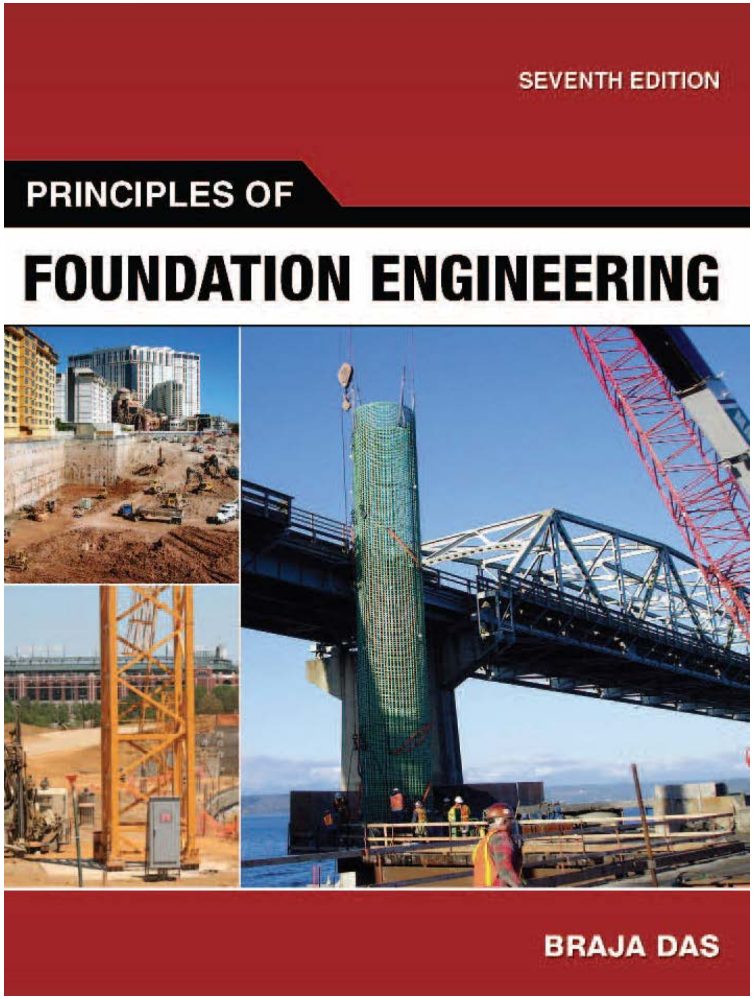
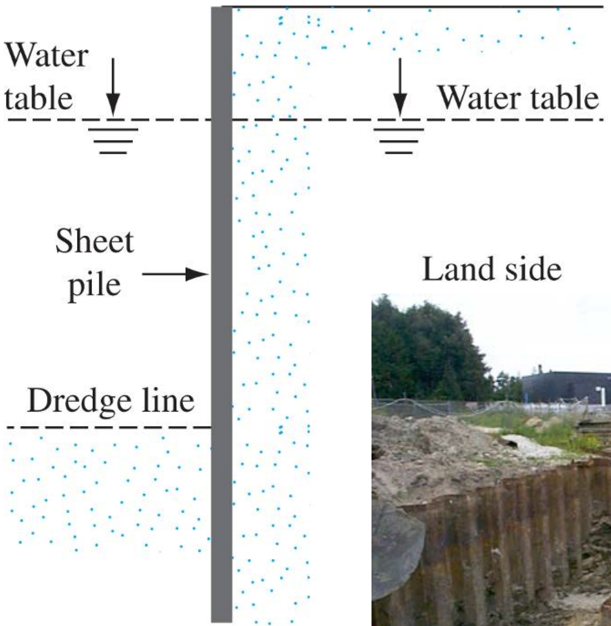


Chapter 9:

Sheet Pile Walls


Water table
Water table
Sheet pile
Land side
Dredge line

Types of Sheet Pile Wall

- Wooden Sheet Pile Wall
- Precast concrete sheet pile wall
- Steel Sheet Pile wall
- Aluminium Sheet Pile wall

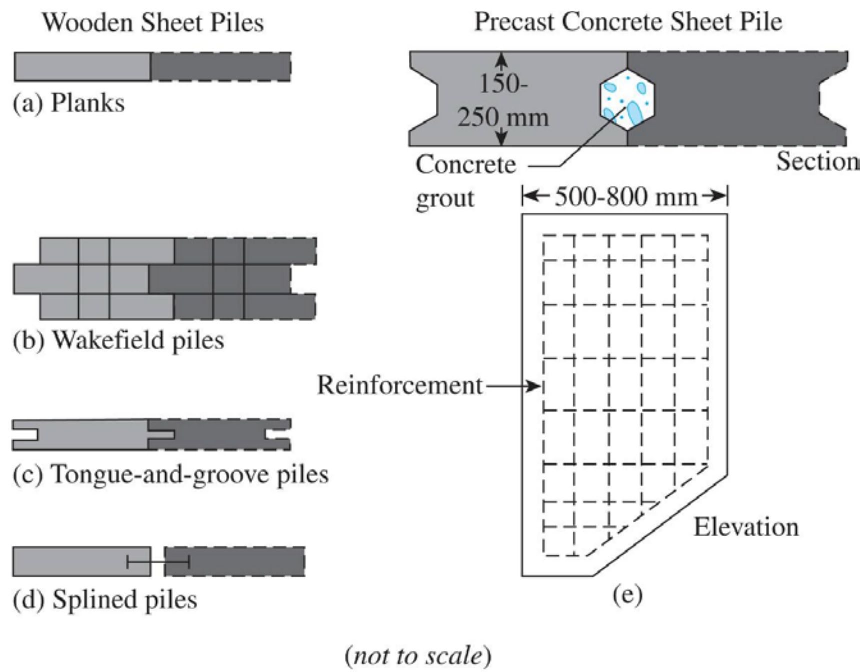


Figure 9.2 Various types of wooden and concrete sheet pile

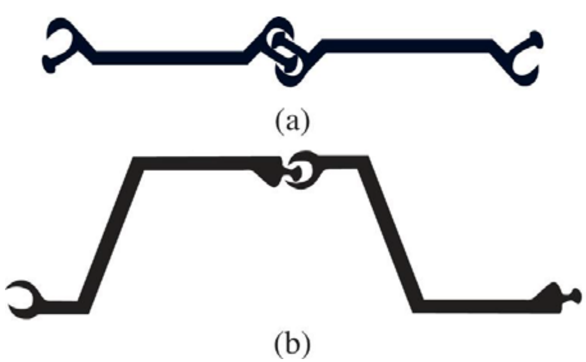


Figure 9.3 (a) Thumb-and-finger type sheet pile connection; (b) ball-and-socket type sheet-pile connection

Figure 9.4 A steel sheet pile wall (*Courtesy of N. Sivakugan, James Cook University, Australia*)

Table 9.1 Properties of Some Sheet-Pile Sections Produced by Bethlehem Steel Corporation

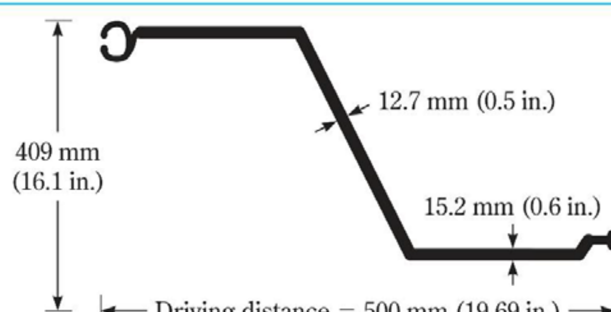
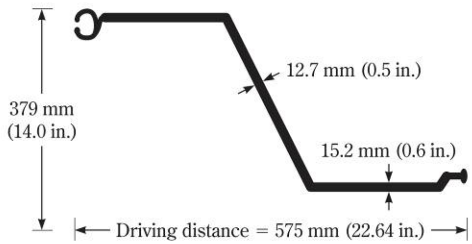
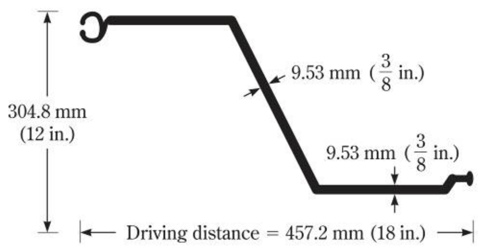
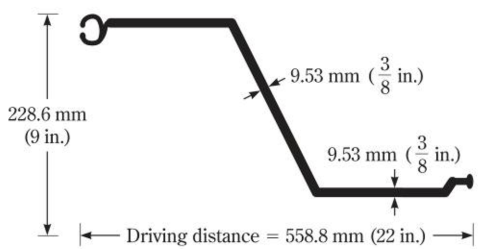
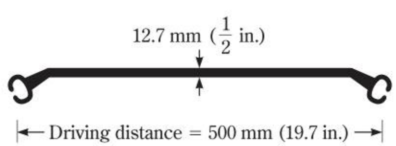
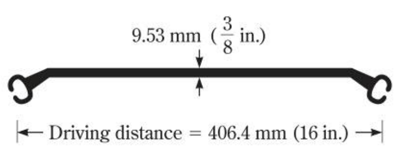
		Section modulus		Moment of inertia	
Section designation	**Sketch of section**	**m^3/m of wall**	**in^3/ft of wall**	**m^4/m of wall**	**in^4/ft of wall**
PZ-40		326.4×10^{-5}	60.7	670.5×10^{-6}	490.8

Table 9.1 (*Continued*)

Section designation	Sketch of section	Section modulus: m^3/m of wall	Section modulus: in^3/ft of wall	Moment of inertia: m^4/m of wall	Moment of inertia: in^4/ft of wall
PZ-35		260.5×10^{-5}	48.5	493.4×10^{-6}	361.2
PZ-27		162.3×10^{-5}	30.2	251.5×10^{-6}	184.2
PZ-22		97×10^{-5}	18.1	115.2×10^{-6}	84.4
PSA-31		10.8×10^{-5}	2.01	4.41×10^{-6}	3.23
PSA-23		12.8×10^{-5}	2.4	5.63×10^{-6}	4.13

Construction Methods

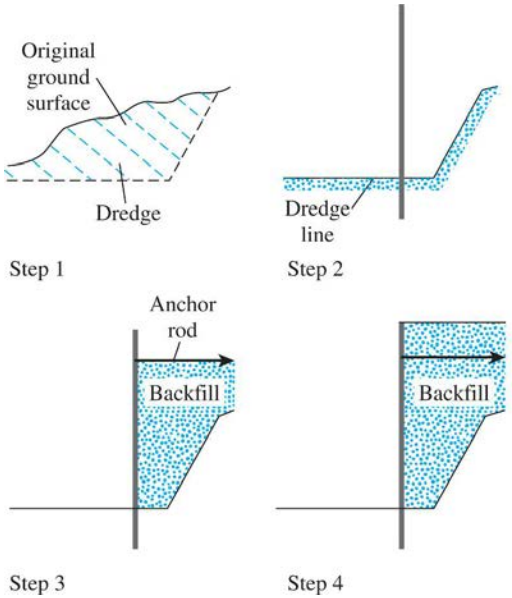


Figure 9.5 Sequence of construction for a backfilled structure

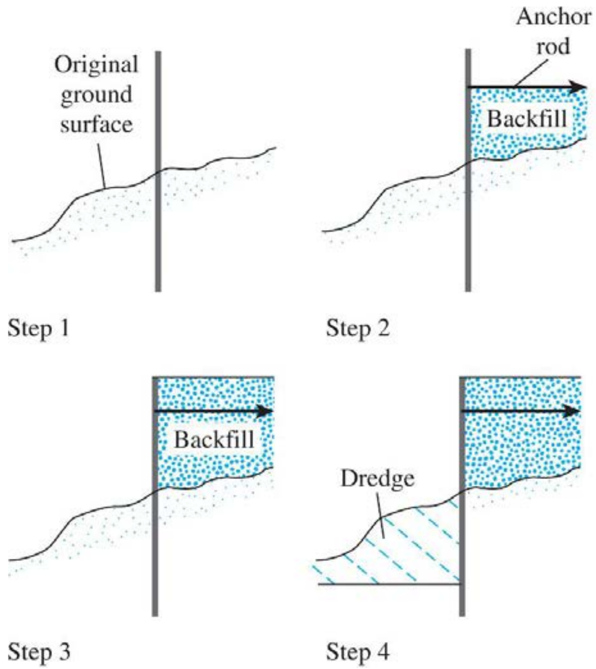


Figure 9.6 Sequence of construction for a dredged structure

<u>Cantilever Sheet Pile walls</u>

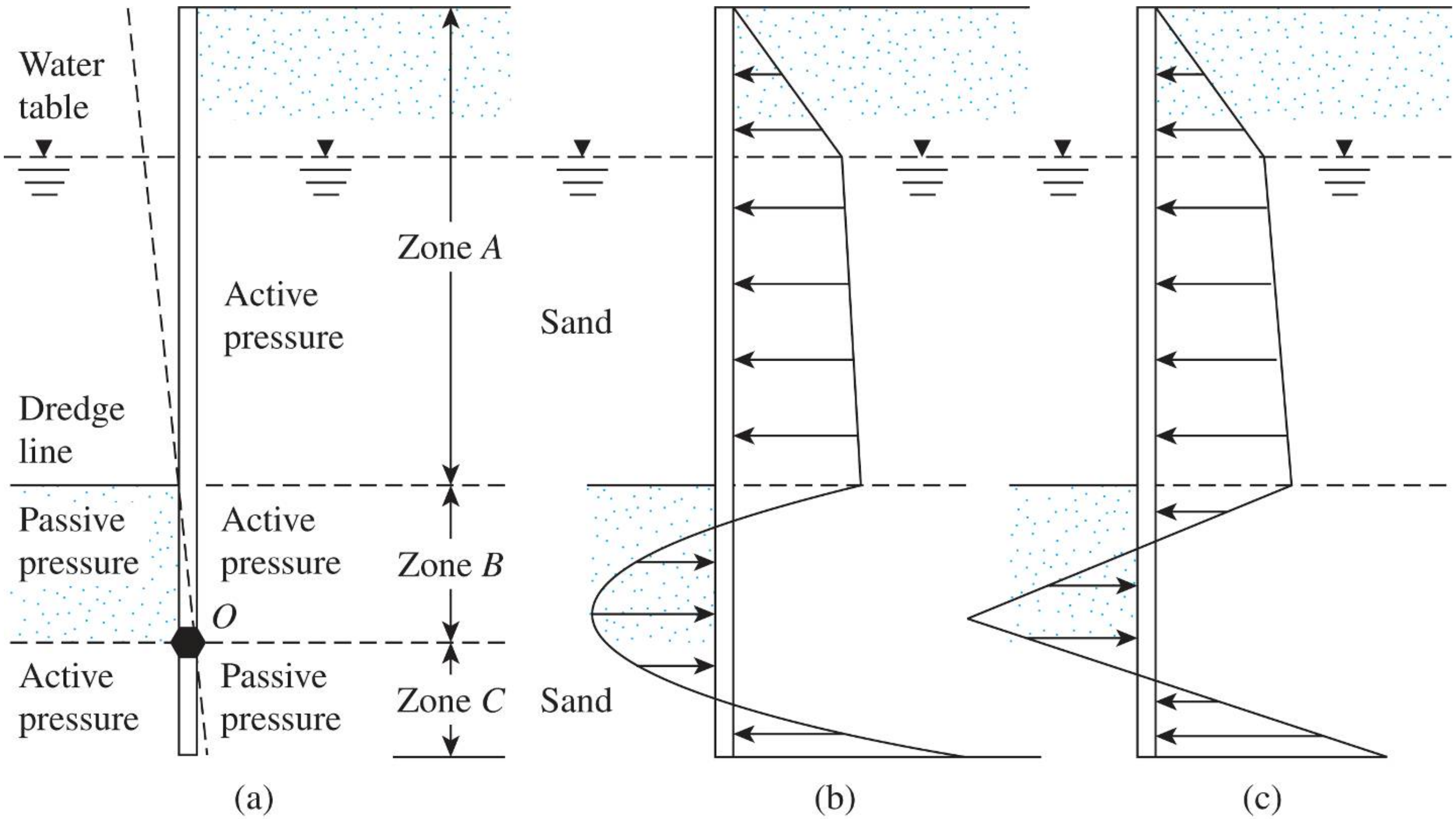


Figure 9.7 Cantilever sheet pile penetrating sand

Cantilever Sheet Pile walls penetrating sandy soils

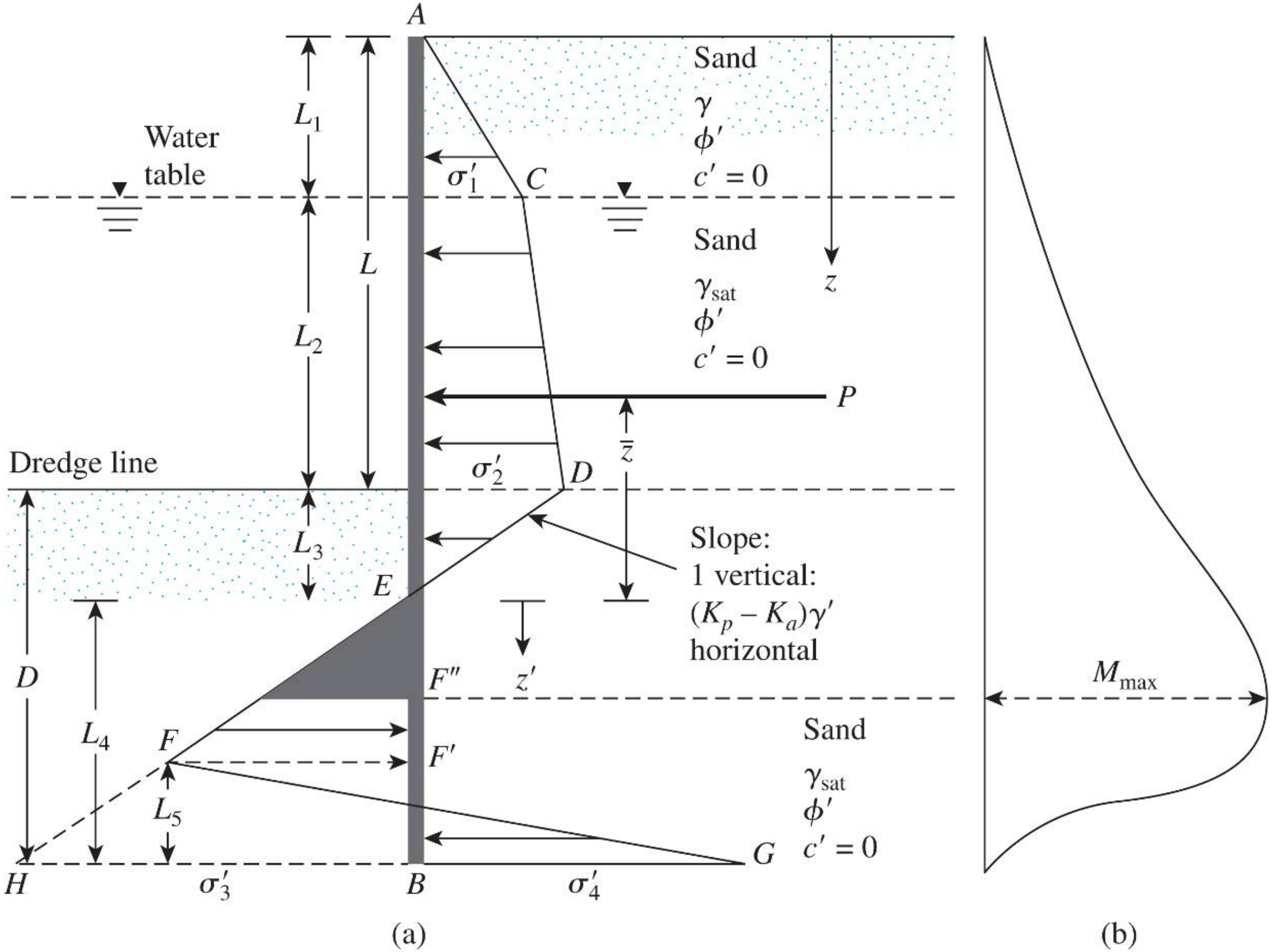


Figure 9.8 Cantilever sheet pile penetrating sand: (a) variation of net pressure diagram; (b) variation of moment

Step-by-Step Procedure for Obtaining the Pressure Diagram

Based on the preceding theory, a step-by-step procedure for obtaining the pressure diagram for a cantilever sheet pile wall penetrating a granular soil is as follows:

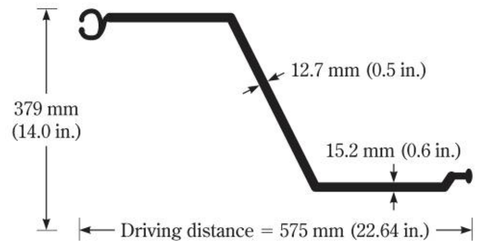
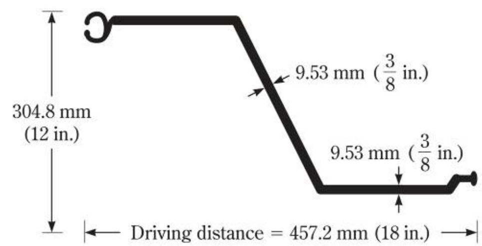
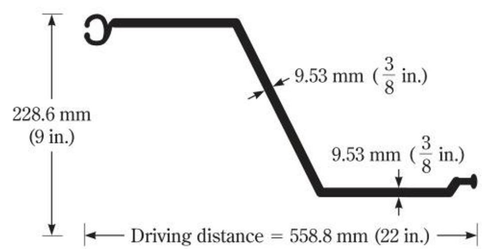
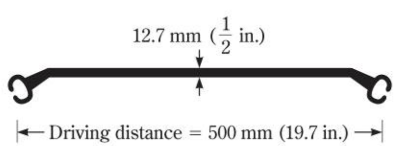
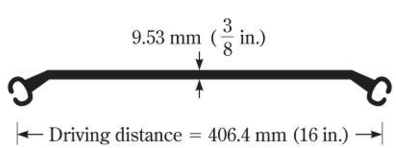
Step 1. Calculate K_a and K_p.
Step 2. Calculate σ'_1 [Eq. (9.1)] and σ'_2 [Eq. (9.2)]. (*Note:* L_1 and L_2 will be given.)
Step 3. Calculate L_3 [Eq. (9.6)].
Step 4. Calculate P.
Step 5. Calculate $\bar{z}$ (i.e., the center of pressure for the area *ACDE*) by taking the moment about E.
Step 6. Calculate σ'_5 [Eq. (9.11)].
Step 7. Calculate A_1, A_2, A_3, and A_4 [Eqs. (9.17) through (9.20)].
Step 8. Solve Eq. (9.16) by trial and error to determine L_4.
Step 9. Calculate σ'_4 [Eq. (9.10)].
Step 10. Calculate σ'_3 [Eq. (9.7)].
Step 11. Obtain L_5 from Eq. (9.15).
Step 12. Draw a pressure distribution diagram like the one shown in Figure 9.8a.
Step 13. Obtain the theoretical depth [see Eq. (9.12)] of penetration as $L_3 + L_4$. The actual depth of penetration is increased by about 20 to 30%.

Note that some designers prefer to use a factor of safety on the passive earth pressure coefficient at the beginning. In that case, in Step 1,

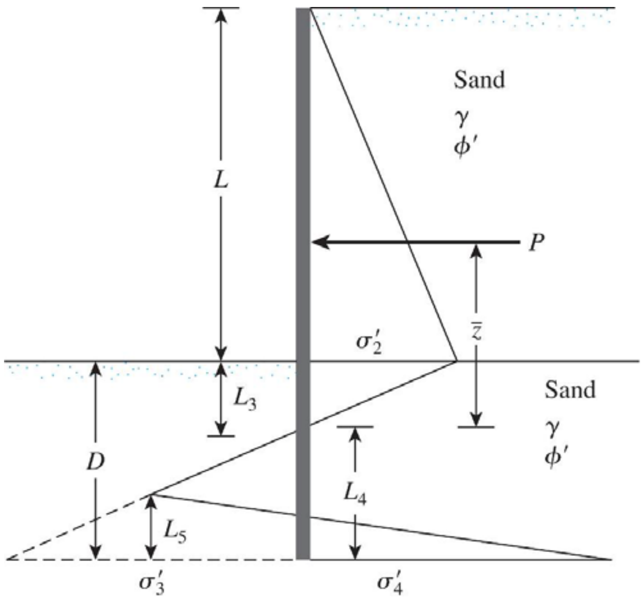
$$K_{p(\text{design})} = \frac{K_p}{\text{FS}}$$

where FS = factor of safety (usually between 1.5 and 2).

Table 9.1 *(Continued)*

Section designation	Sketch of section	Section modulus m^3/m of wall	Section modulus in^3/ft of wall	Moment of inertia m^4/m of wall	Moment of inertia in^4/ft of wall
PZ-35		260.5×10^{-5}	48.5	493.4×10^{-6}	361.2
PZ-27		162.3×10^{-5}	30.2	251.5×10^{-6}	184.2
PZ-22		97×10^{-5}	18.1	115.2×10^{-6}	84.4
PSA-31		10.8×10^{-5}	2.01	4.41×10^{-6}	3.23
PSA-23		12.8×10^{-5}	2.4	5.63×10^{-6}	4.13

Cantilever Sheet Pile walls penetrating sandy soils – Special case #1



$$\sigma'_2 = \gamma L K_a$$
$$\sigma'_3 = L_4(K_p - K_a)\gamma$$
$$\sigma'_4 = \sigma'_5 + \gamma L_4(K_p - K_a)$$
$$\sigma'_5 = \gamma L K_p + \gamma L_3(K_p - K_a)$$
$$L_3 = \frac{\sigma'_2}{\gamma(K_p - K_a)} = \frac{LK_a}{(K_p - K_a)}$$
$$P = \tfrac{1}{2}\sigma'_2 L + \tfrac{1}{2}\sigma'_2 L_3$$
$$\bar{z} = L_3 + \frac{L}{3} = \frac{LK_a}{K_p - K_a} + \frac{L}{3} = \frac{L(2K_a + K_p)}{3(K_p - K_a)}$$

and Eq. (9.16) transforms to

$$L_4^4 + A'_1 L_4^3 - A'_2 L_4^2 - A'_3 L_4 - A'_4 = 0$$

where

$$A'_1 = \frac{\sigma'_5}{\gamma(K_p - K_a)}$$
$$A'_2 = \frac{8P}{\gamma(K_p - K_a)}$$
$$A'_3 = \frac{6P[2\bar{z}\gamma(K_p - K_a) + \sigma'_5]}{\gamma^2(K_p - K_a)^2}$$
$$A'_4 = \frac{P(6\bar{z}\sigma'_5 + 4P)}{\gamma^2(K_p - K_a)^2}$$

Cantilever Sheet Pile walls penetrating sandy soils – Special case #2

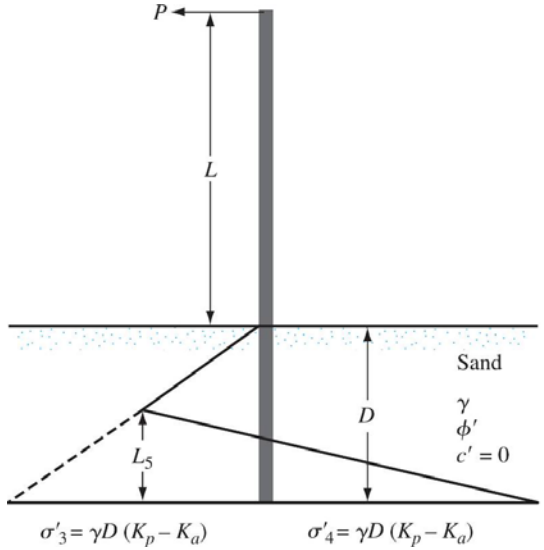


Figure 9.11 Free cantilever sheet piling penetrating a layer of sand

Free Cantilever Sheet Piling

Figure 9.11 shows a free cantilever sheet-pile wall penetrating a sandy soil and subjected to a line load of P per unit length of the wall. For this case,

$$D^4 - \left[\frac{8P}{\gamma(K_p - K_a)}\right]D^2 - \left[\frac{12PL}{\gamma(K_p - K_a)}\right]D - \left[\frac{2P}{\gamma(K_p - K_a)}\right]^2 = 0 \tag{9.36}$$

$$L_5 = \frac{\gamma(K_p - K_a)D^2 - 2P}{2D(K_p - K_a)\gamma} \tag{9.37}$$

$$M_{max} = P(L + z') - \frac{\gamma z'^3(K_p - K_a)}{6} \tag{9.38}$$

and

$$z' = \sqrt{\frac{2P}{\gamma'(K_p - K_a)}} \tag{9.39}$$

Cantilever Sheet Pile walls penetrating Clay

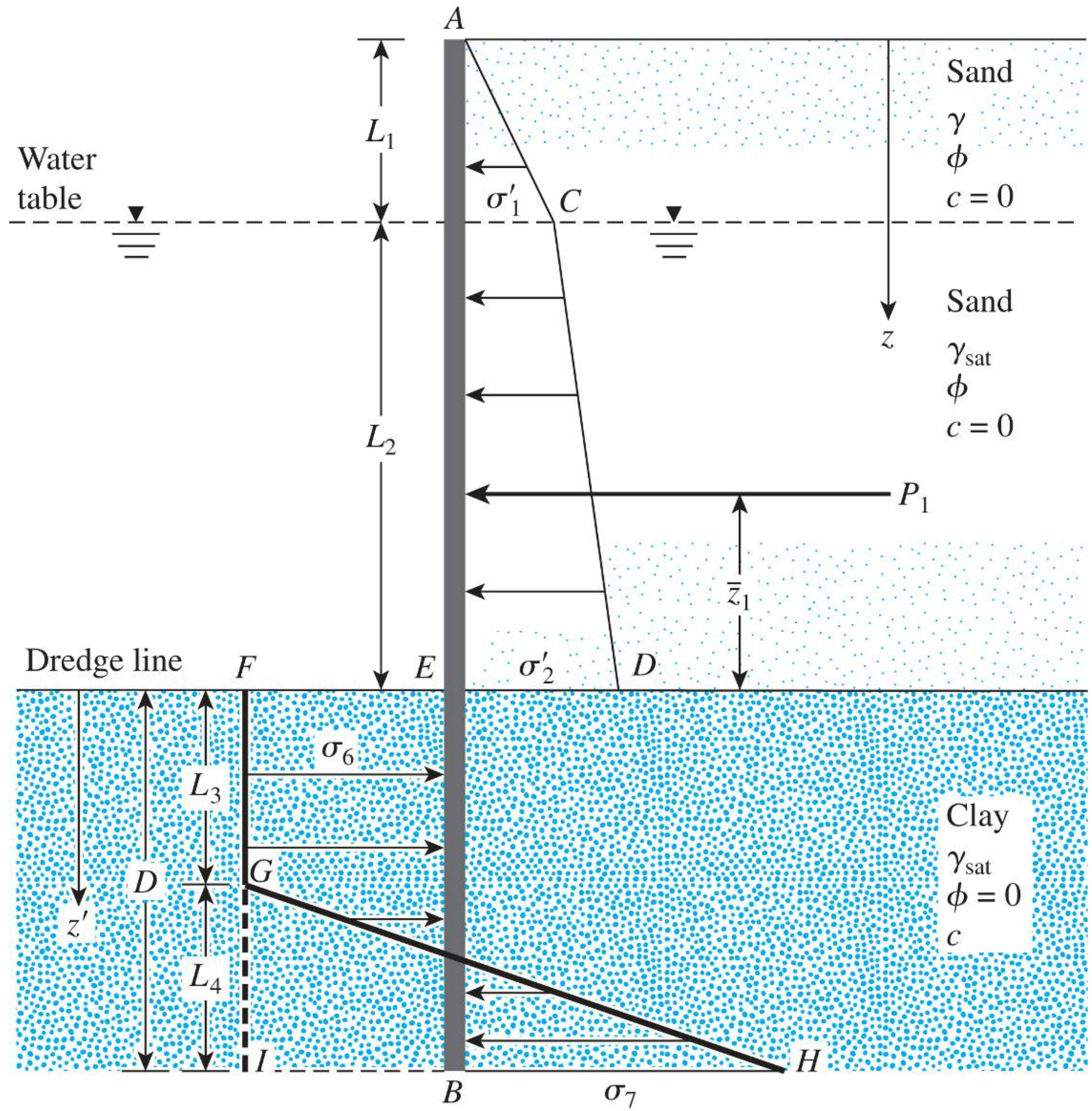


Figure 9.12 Cantilever sheet pile penetrating clay

Cantilever Sheet Pile walls penetrating Clay – Design Steps

Step-by-Step Procedure for Obtaining the Pressure Diagram

Step 1. Calculate $K_a = \tan^2(45 - \phi'/2)$ for the granular soil (backfill).

Step 2. Obtain σ'_1 and σ'_2. [See Eqs. (9.1) and (9.2).]

Step 3. Calculate P_1 and $\bar{z}_1$.

Step 4. Use Eq. (9.48) to obtain the theoretical value of D.

Step 5. Using Eq. (9.46), calculate L_4.

Step 6. Calculate σ_6 and σ_7. [See Eqs. (9.42) and (9.45).]

Step 7. Draw the pressure distribution diagram as shown in Figure 9.12.

Step 8. The actual depth of penetration is

$$D_{\text{actual}} = 1.4 \text{ to } 1.6(D_{\text{theoretical}})$$

Cantilever Sheet Pile walls penetrating Clay – Special case #1

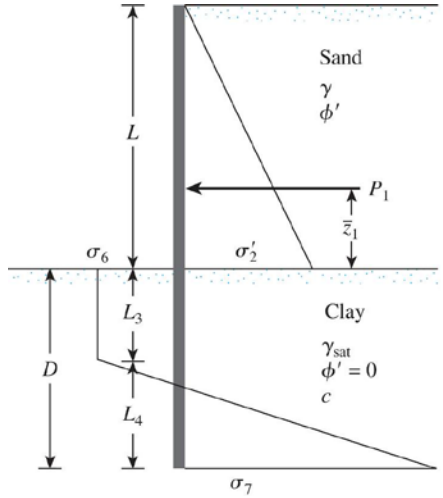


Figure 9.14 Sheet-pile wall penetrating clay

$$\sigma'_2 = \gamma L K_a$$

$$\sigma_6 = 4c - \gamma L$$

$$\sigma_7 = 4c + \gamma L$$

$$P_1 = \tfrac{1}{2} L \sigma'_2 = \tfrac{1}{2} \gamma L^2 K_a$$

$$L_4 = \frac{D(4c - \gamma L) - \frac{1}{2}\gamma L^2 K_a}{4c}$$

$$D^2(4c - \gamma L) - 2DP_1 - \frac{P_1(P_1 + 12c\bar{z}_1)}{\gamma L + 2c} = 0$$

where $\bar{z}_1 = \dfrac{L}{3}$.

The magnitude of the maximum moment in the wall is

$$M_{\max} = P_1(z' + \bar{z}_1) - \frac{\sigma_6 z'^2}{2}$$

where $z' = \dfrac{P_1}{\sigma_6} = \dfrac{\frac{1}{2}\gamma L^2 K_a}{4c - \gamma L}$.

Cantilever Sheet Pile walls penetrating Clay – Special case #2

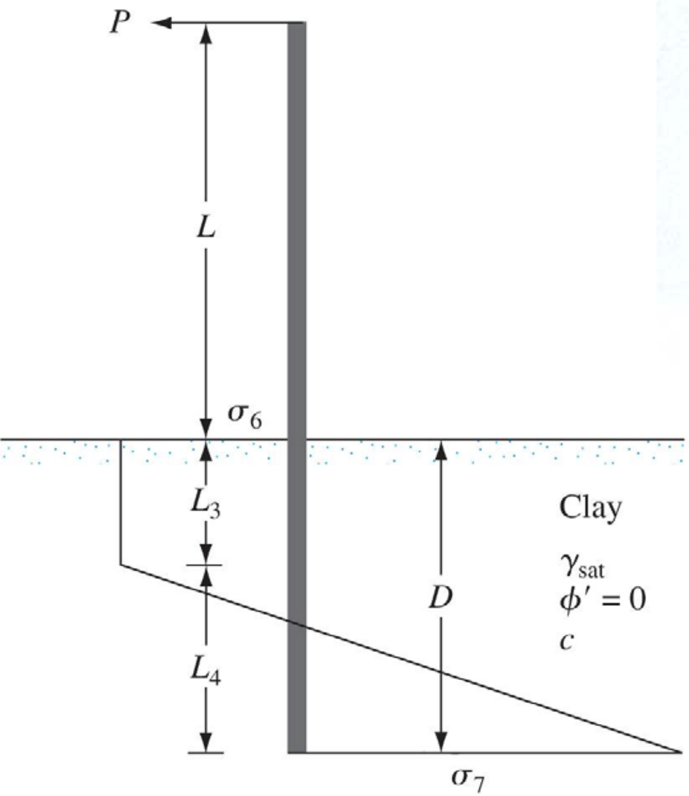


Figure 9.15 Free cantilever sheet piling penetrating clay

$$\sigma_6 = \sigma_7 = 4c$$

The depth of penetration, D, may be obtained from the relation

$$4D^2c - 2PD - \frac{P(P + 12cL)}{2c} = 0$$

Also, note that, for a construction of the pressure diagram,

$$L_4 = \frac{4cD - P}{4c}$$

The maximum moment in the wall is

$$M_{max} = P(L + z') - \frac{4cz'^2}{2}$$

where $z' = \dfrac{P}{4c}$

Anchored Sheet Pile Walls

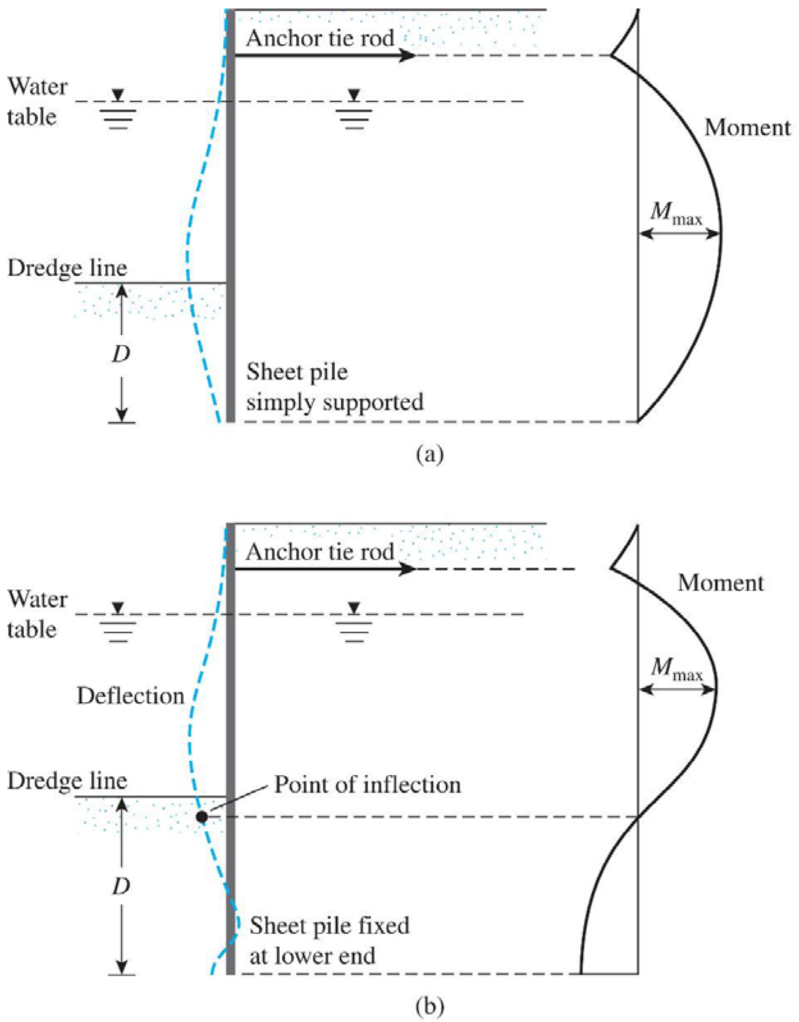


Figure 9.16 Nature of variation of deflection and moment for anchored sheet piles: (a) free earth support method; (b) fixed earth support method

- for sheet pile wall height >20 feet
- free earth support method
- fixed earth support method

Anchored sheet pile --- free earth support method for penetration of sandy soil

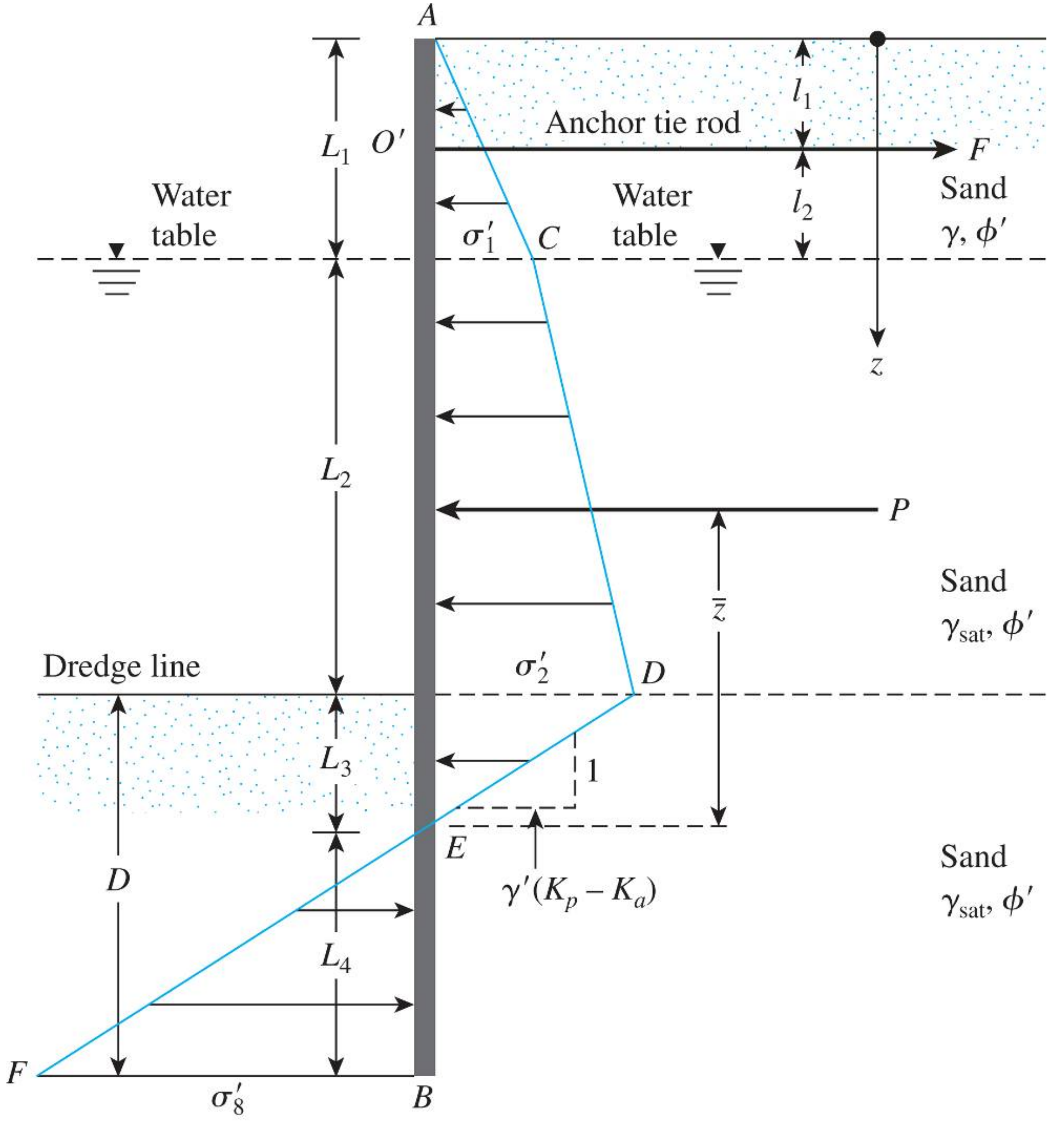


Figure 9.17 Anchored sheet-pile wall penetrating sand

Anchored sheet pile – Design charts for free earth support method (penetration into sandy soil)

Hagerty & Nofal (1992)

$$\frac{D}{L_1 + L_2} = (GD)(CDL_1)$$

$$\frac{F}{\gamma_a (L_1 + L_2)^2} = (GF)(CFL_1)$$

$$\frac{M_{max}}{\gamma_a (L_1 + L_2)^3} = (GM)(CML_1)$$

where

γ_a = average unit weight of soil

$$= \frac{\gamma L_1^2 + (\gamma_{sat} - \gamma_w) L_2^2 + 2\gamma L_1 L_2}{(L_1 + L_2)^2}$$

GD = generalized nondimensional embedment

$$= \frac{D}{L_1 + L_2} \quad \text{(for } L_1 = 0 \text{ and } L_2 = L_1 + L_2\text{)}$$

GF = generalized nondimensional anchor force

$$= \frac{F}{\gamma_a (L_1 + L_2)^2} \quad \text{(for } L_1 = 0 \text{ and } L_2 = L_1 + L_2\text{)}$$

GM = generalized nondimensional moment

$$= \frac{M_{max}}{\gamma_a (L_1 + L_2)^3} \quad \text{(for } L_1 = 0 \text{ and } L_2 = L_1 + L_2\text{)}$$

CDL_1, CFL_1, CML_1 = correction factors for $L_1 \neq 0$

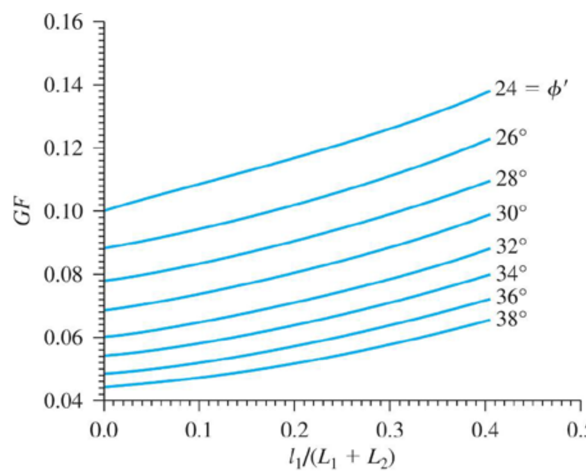


Figure 9.19 Variation of GF with $l_1/(L_1 + L_2)$ and ϕ' (After Hagerty and Nofal, 1992) (Hagerty, D. J., and Nofal, M. M. (1992). "Design Aids: Anchored Bulkheads in Sand," *Canadian Geotechnical Journal*, Vol. 29, No. 5, pp. 789-795. © 2008 NRC Canada or its licensors. Reproduced with permission.

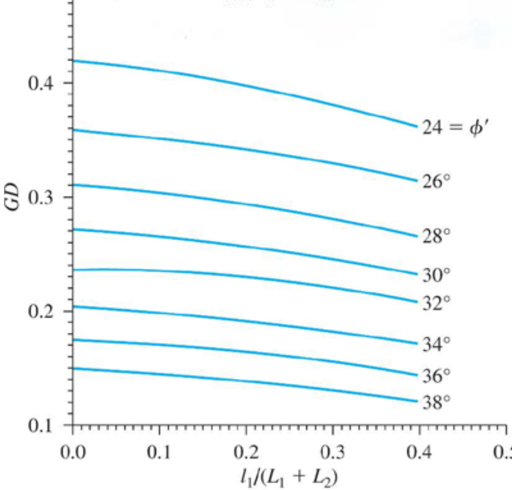
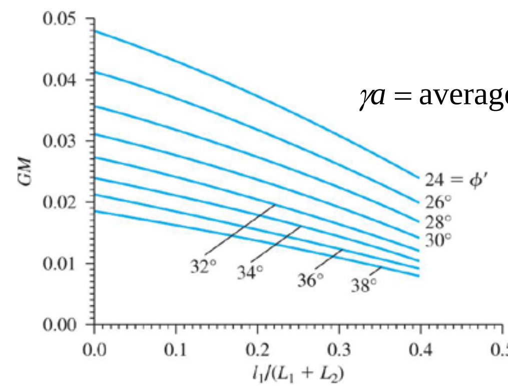


Figure 9.18 Variation of GD with $l_1/(L_1 + L_2)$ and ϕ' (Hagerty, D. J., and Nofal, M. M. (1992). "Design Aids: Anchored Bulkheads in Sand," *Canadian Geotechnical Journal*, Vol. 29, No. 5, pp. 789–795. © 2008 NRC Canada or its licensors. Reproduced with permission.)



γa = average unit weight of soil

Figure 9.20 Variation of GM with $l_1/(L_1 + L_2)$ and ϕ' (Hagerty, D. J., and Nofal, M. M. (1992). "Design Aids: Anchored Bulkheads in Sand," *Canadian Geotechnical Journal*, Vol. 29, No. 5, pp. 789–795. © 2008 NRC Canada or its licensors. Reproduced with permission.)

Anchored sheet pile – Design charts for free earth support method (penetration into sandy soil)

$$\frac{D}{L_1 + L_2} = (GD)(CDL_1)$$

$$\frac{F}{\gamma_a (L_1 + L_2)^2} = (GF)(CFL_1)$$

$$\frac{M_{max}}{\gamma_a (L_1 + L_2)^3} = (GM)(CML_1)$$

where

γ_a = average unit weight of soil

$$= \frac{\gamma L_1^2 + (\gamma_{sat} - \gamma_w) L_2^2 + 2\gamma L_1 L_2}{(L_1 + L_2)^2}$$

GD = generalized nondimensional embedment

$$= \frac{D}{L_1 + L_2} \quad \text{(for } L_1 = 0 \text{ and } L_2 = L_1 + L_2\text{)}$$

GF = generalized nondimensional anchor force

$$= \frac{F}{\gamma_a (L_1 + L_2)^2} \quad \text{(for } L_1 = 0 \text{ and } L_2 = L_1 + L_2\text{)}$$

GM = generalized nondimensional moment

$$= \frac{M_{max}}{\gamma_a (L_1 + L_2)^3} \quad \text{(for } L_1 = 0 \text{ and } L_2 = L_1 + L_2\text{)}$$

CDL_1, CFL_1, CML_1 = correction factors for $L_1 \neq 0$

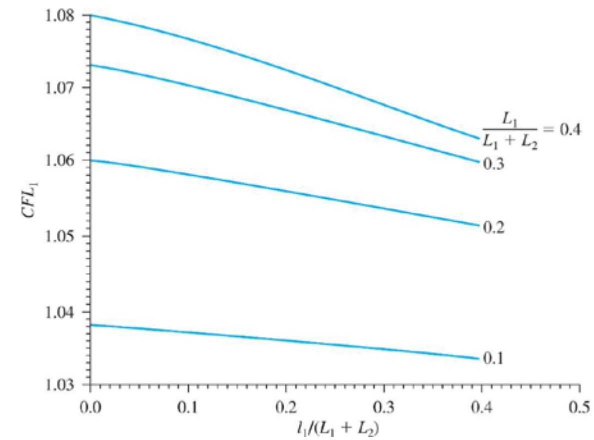


Figure 9.22 Variation of CFL_1 with $L_1/(L_1 + L_2)$ and $l_1/(L_1 + L_2)$ (Hagerty, D. J., and Nofal, M. M. (1992). "Design Aids: Anchored Bulkheads in Sand," *Canadian Geotechnical Journal*, Vol. 29, No. 5, pp. 789–795. © 2008 NRC Canada or its licensors. Reproduced with permission.)

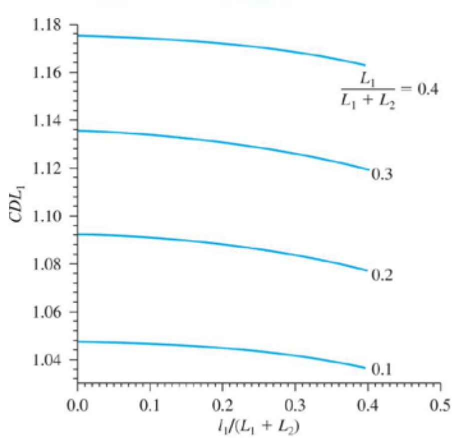


Figure 9.21 Variation of CDL_1 with $L_1/(L_1 + L_2)$ and $l_1/(L_1 + L_2)$ (Hagerty, D. J., and Nofal, M. M. (1992). "Design Aids: Anchored Bulkheads in Sand," *Canadian Geotechnical Journal*, Vol. 29, No. 5, pp. 789–795. © 2008 NRC Canada or its licensors. Reproduced with permission.)

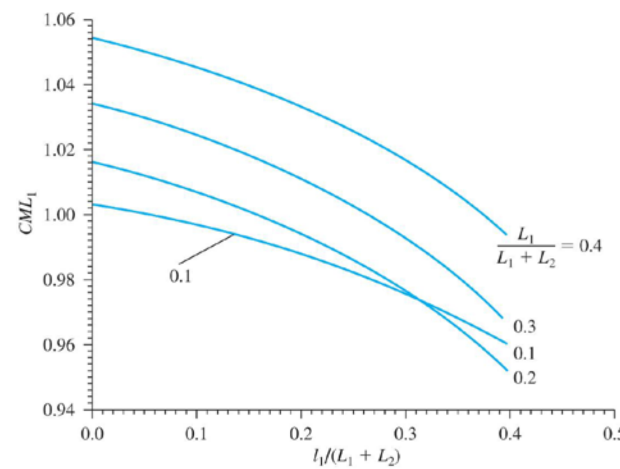


Figure 9.23 Variation of CML_1 with $L_1/(L_1 + L_2)$ and $l_1/(L_1 + L_2)$ (Hagerty, D. J., and Nofal, M. M. (1992). "Design Aids: Anchored Bulkheads in Sand," *Canadian Geotechnical Journal*, Vol. 29, No. 5, pp. 789–795. © 2008 NRC Canada or its licensors. Reproduced with permission.)

Moment reduction for Anchored sheet pile walls

(Rowe, 1952, 1957)

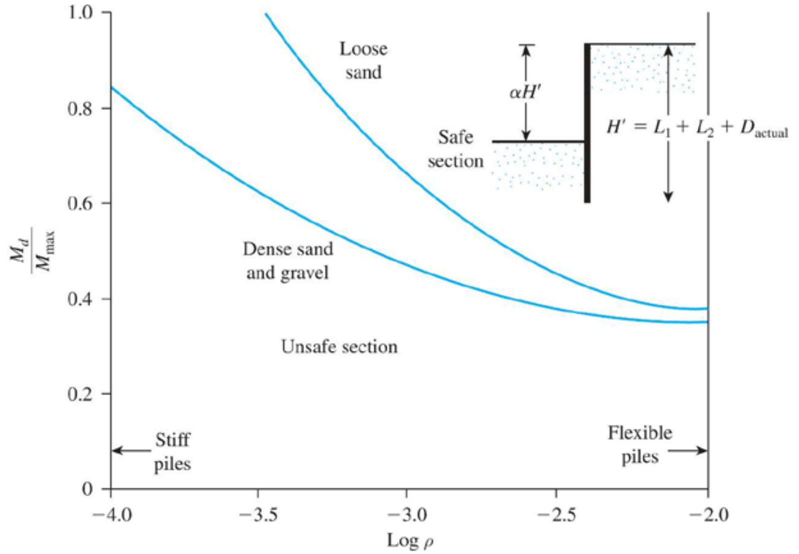


Figure 9.24 Plot of log ρ against M_d/M_{max} for sheet-pile walls penetrating sand (From Rowe, P. W. (1952). "Anchored Sheet Pile Walls," Proceedings, Institute of Civil Engineers, Vol. 1, Part 1, pp. 27–70.)

1. H' = total height of pile driven (i.e., $L_1 + L_2 + D_{actual}$)
2. Relative flexibility of pile $= \rho = 10.91 \times 10^{-7}\left(\frac{H'^4}{EI}\right)$ (9.74a)

where

H' is in meters
E = modulus of elasticity of the pile material (MN/m²)
I = moment of inertia of the pile section per meter of the wall (m⁴/m of wall)

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

In English units, Eq. (9.74a) takes the form

$$\rho = \frac{H'^4}{EI} \quad (9.74b)$$

where H' is in ft, E is in lb/in², and I is in in⁴/ft of the wall.

Step 1. Choose a sheet pile section (e.g., from among those given in Table 9.1).
Step 2. Find the modulus S of the selected section (Step 1) per unit length of the wall.
Step 3. Determine the moment of inertia of the section (Step 1) per unit length of the wall.
Step 4. Obtain H' and calculate ρ [see Eq. (9.74a) or Eq. (9.74b)].
Step 5. Find log ρ.
Step 6. Find the moment capacity of the pile section chosen in Step 1 as $M_d = \sigma_{all} S$.
Step 7. Determine M_d/M_{max}. Note that M_{max} is the maximum theoretical moment determined before.
Step 8. Plot log ρ (Step 5) and M_d/M_{max} in Figure 9.24.
Step 9. Repeat Steps 1 through 8 for several sections. The points that fall above the curve (in loose sand or dense sand, as the case may be) are *safe sections.*

The points that fall below the curve are *unsafe sections.* The cheapest section may now be chosen from those points which fall above the proper curve. Note that the section chosen will have an $M_d < M_{max}$.

Computational Pressure Diagram method for penetration into sandy soil (Natarag & Hoadley)

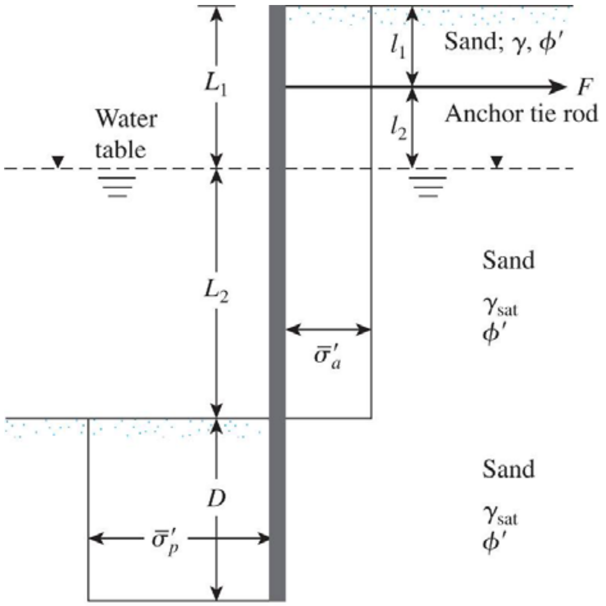


Figure 9.26 Computa
diagram method (*Note:*

$$\bar{\sigma}'_a = CK_a\gamma'_{av}L$$

and

$$\bar{\sigma}'_p = RCK_a\gamma'_{av}L = R\bar{\sigma}'_a$$

where

γ'_{av} = average effective unit weight of sand $\approx \dfrac{\gamma L_1 + \gamma' L_2}{L_1 + L_2}$

C = coefficient

R = coefficient $= \dfrac{L(L - 2l_1)}{D(2L + D - 2l_1)}$

The range of values for C and R is given in Table 9.2.

Depth of Penetration

For the depth of penetration, we have

$$D^2 + 2DL\left[1 - \left(\frac{l_1}{L}\right)\right] - \left(\frac{L^2}{R}\right)\left[1 - 2\left(\frac{l_1}{L}\right)\right] = 0 \tag{9.79}$$

Anchor Force

The anchor force is

$$F = \bar{\sigma}'_a(L - RD) \tag{9.80}$$

Table 9.2 Range of Values for C and R [from Eqs. (9.75) and (9.76)]

Soil type	***C*** [a]	***R***
Loose sand	0.8–0.85	0.3–0.5
Medium sand	0.7–0.75	0.55–0.65
Dense sand	0.55–0.65	0.60–0.75

Maximum Moment

The maximum moment is calculated from

$$M_{max} = 0.5\bar{\sigma}'_a L^2\left[\left(1 - \frac{RD}{L}\right)^2 - \left(\frac{2l_1}{L}\right)\left(1 - \frac{RD}{L}\right)\right]$$

Fixed Earth Support method for Penetration into Sandy soil

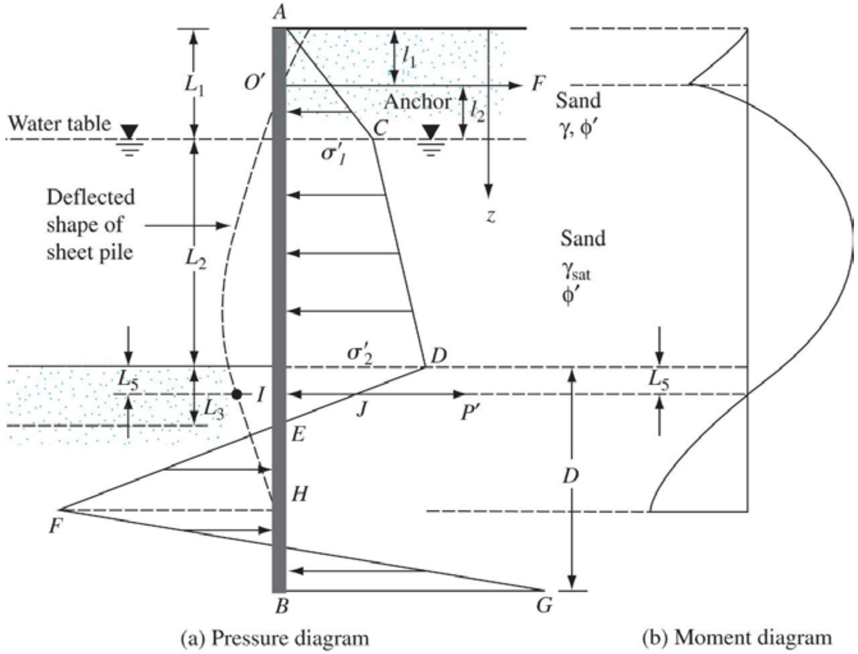


FIGURE 9.28 Fixed earth support method for penetration of sandy soil

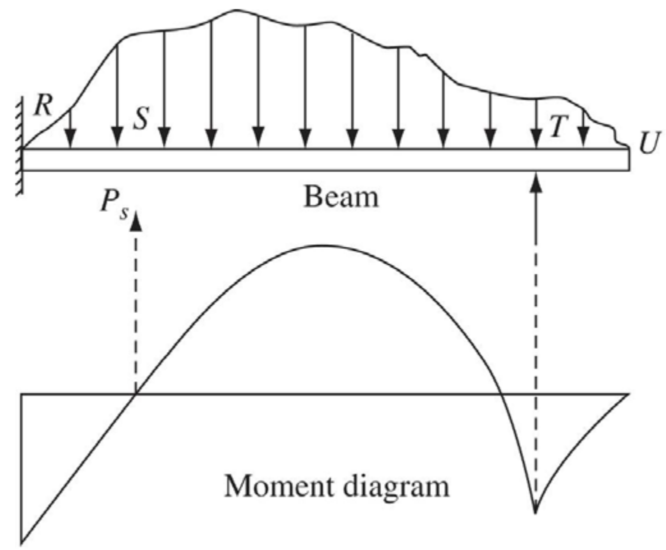


Figure 9.29 Equivalent cantilever beam concept

Step 1. Determine L_5, which is a function of the soil friction angle ϕ' below the dredge line, from the following:

ϕ' (deg)	$\frac{L_5}{L_1 + L_2}$
30	0.08
35	0.03
40	0

Step 2. Calculate the span of the equivalent beam as $l_2 + L_2 + L_5 = L'$.

Step 3. Calculate the total load of the span, W. This is the area of the pressure diagram between O' and I.

Step 4. Calculate the maximum moment, M_{max}, as $WL'/8$.

Step 5. Calculate P' by taking the moment about O', or

$$P' = \frac{1}{L'}\,(\text{moment of area } ACDJI \text{ about } O') \tag{9.82}$$

Step 6. Calculate D as

$$D = L_5 + 1.2\sqrt{\frac{6P'}{(K_p - K_a)\gamma'}} \tag{9.83}$$

Step 7. Calculate the anchor force per unit length, F, by taking the moment about I, or

$$F = \frac{1}{L'}\,(\text{moment of area } ACDJI \text{ about } I)$$

Free Earth Support method for Penetration of clay

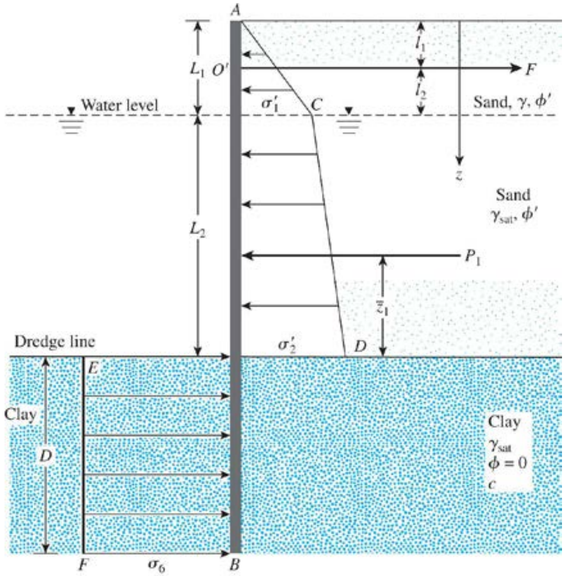


Figure 9.34 Anchored sheet-pile wall penetrating clay

A moment reduction technique similar to that in Section 9.11 for anchored sheet piles penetrating into clay has also been developed by Rowe (1952, 1957). This technique is presented in Figure 9.35, in which the following notation is used:

1. The stability number is

$$S_n = 1.25\frac{c}{(\gamma L_1 + \gamma' L_2)} \tag{9.86}$$

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

For the definition of γ, γ', L_1, and L_2, see Figure 9.34.

2. The nondimensional wall height is

$$\alpha = \frac{L_1 + L_2}{L_1 + L_2 + D_{actual}} \tag{9.87}$$

3. The flexibility number is ρ [see Eq. (9.74a) or Eq. (9.74b)]
4. M_d = design moment
   M_{max} = maximum theoretical moment

The procedure for moment reduction, using Figure 9.35, is as follows:

Step 1. Obtain $H' = L_1 + L_2 + D_{actual}$.

Step 2. Determine $\alpha = (L_1 + L_2)/H'$.

Step 3. Determine S_n [from Eq. (9.86)].

Step 4. For the magnitudes of α and S_n obtained in Steps 2 and 3, determine M_d/M_{max} for various values of log ρ from Figure 9.35, and plot M_d/M_{max} against log ρ.

Step 5. Follow Steps 1 through 9 as outlined for the case of moment reduction of sheet-pile walls penetrating granular soil. (See Section 9.11.)

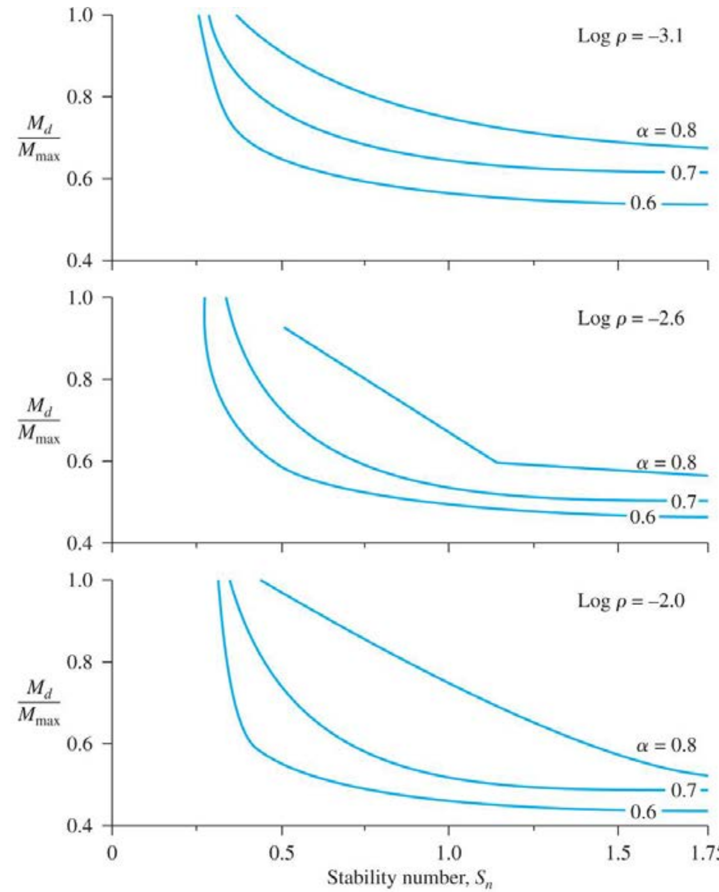


Figure 9.35 Plot of M_d/M_{max} against stability number for sheet-pile wall penetrating clay (From Rowe, P. W. (1957). "Sheet Pile Walls in Clay," *Proceedings*, Institute of Civil Engineers, Vol. 7, pp. 654–692.)

Anchors

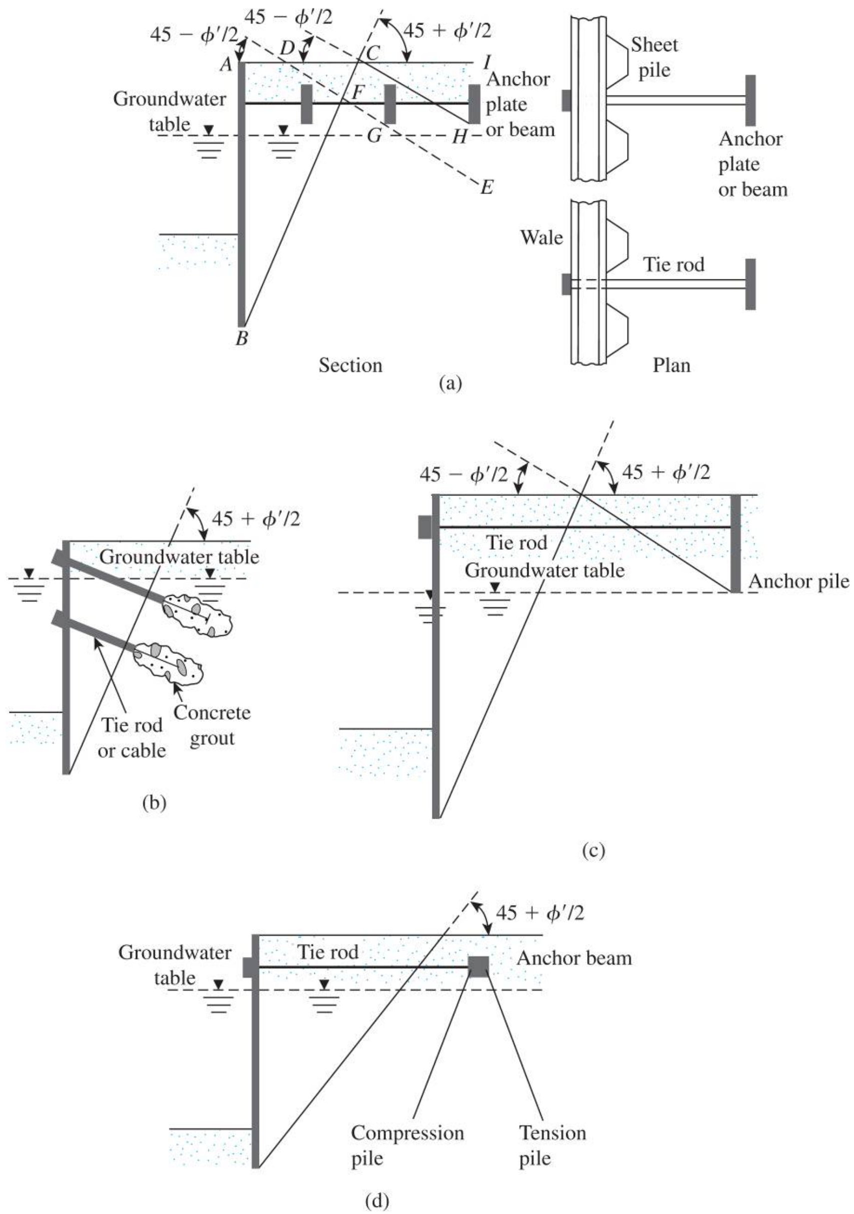


Figure 9.37 Various types of anchoring for sheet-pile walls: (a) anchor plate or beam; (b) tieback; (c) vertical anchor pile; (d) anchor beam with batter piles

Holding Capacity of Anchor plates in Sand

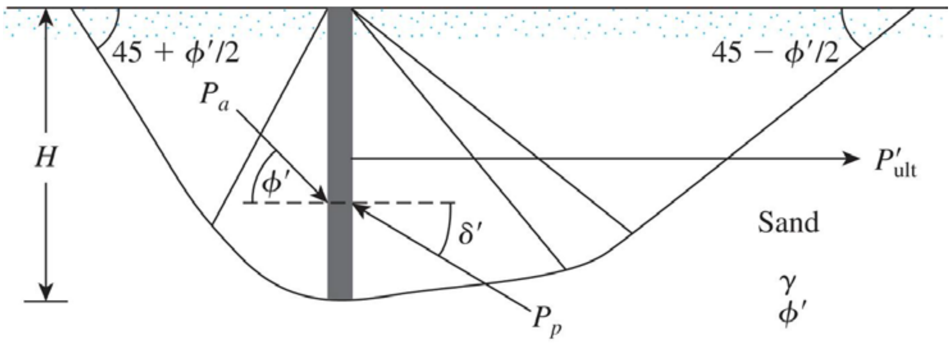


Figure 9.38 Basic case: continuous vertical anchor in granular soil

Holding Capacity of Anchor plates in Sand

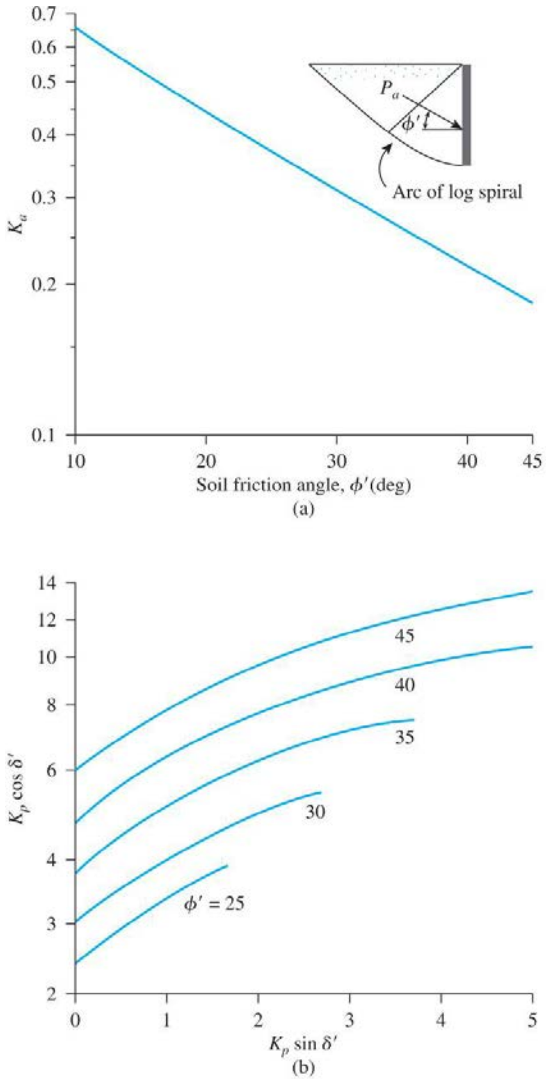


Figure 9.39 (a) Variation of K_a for $\delta' = \phi'$, (b) variation of $K_p \cos \delta'$ with $K_p \sin \delta'$ (Based on Ovesen and Stromann, 1972)

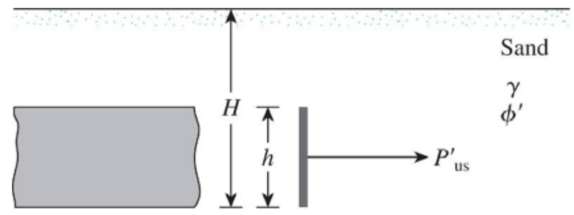


Figure 9.40 Strip case: vertical anchor

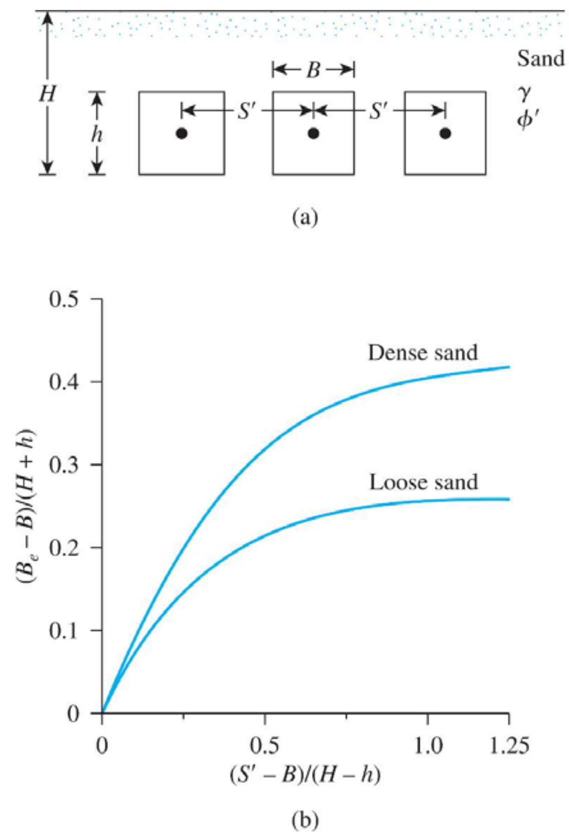


Figure 9.41 (a) Actual case for row of anchors; (b) variation of $(B_e - B)/(H + h)$ with $(S' - B)/(H + h)$ (Based on Ovesen and Stromann, 1972)

Holding Capacity of Anchor plates in Sand

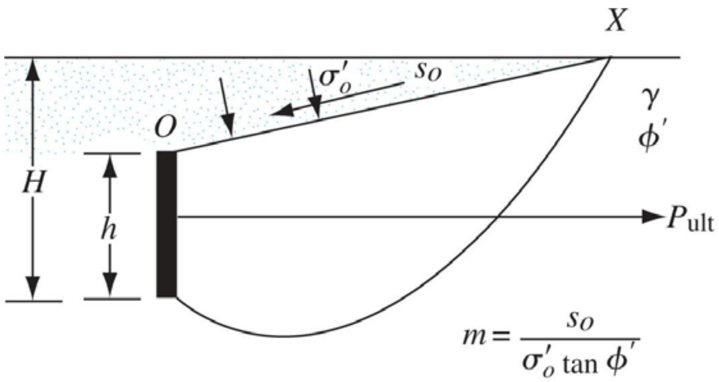


Figure 9.42 Assumed failure surface in soil for stress characteristic solution

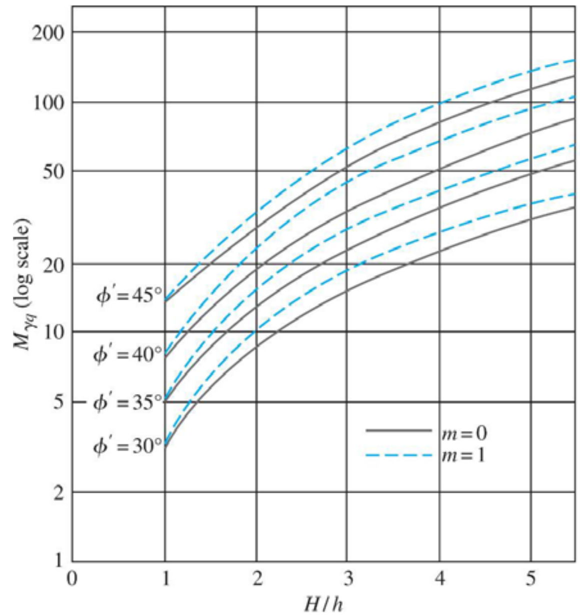


Figure 9.43 Variation of $M_{\gamma q}$ with H/h and ϕ' (After Neeley *et al.*, 1973. With permission from ASCE.)

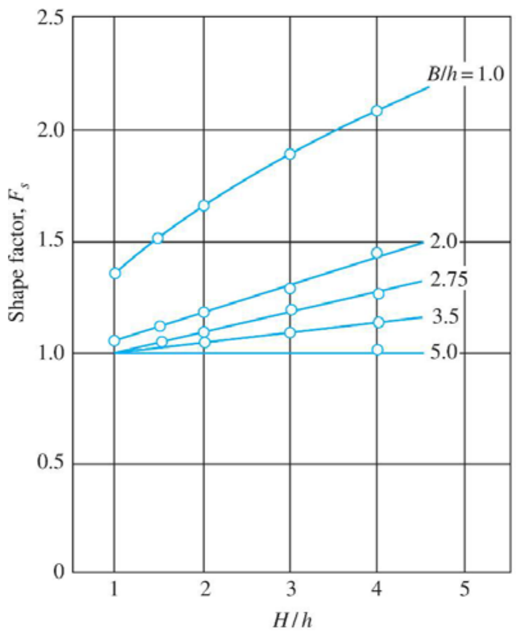


Figure 9.44 Variation of shape factor with H/h and B/h (After Neeley *et al.*, 1973. With permission from ASCE.)

Holding Capacity of Anchor plates in Clay

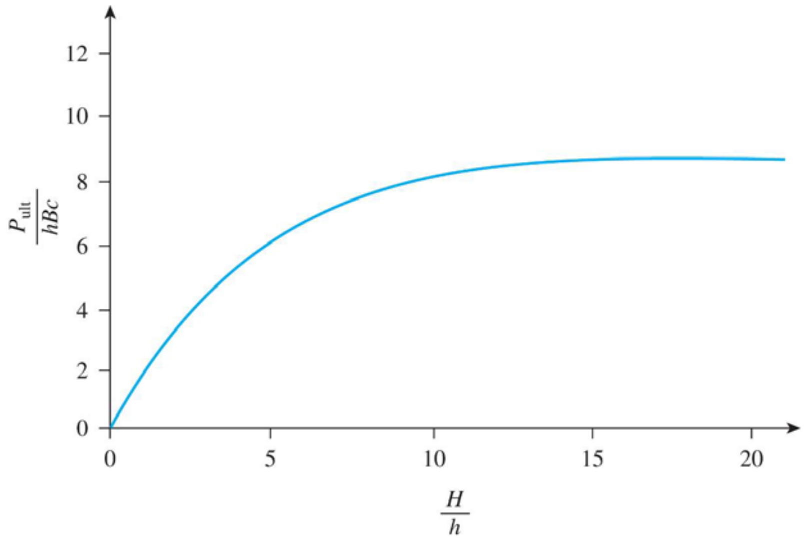


Figure 9.45 Experimental variation of $\frac{P_{ult}}{hBc}$ with H/h for plate anchors in clay (Based on Mackenzie (1955) and Tschebotarioff (1973))

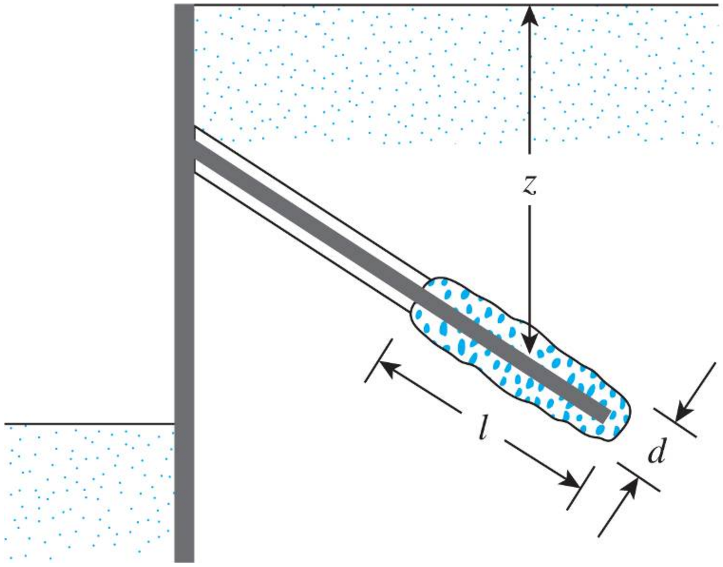


Figure 9.46 Parameters for defining the ultimate resistance of tiebacks

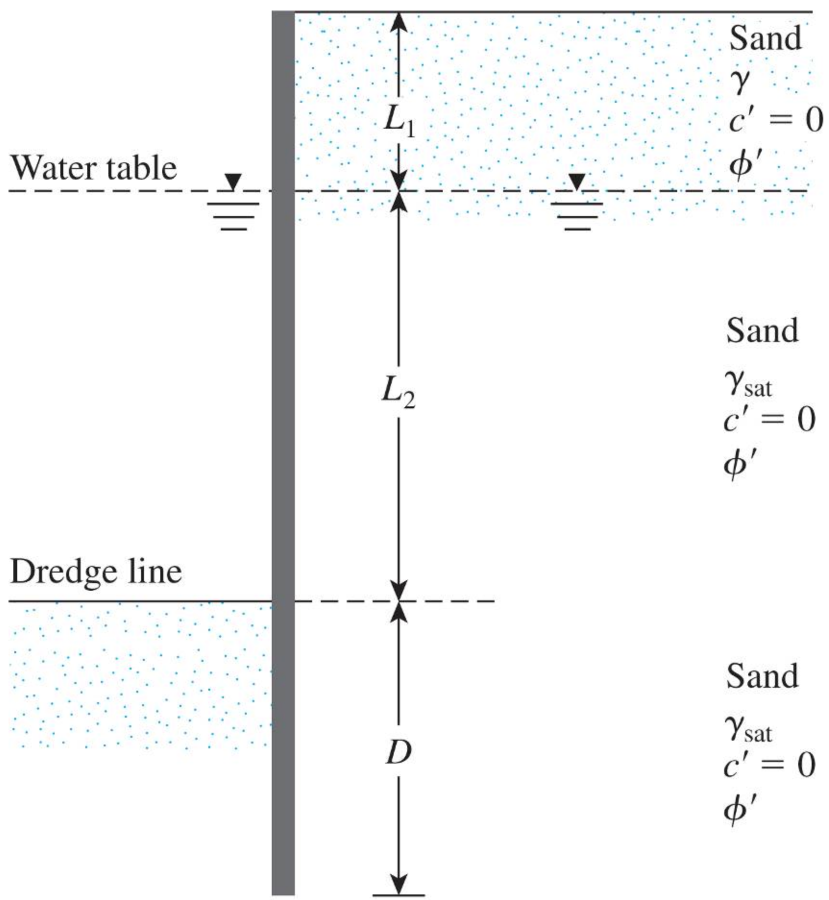

Sand
γ
c′ = 0
ϕ′
L1
Water table
Sand
γsat
c′ = 0
ϕ′
L2
Dredge line
Sand
γsat
c′ = 0
ϕ′
D

Figure P9.1

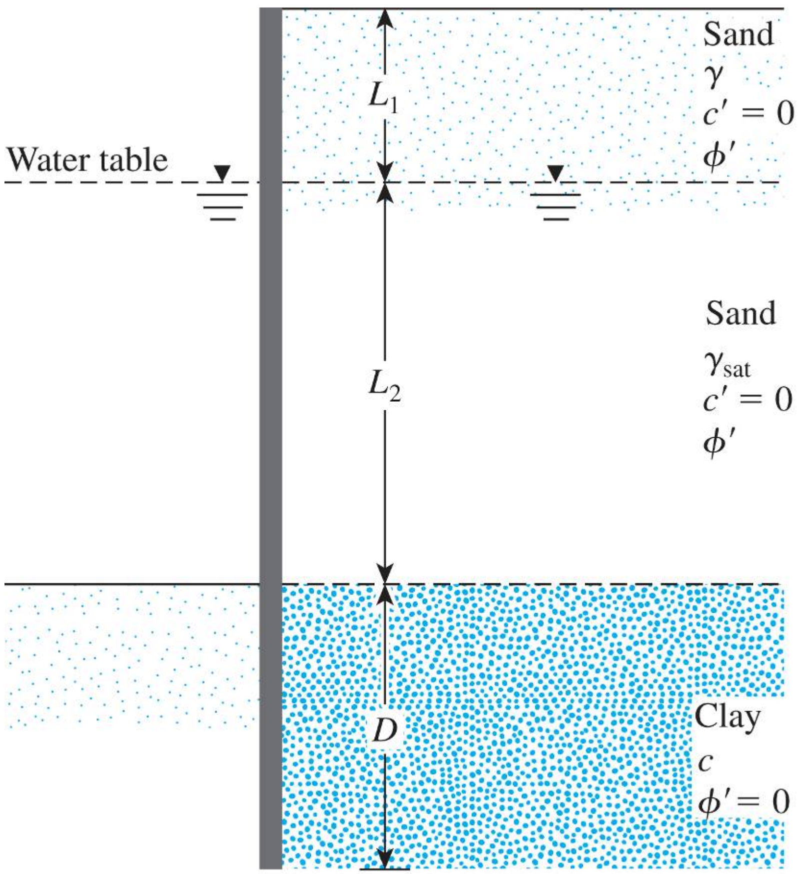
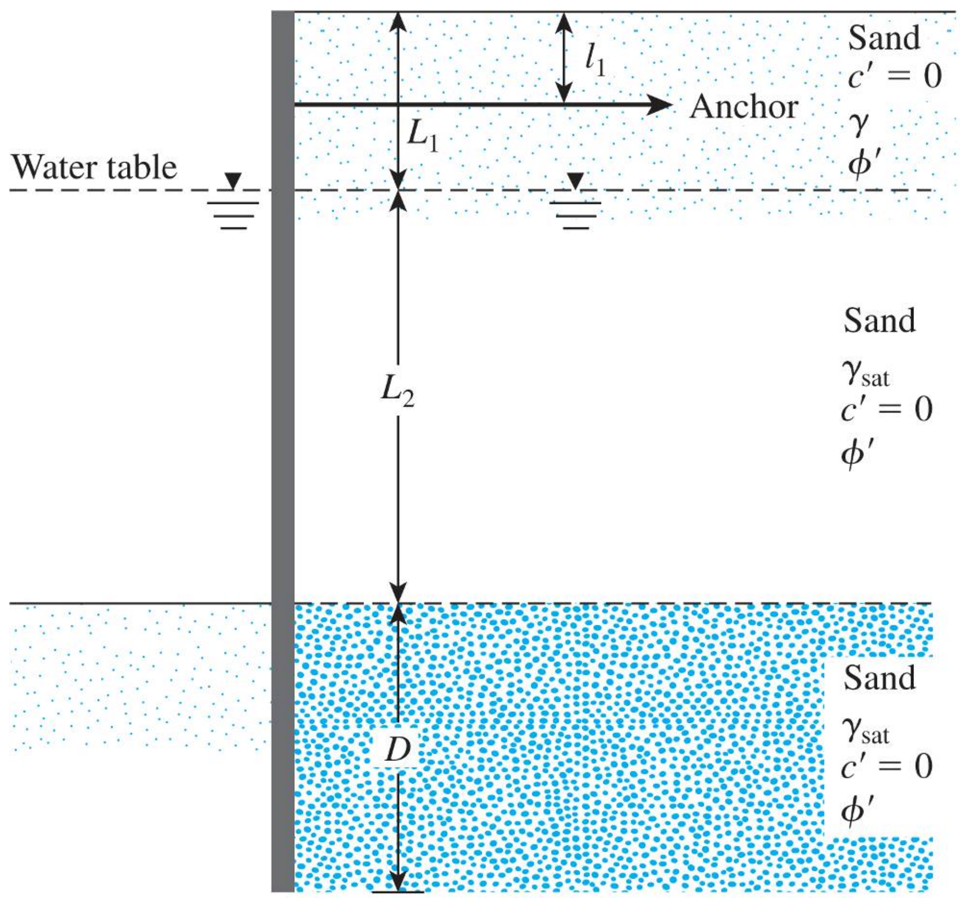
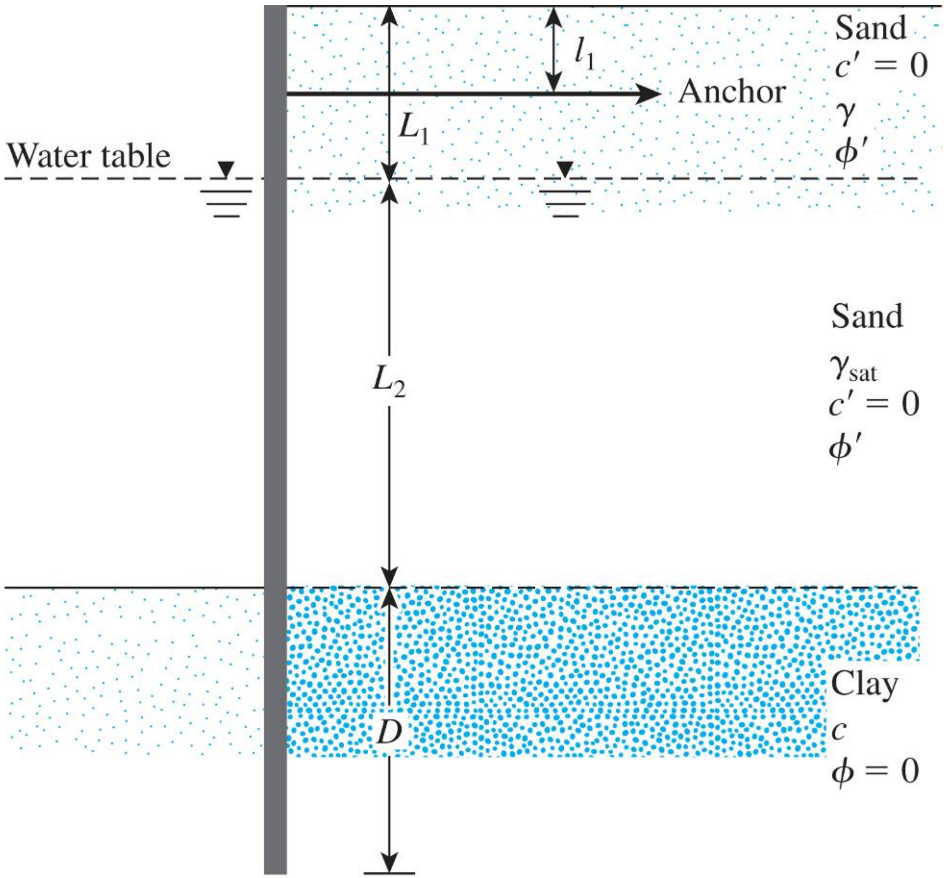


Figure P9.4



l_1
Anchor
L_1
Sand
$c' = 0$
γ
ϕ'
Water table
L_2
Sand
γ_{sat}
$c' = 0$
ϕ'
D
Sand
γ_{sat}
$c' = 0$
ϕ'

Figure P9.6



Sand
c′ = 0
γ
φ′
l_1
Anchor
L_1
Water table
Sand
γ_{sat}
c′ = 0
φ′
L_2
Clay
c
φ = 0
D

Figure P9.10

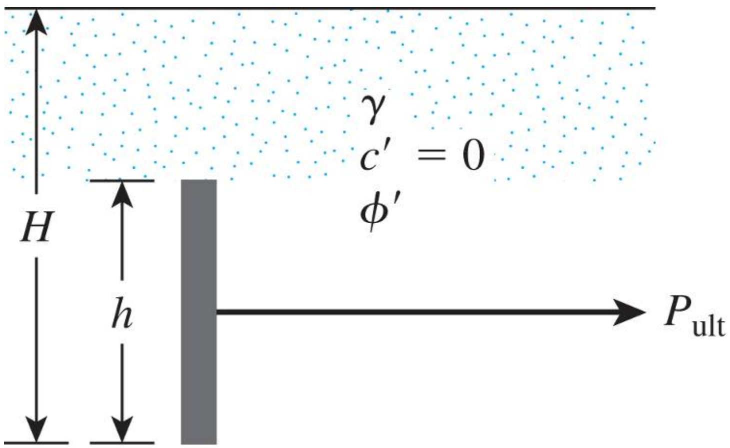


Figure P9.12