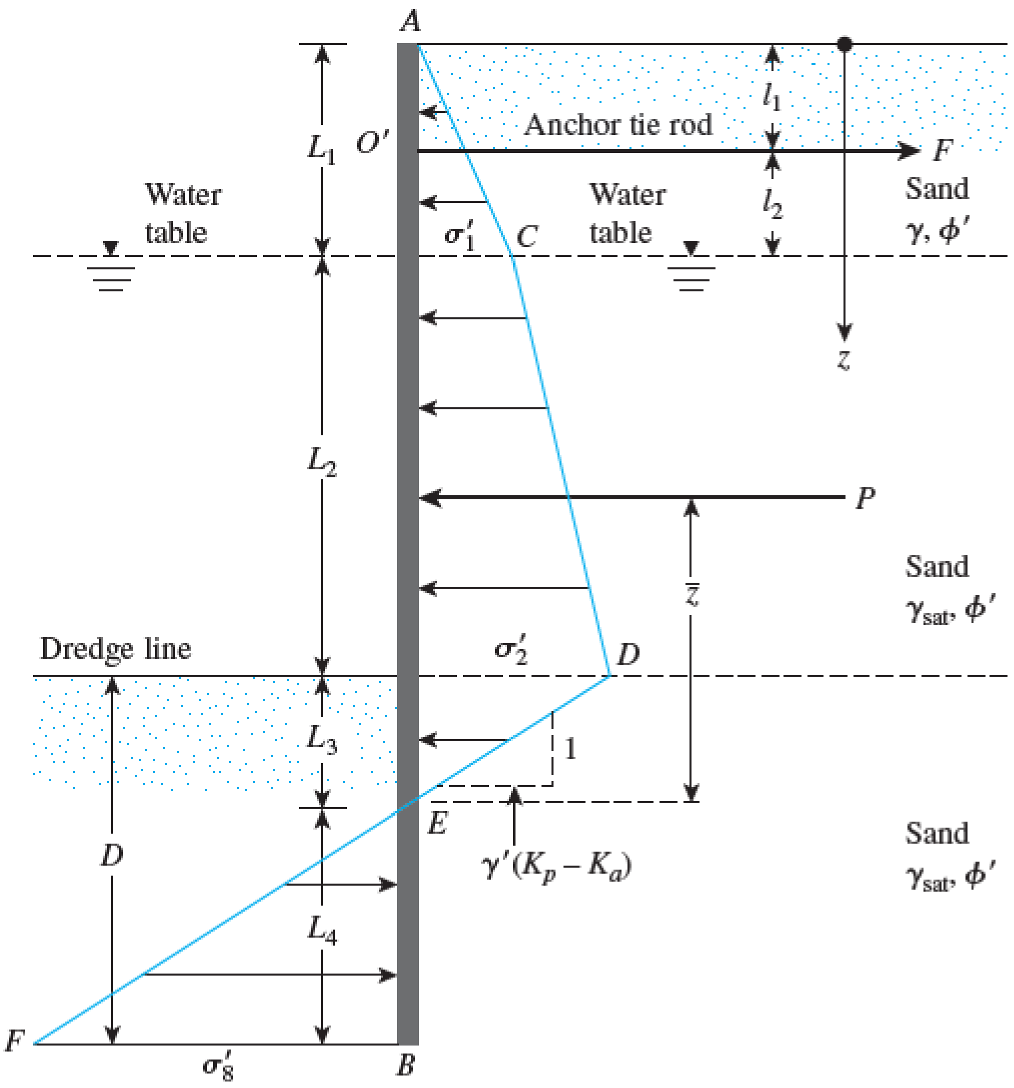
Quantity required	Equation and calculation
L_4	$L_4^3 + 1.5L_4^2(l_2 + L_2 + L_3) - \dfrac{3P[(L_1 + L_2 + L_3) - (\bar{z} + l_1)]}{\gamma'(K_p - K_a)} = 0$
	$L_4^3 + 1.5L_4^2(1.52 + 6.1 + 1.39)$
	$- \dfrac{(3)(209.07)[(3.05 + 6.1 + 1.39) - (4.21 + 1.53)]}{(9.69)(2.667)} = 0$
	$L_4 = 2.7$ m
D_{theory}	$L_3 + L_4 = 1.39 + 2.7 = 4.09 \approx$ **4.1 m**
D_{actual}	$1.3D_{theory} = (1.3)(4.1) =$ **5.33 m**

Part b : Find the anchor force per unit length of the wall.

Part b

The anchor force per unit length of the wall is

$$F = P - \tfrac{1}{2}\gamma'(K_p - K_a)L_4^2$$
$$= 209.07 - \left(\tfrac{1}{2}\right)(9.69)(2.667)(2.7)^2 = 114.87 \text{ kN/m} \approx \mathbf{115\ kN/m}$$



Free Earth Support Method for Penetrating of Sandy Soils

Part c : Determine the maximum moment, M max

Part c

From Eq. (14.69), for zero shear,

$$\tfrac{1}{2}\sigma_1' L_1 - F + \sigma_1'(z - L_1) + \tfrac{1}{2}K_a\gamma'(z - L_1)^2 = 0$$

Let $z - L_1 = x$, so that

$$\tfrac{1}{2}\sigma_1' L_1 - F + \sigma_1' x + \tfrac{1}{2}K_a\gamma' x^2 = 0$$

or

$$(\tfrac{1}{2})(16.27)(3.05) - 115 + (16.27)(x) + (\tfrac{1}{2})(\tfrac{1}{3})(9.69)x^2 = 0$$

giving $\quad x^2 + 10.07x - 55.84 = 0$

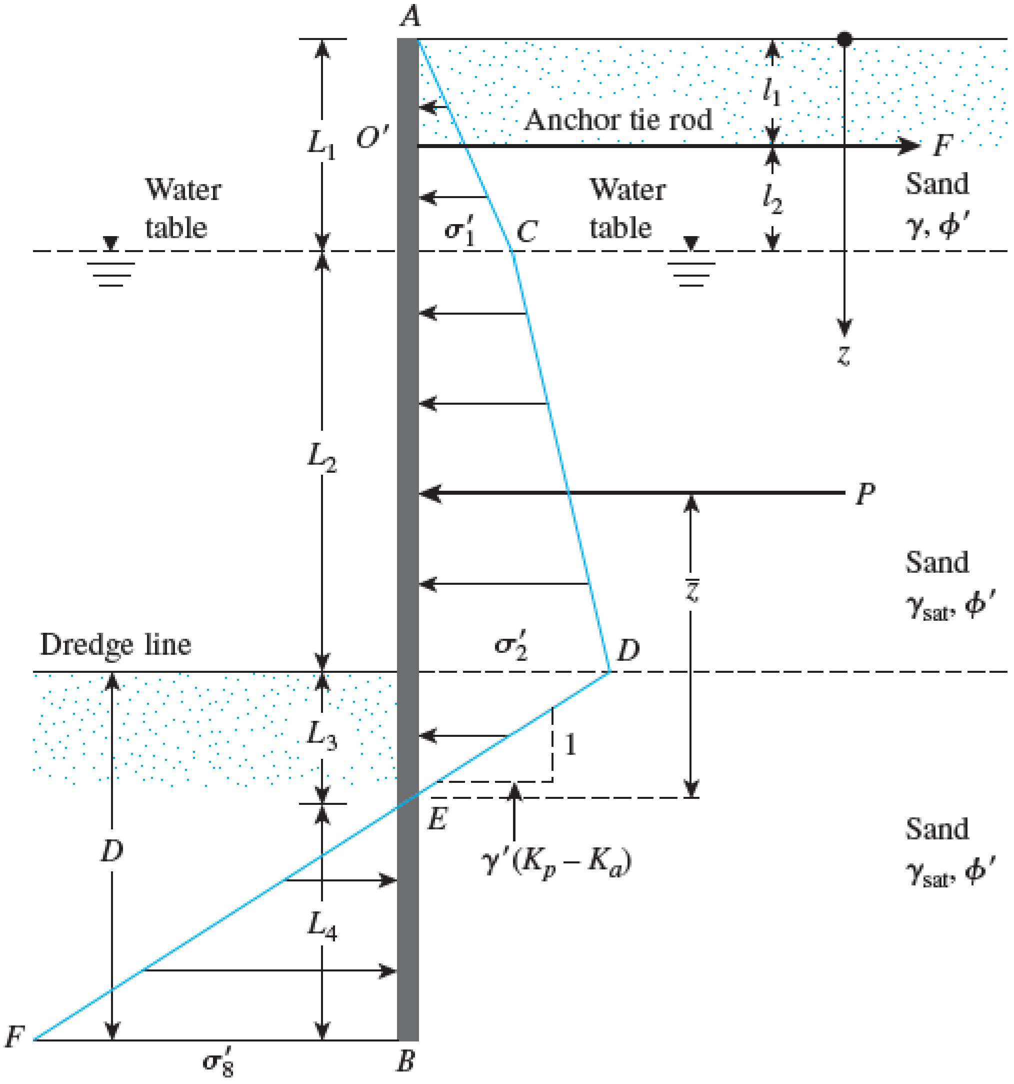
Now, $x = 4$ m and $z = x + L_1 = 4 + 3.05 = 7.05$ m. Taking the moment about the point of zero shear, we obtain

$$M_{max} = -\frac{1}{2}\sigma_1' L_1\left(x + \frac{3.05}{3}\right) + F(x + 1.52) - \sigma_1'\frac{x^2}{2} - \frac{1}{2}K_a\gamma' x^2\left(\frac{x}{3}\right)$$

or

$$M_{max} = -\left(\frac{1}{2}\right)(16.27)(3.05)\left(4 + \frac{3.05}{3}\right) + (115)(4 + 1.52) - (16.27)\left(\frac{4^2}{2}\right)$$

$$-\left(\frac{1}{2}\right)\left(\frac{1}{3}\right)(9.69)(4)^2\left(\frac{4}{3}\right) = \mathbf{344.9\ kN\text{-}m/m}$$



Free Earth Support Method for Penetrating of Sandy Soils

Part d : Use Rowe's moment reduction technique to appropriate sheet-pile section. For the sheet pile, use E= 207 x 103 MN/m2 and σ all=172500 kN/m2)

Solution

$$H' = L_1 + L_2 + D_{actual} = 3.05 + 6.1 + 5.33 = 14.48 \text{ m}$$

$M_{max} = 344.9$ kN · m/m. Now the following table can be prepared.

Section	I(m^4/m)	H'(m)	$\rho = 10.91 \times 10^{-7}\left(\frac{H'^4}{EI}\right)$	log ρ	S(m^3/m)	$M_d = S\sigma_{all}$ (kN · m/m)	$\frac{M_d}{M_{max}}$
PZ-22	116.2×10^{-6}	14.48	19.94×10^{-4}	−2.7	98.92×10^{-5}	170.64	0.495
PZ-27	255.9×10^{-6}	14.48	9.05×10^{-4}	−3.04	166.66×10^{-5}	287.49	0.834

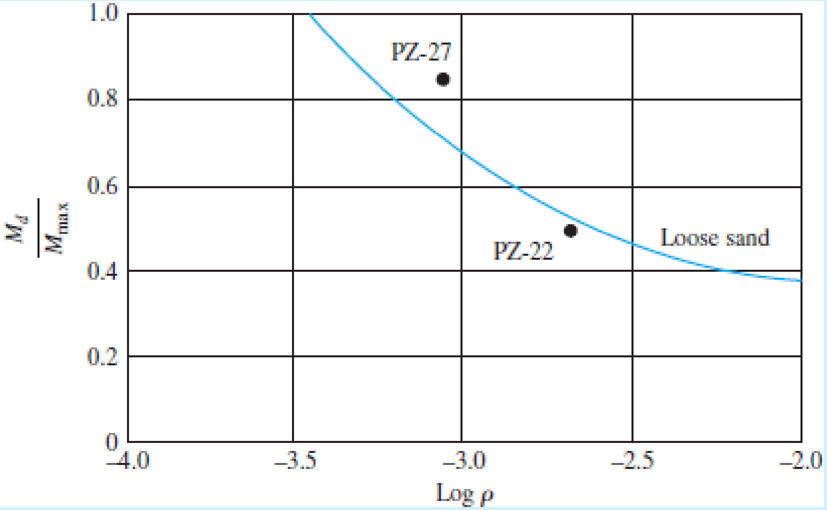
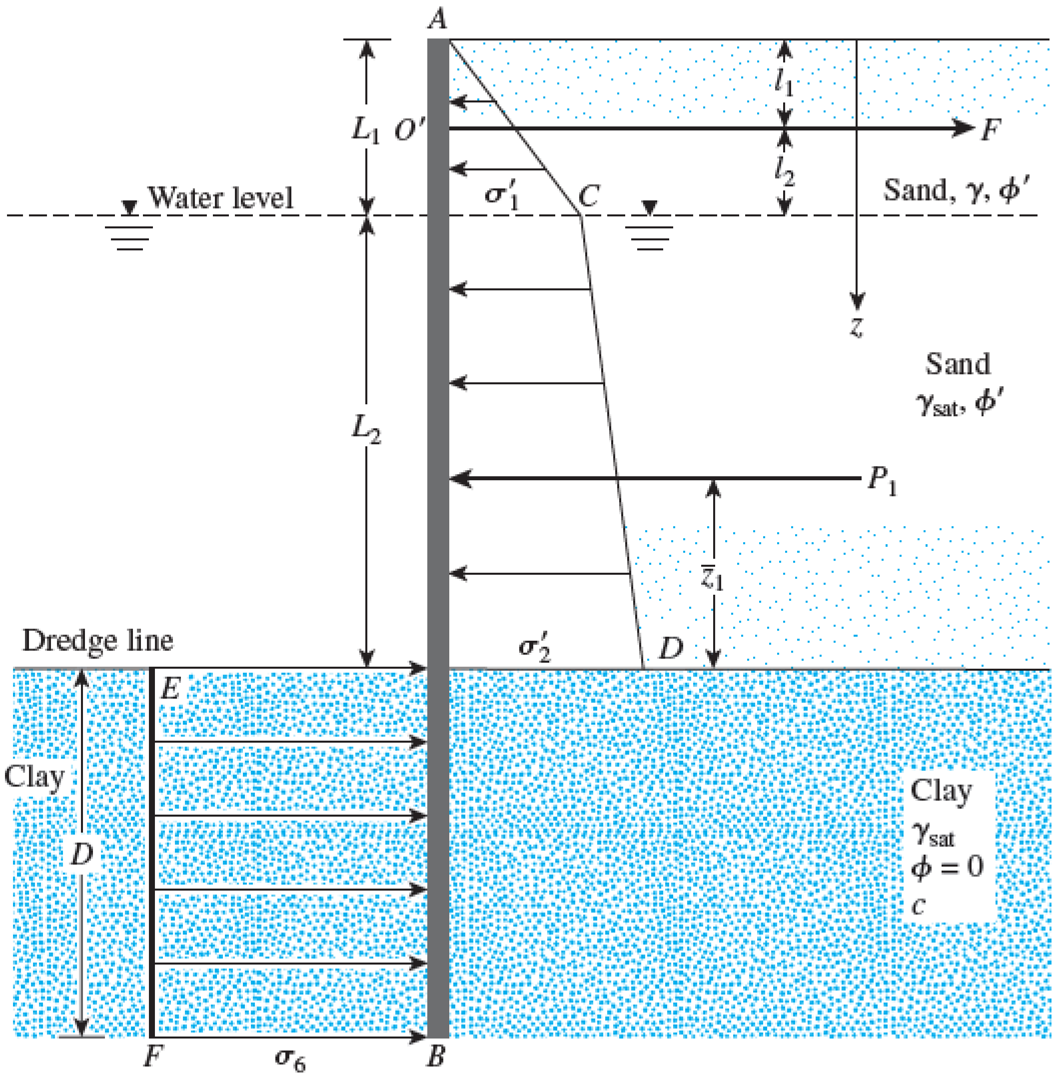


Figure 14.26 Plot of M_d/M_{max} versus log ρ

Free Earth Support Method for Penetrating of CLAY Soils



The intensity of the active pressure at a depth $z = L_1$

$$\sigma'_1 = \gamma .\ L_1 .\ K_a$$

The active pressure at a depth of $z = L_1 + L_2$

$$\sigma'_2 = (\gamma L_1 + \gamma' L_2) K_a$$

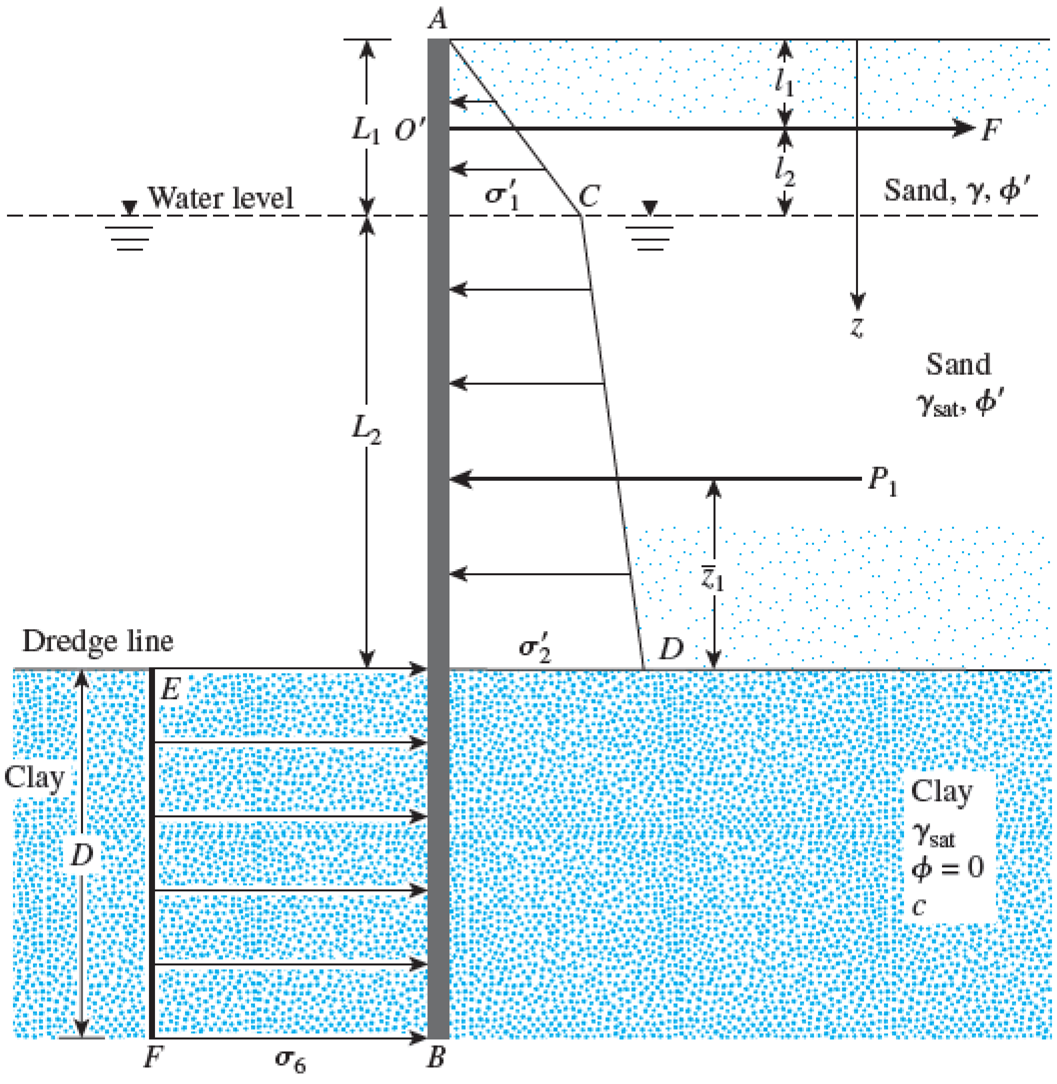
The net pressure below the dredge line, from $z = L_1 + L_2$ to $z = L_1 + L_2 + D$) is

$$\sigma'_6 = 4c - (\gamma L_1 + \gamma' L_2)$$

For static equilibrium, the sum of the force in the horizontal direction is :

$$P_1 - \sigma'_6 D = F$$

Free Earth Support Method for Penetrating of CLAY Soils



Taking the moment about point O' produces :

$$P_1(L_1 + L_2 - l_1 - \bar{z}_1) - \sigma_6 D\left(l_2 + L_2 + \frac{D}{2}\right) = 0$$

Simplification yield :

$$\sigma_6 D^2 + 2\sigma_6 D(L_1 + L_2 - l_1) - 2P_1(L_1 + L_2 - l_1 - \bar{z}_1) = 0$$

Calculation of maximum bending moment:

The maximum theoretical moment to which the sheet pile wall be subjected occurs at a depth between $z = L_1$ and $z = L_1 + L_2$. The depth z for zero shear and hence maximum moment may be evaluated from :

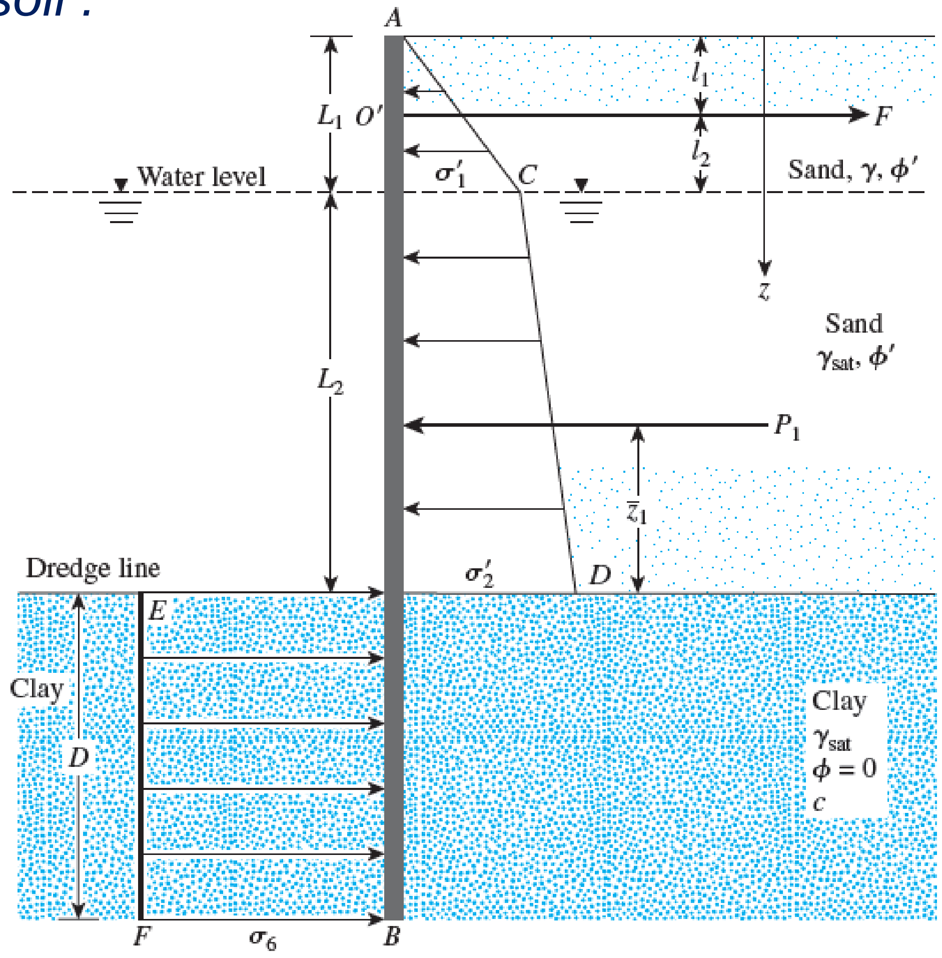
$$\tfrac{1}{2}\sigma'_1 L_1 - F + \sigma'_1(z - L_1) + \tfrac{1}{2}K_a\gamma'(z - L_1)^2 = 0$$

Free Earth Support Method for Penetrating of CLAY Soils

Step by step procedure to obtaining the pressure diagram for a cantilever sheet pile wall penetrating a granular soil :

1. Calculate K_a and K_p
2. Calculate σ'_1 and σ'_2 (L_1 and L_2 will be given)
3. Calculate P_1
4. Calculate $\hat{z}$ (the center of pressure for area ACDE, by taking moment about E)
5. Solve σ'_6 and F
6. Calculate D
7. Draw the pressure distribution diagram.
8. The theoretical depth is increased about 30% to 40% for actual construction, or

$$D_{actual} = 1.3 \text{ to } 1.4\ D_{theoretical}$$



Free Earth Support Method for Penetrating of CLAY Soils

Moment Reduction for Anchored Sheet Pile

A moment reduction technique for anchored sheet piles penetrating into clay has also been developed by Rowe (1952, 1957).

1. The stability number is :

$$S_n = 1.25\frac{c}{(\gamma L_1 + \gamma' L_2)}$$

where c = undrained cohesion ($\phi = 0$).

For the definition of γ, γ', L_1, and L_2, see Figure 14.32.

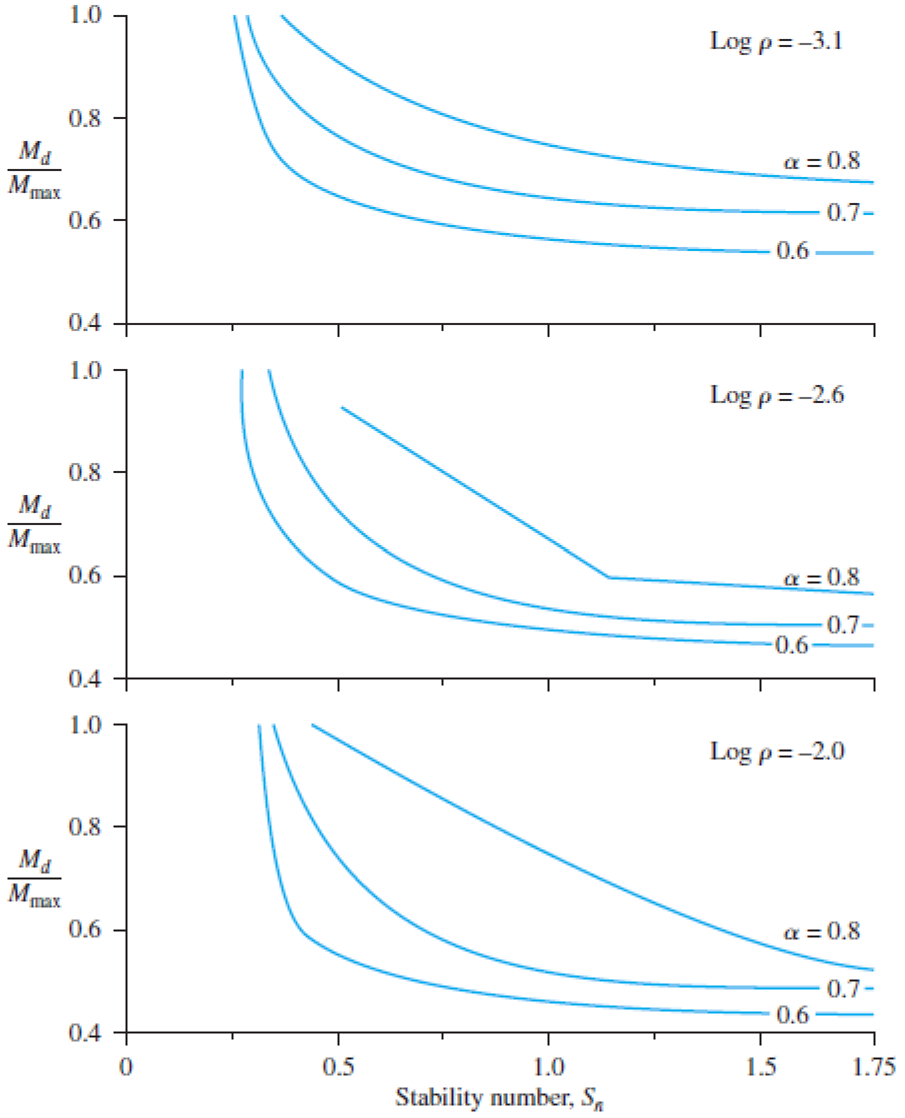
2. The non dimensional wall height is :

$$\alpha = \frac{L_1 + L_2}{L_1 + L_2 + D_{actual}}$$

3. The flexibility number (ρ) is see on figure :

$$\rho = 10.91 \times 10^{-7}\left(\frac{H'^4}{EI}\right)$$

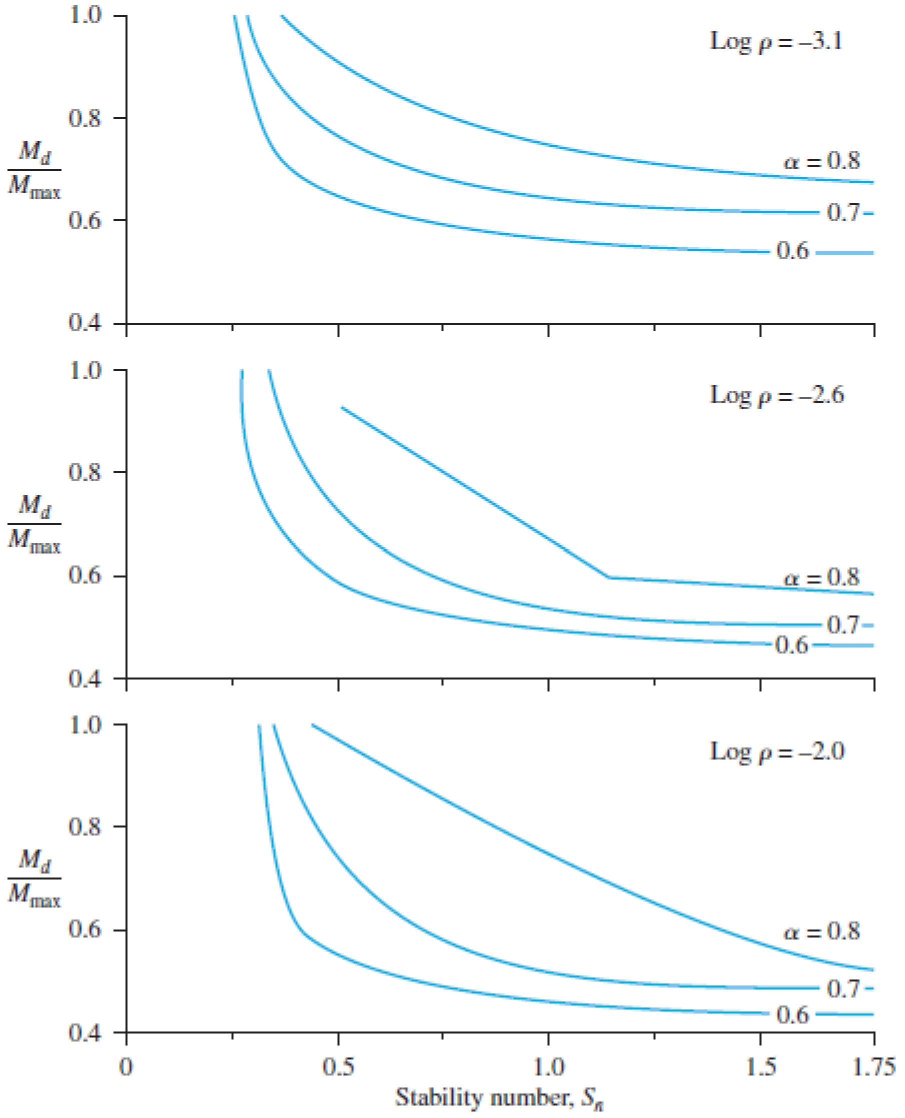
4. M_d = design Moment
5. M_{max} = maximum theoretical moment



Free Earth Support Method for Penetrating of CLAY Soils

The procedure for the use of the moment reduction diagram:

1. Obtain H' and calculate α. Determine S_n
2. For the magnitudes of α and S_n obtained in Steps 1, determine M_d / M_{max} for various values of log ρ from this Figure and plot M_d / M_{max} against log ρ .
3. Follow Steps 1 through 9 as outlined for the case of moment reduction of sheet-pile walls penetrating granular soil. *(on page 9)*

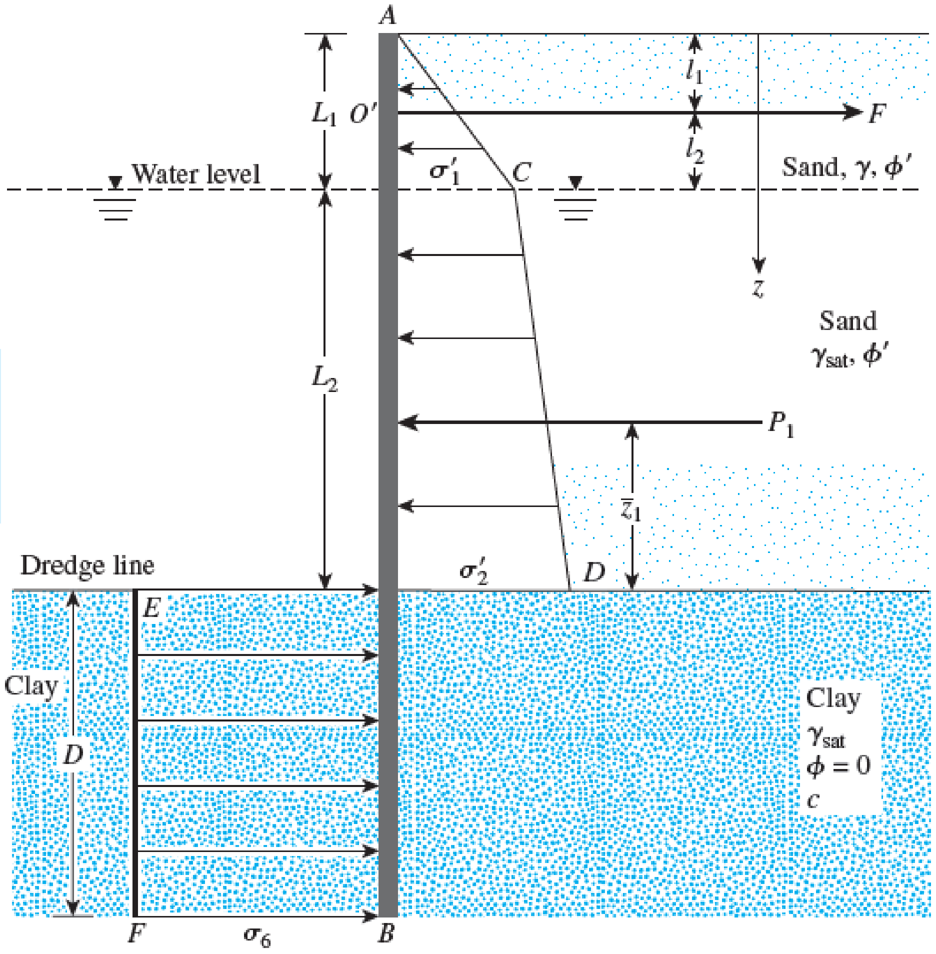


EXAMPLE

In Figure 14.32, let $L_1 = 3$ m, $L_2 = 6$ m, and $l_1 = 1.5$ m. Also, let $\gamma = 17$ kN/m^3, $\gamma_{sat} = 20$ kN/m^3, $\phi' = 35°$, and $c = 41$ kN/m^2.

a. Determine the theoretical depth of embedment of the sheet-pile wall.
b. Calculate the anchor force per unit length of the wall.

c. Use Rowe's moment reduction diagram (Figure 14.33) to find an appropriate sheet-pile section. For the sheet pile (Table 14.1), use $E = 207 \times 10^3$ MN/m^2 and $\sigma_{all} = 172{,}500$ kN/m^2.



Free Earth Support Method for Penetrating of CLAY Soils

EXAMPLE

Solution

Part a

We have

$$K_a = \tan^2\left(45 - \frac{\phi'}{2}\right) = \tan^2\left(45 - \frac{35}{2}\right) = 0.271$$

and

$$K_p = \tan^2\left(45 + \frac{\phi'}{2}\right) = \tan^2\left(45 + \frac{35}{2}\right) = 3.69$$

From the pressure diagram in Figure 14.34,

$$\sigma'_1 = \gamma L_1 K_a = (17)(3)(0.271) = 13.82 \text{ kN/m}^2$$

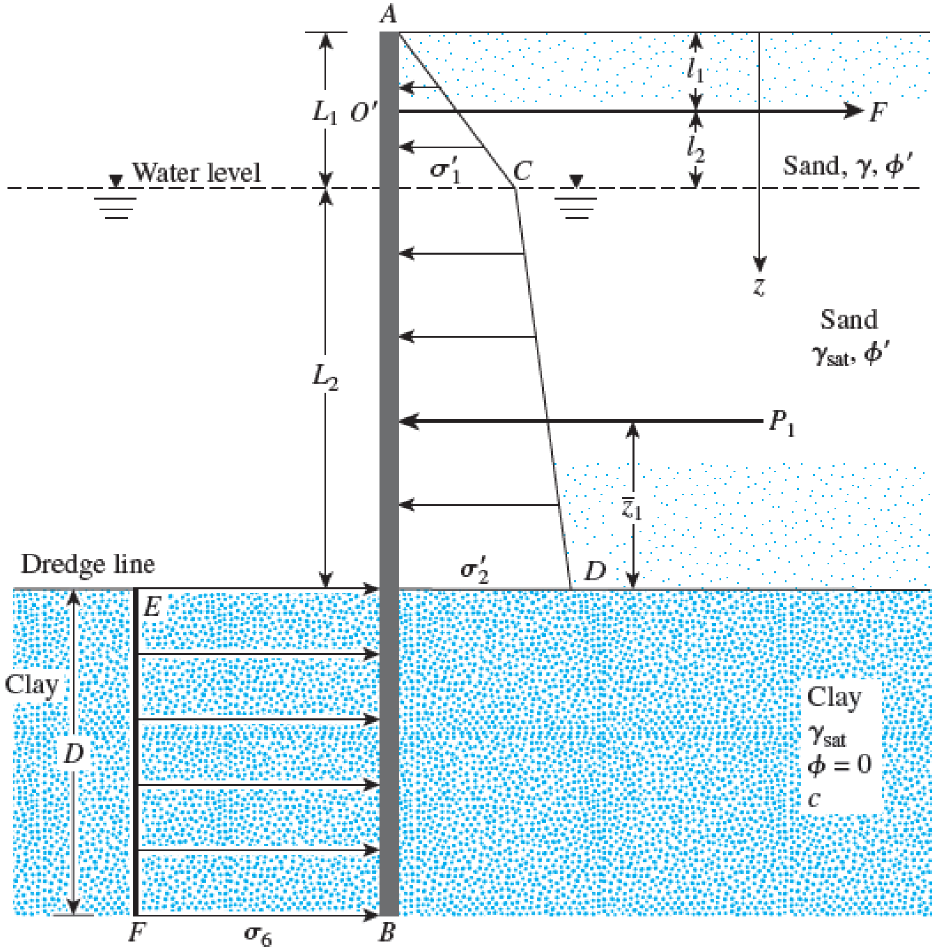
$$\sigma'_2 = (\gamma L_1 + \gamma' L_2)K_a = [(17)(3) + (20 - 9.81)(6)](0.271) = 30.39 \text{ kN/m}^2$$

$$P_1 = \text{areas } 1 + 2 + 3 = 1/2(3)(13.82) + (13.82)(6) + 1/2(30.39 - 13.82)(6)$$

$$= 20.73 + 82.92 + 49.71 = 153.36 \text{ kN/m}$$

and

$$\bar{z}_1 = \frac{(20.73)\left(6 + \frac{3}{3}\right) + (82.92)\left(\frac{6}{2}\right) + (49.71)\left(\frac{6}{3}\right)}{153.36} = 3.2 \text{ m}$$



Free Earth Support Method for Penetrating of CLAY Soils

EXAMPLE

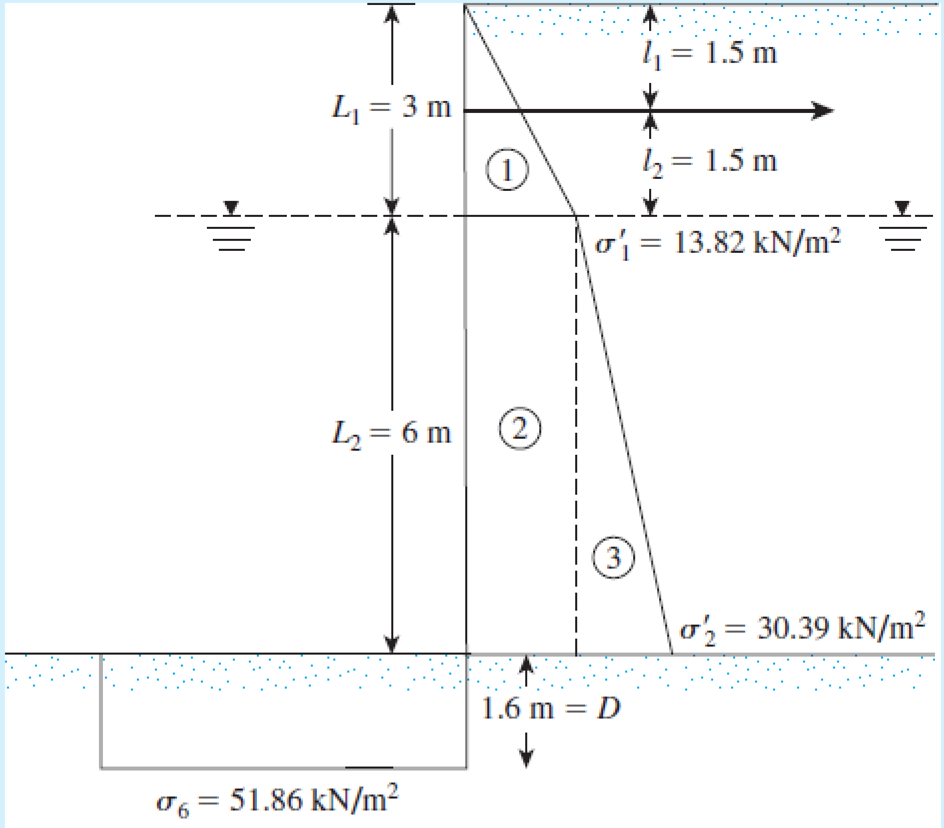


Figure 14.34 Free earth support method, with sheet pile penetrating into clay

$$\sigma_6 D^2 + 2\sigma_6 D(L_1 + L_2 - l_1) - 2P_1(L_1 + L_2 - l_1 - \bar{z}_1) = 0$$

$$\sigma_6 = 4c - (\gamma L_1 + \gamma' L_2) = (4)(41) - [(17)(3) + (20 - 9.81)(6)] = 51.86 \text{ kN/m}^2$$

Free Earth Support Method for Penetrating of CLAY Soils

EXAMPLE

or

$$D^2 + 15D - 25.43 = 0$$

Hence,

$$D \approx \mathbf{1.6\ m}$$

Part b

From Eq. (14.82),

$$F = P_1 - \sigma_6 D = 153.36 - (51.86)(1.6) = \mathbf{70.38\ kN/m}$$

Free Earth Support Method for Penetrating of CLAY Soils

EXAMPLE

Part c

$$s_n = 1.25\frac{c}{\gamma L_1 + \gamma' L_2} = 1.25\left[\frac{41}{(17 \times 3) + (20 - 9.81)(6)}\right] = 0.457$$

$$D_{\text{actual}} = 1.75 D_{\text{theory}} = (1.75)(1.6) = \mathbf{2.8\,m}$$

$$\alpha = \frac{L_1 + L_2}{L_1 + L_2 + D_{\text{actual}}} = \frac{3 + 6}{3 + 6 + 2.8} = 0.763$$

Free Earth Support Method for Penetrating of CLAY Soils

EXAMPLE

Now, referring to Figure 14.33 for $S_n = 0.457$ and $\alpha = 0.763$, we have

$\log \rho$	M_d/M_{max}
−3.1	≈ 0.9
−2.6	≈ 0.9
−2.0	≈ 0.9

Hence, for all $\log \rho$ values, $M_d/M_{max} \approx 0.9$. The following table now can be prepared.

Section	I (m⁴/m)	H' (m)	$\rho = (10.91 \times 10^{-7}) \times (H'^4/EI)$	$\log \rho$	S (m³/m)	$M_d = S\sigma_{all}$	M_d/M_{max}
PZC-12	192.06×10^{-6}	11.8	5.93×10^{-4}	−3.2	120.42×10^{-5}	207.72	0.92

Note: $H' = L_1 + L_2 + D_{actual} = 3 + 6 + 2.8 = 11.8$ m
$M_{max} = 225.66$ kN · m/m

Figure 14.35 shows the plot of M_d/M_{max} versus $\log \rho$. Section PZC-12 falls above the line of $M_d/M_{max} = 0.9$. So,

PZC-12 will be sufficient.

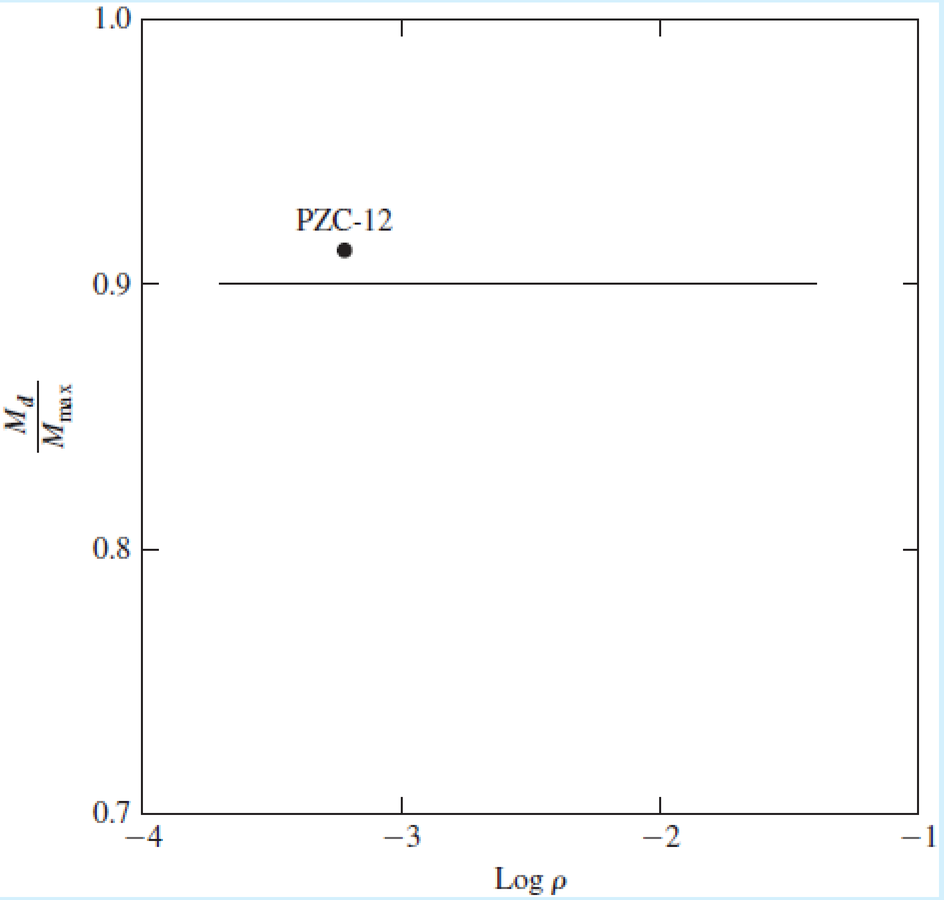


Figure 14.35 Plot of M_d/M_{max} versus $\log \rho$ (Example 14.12)