University of Anbar
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CHAPTER FIVE

BRACED CUTS

LECTURE
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5.1 Introduction

Sometimes construction work requires ground excavations with vertical or near-vertical faces—for example, basements of buildings in developed areas or underground transportation facilities at shallow depths below the ground surface (a cut-and-cover type of construction). The vertical faces of the cuts need to be protected by temporary bracing systems to avoid failure that may be accompanied by considerable settlement or by bearing capacity failure of nearby foundations.

Figure 5.1 shows two types of braced cut commonly used in construction work. One type uses the ***soldier beam*** (Figure 5.1a), which is driven into the ground before excavation and is a vertical steel or timber beam. ***Laggings,*** which are horizontal timber planks, are placed between soldier beams as the excavation proceeds. When the excavation reaches the desired depth, ***wales*** and ***struts*** (horizontal steel beams) are installed. The struts are compression members. Figure 5.1b shows another type of braced excavation. In this case, interlocking *sheet piles* are driven into the soil before excavation. Wales and struts are inserted immediately after excavation reaches the appropriate depth.

Figure 5.2 shows the braced-cut construction used for the Chicago subway in 1940. Timber lagging, timber struts, and steel wales were used. Figure 5.3 shows a braced cut made during the construction of the Washington, DC, metro in 1974. In this cut, timber lagging, steel H-soldier piles, steel wales, and pipe struts were used.

To design braced excavations (i.e., to select wales, struts, sheet piles, and soldier beams), an engineer must estimate the lateral earth pressure to which the braced cuts will be subjected. The theoretical aspects of the lateral earth pressure on a braced cut is discussed in Section 5.2. The total active force per unit length of the wall (P_a) can be calculated by using the general wedge theory. However, that analysis will not provide the relationships required for estimating the variation of lateral pressure with depth, which is a function of several factors, such as the type of soil, the experience of the construction crew, the type of construction equipment used, and so forth. For that reason, empirical pressure envelopes developed from field observations are used for the design of braced cuts. This procedure is discussed in the following sections.

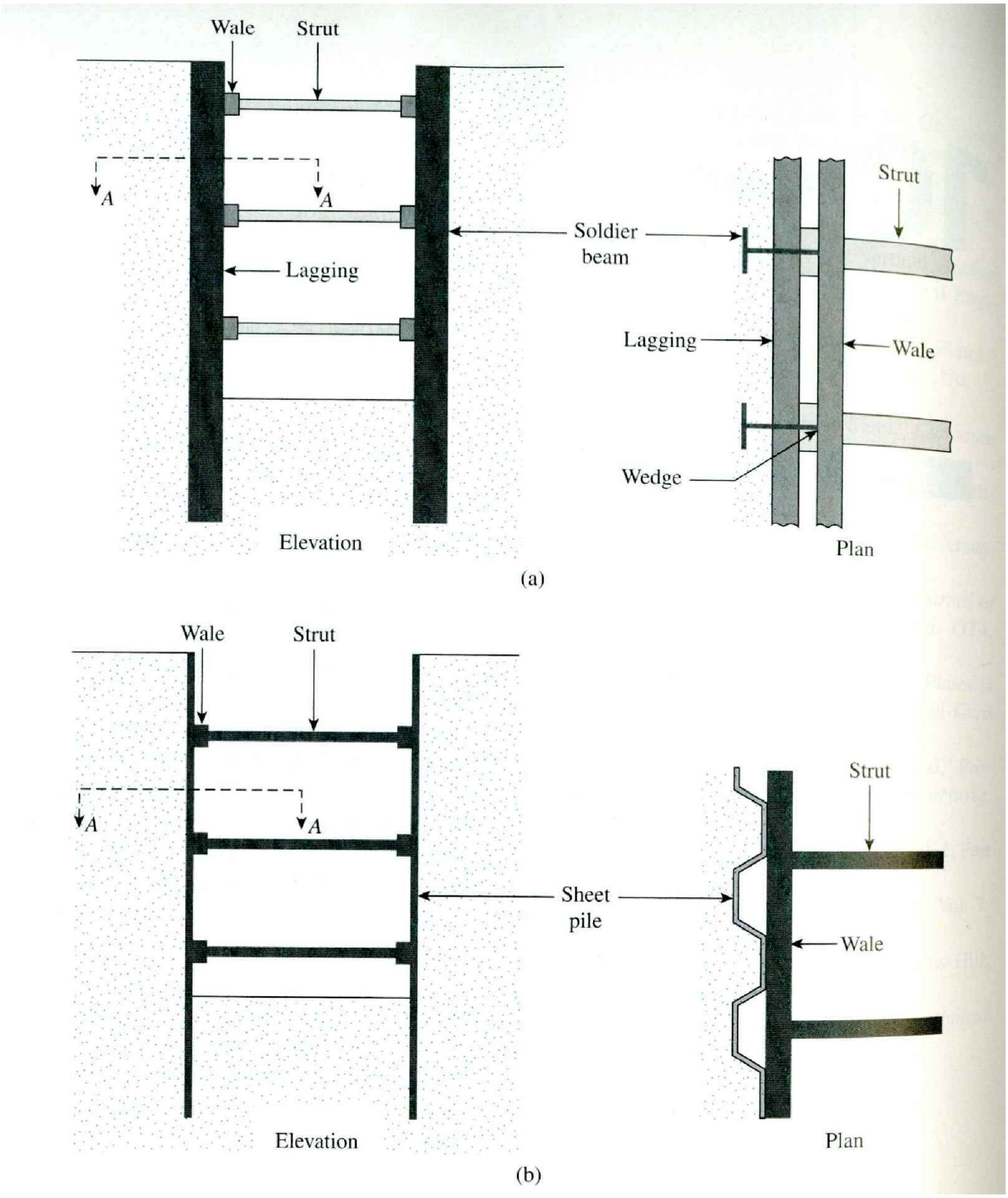

Figure 5.1 Types of braced cut: (a) use of soldier beams; (b) use of sheet piles

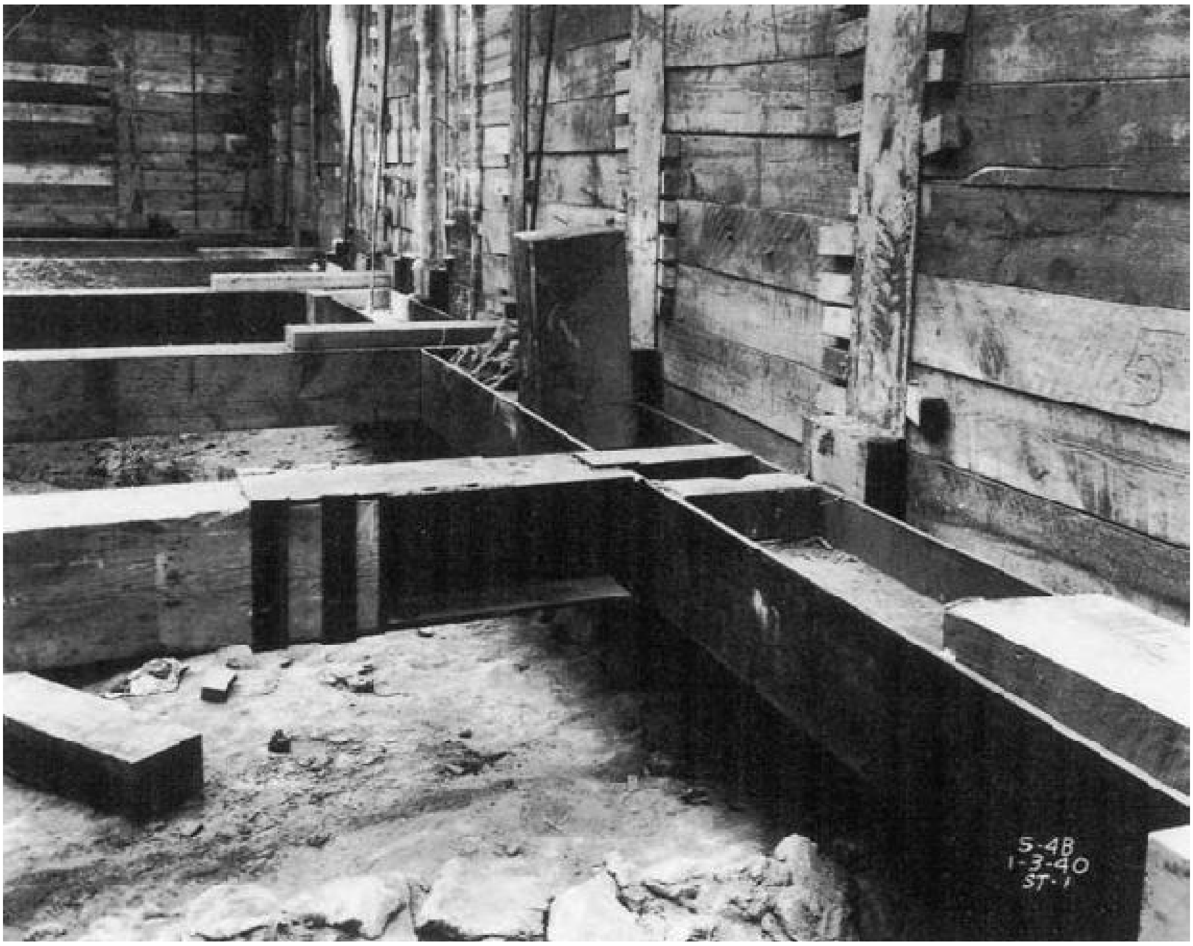

Figure 5.2 Braced cut in Chicago Subway construction, January 1940 (*Courtesy of Ralph B. Peck*)

Figure 5.3 Braced cut in the construction of Washington, D.C. Metro, May 1974 (Courtesy of Ralph B. Peck)

5.2 Pressure Envelope for Braced-Cut Design

As mentioned in Section 5.1, the lateral earth pressure in a braced cut is dependent on the type of soil, construction method, and type of equipment used. The lateral earth pressure changes from place to place. Each strut should also be designed for the maximum load to which it may be subjected. Therefore, the braced cuts should be designed using apparent-pressure diagrams that are envelopes of all the pressure diagrams determined from measured strut loads in the field. Figure 5.4 shows the method for obtaining the apparent-pressure diagram at a section from strut loads. In this figure, let P_1 , P_2 , P_3 , P_4 , …. be the measured strut loads. The apparent horizontal pressure can then be calculated as

$$\sigma_1 = \frac{P_1}{(s)\left(d_1 + \frac{d_2}{2}\right)}$$

$$\sigma_2 = \frac{P_2}{(s)\left(\frac{d_2}{2} + \frac{d_3}{2}\right)}$$

$$\sigma_3 = \frac{P_3}{(s)\left(\frac{d_3}{2} + \frac{d_4}{2}\right)}$$

$$\sigma_4 = \frac{P_4}{(s)\left(\frac{d_4}{2} + \frac{d_5}{2}\right)}$$

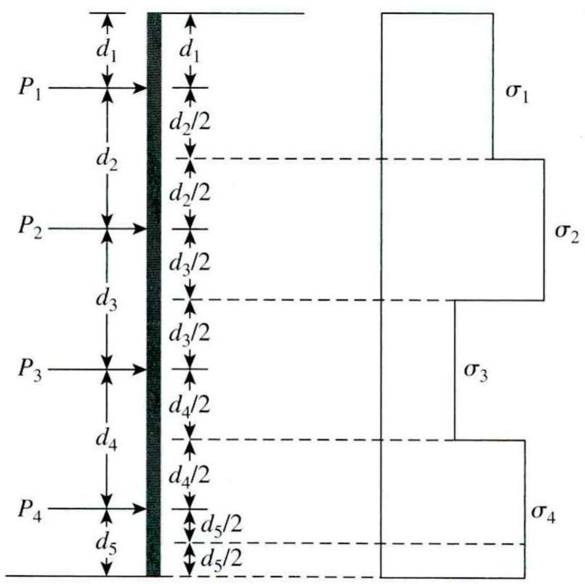

Figure 5.4 Procedure for calculating apparent-pressure diagram from measured strut loads

where

σ_1 , σ_2 , σ_3 , σ_4 = apparent pressures

S= center-to-center spacing of the struts

Using the procedure just described for strut loads observed from the Berlin subway cut, Munich subway cut, and New York subway cut, Peck (1969) provided the envelope of apparent-lateral-pressure diagrams for design of cuts in *sand.* This envelope is illustrated in Figure 5.5, in which

$$\sigma_a = 0.65\gamma H K_a \qquad \textbf{(5.1)}$$

where

γ = unit weight

H = height of the cut

K_a = Rankine active pressure coefficient = $(\tan^2(45+\phi'/2)$

ϕ' = effective friction angle of sand

Cuts in Clay

In a similar manner, Peck (1969) also provided the envelopes of apparent-lateral-pressure diagrams for cuts in *soft to medium clay* and in *stiff clay.* The pressure envelope for soft to medium clay is shown in Figure 5.6 and is applicable to the condition

$$\frac{\gamma H}{c} > 4$$

where c = undrained cohesion ϕ =0.

The pressure, σ_a , is the larger of

$$\sigma_a = \gamma H\left[1 - \left(\frac{4c}{\gamma H}\right)\right] \qquad (5.2)$$

and

$$\sigma_a = 0.3\gamma H$$

where γ = unit weight of clay.

The pressure envelope for cuts in stiff clay is shown in Figure 5.7, in which

$$\sigma_a = 0.2\gamma H \text{ to } 0.4\gamma H \qquad (\text{with an average of } 0.3\gamma H) \qquad (5.3)$$

is applicable to the condition $\gamma H/c \le 4$.

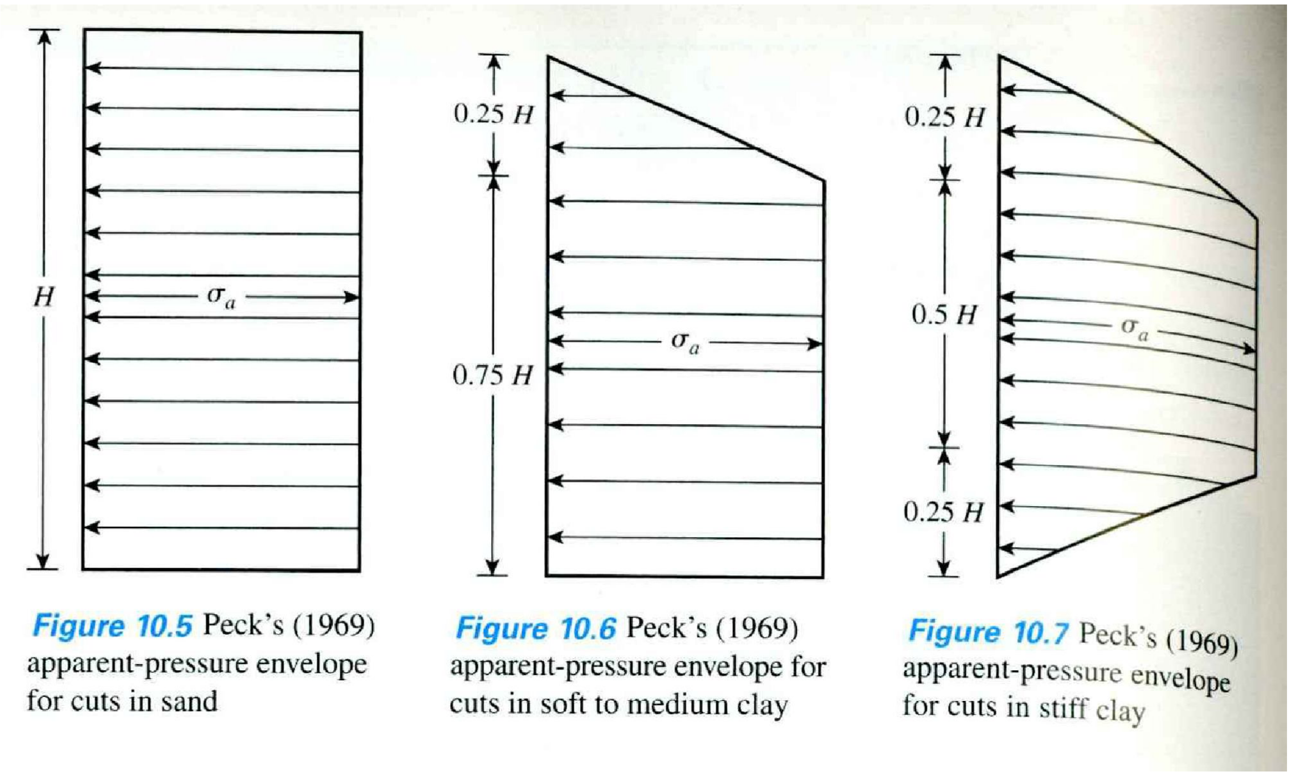

Figure 10.5 Peck's (1969) apparent-pressure envelope for cuts in sand

Figure 10.6 Peck's (1969) apparent-pressure envelope for cuts in soft to medium clay

Figure 10.7 Peck's (1969) apparent-pressure envelope for cuts in stiff clay

When using the pressure envelopes just described, keep the following points in mind:

1. They apply to excavations having depths greater than about 6m(≈20ft).
2. They are based on the assumption that the water table is below the bottom of the cut.
3. Sand is assumed to be drained with zero pore water pressure.
4. Clay is assumed to be undrained and pore water pressure is not considered.

5.3 Pressure Envelope for Cuts in Layered Soil

Sometimes, layers of both sand and clay are encountered when a braced cut is being constructed. In this case, Peck (1943) proposed that an equivalent value of cohesion (ϕ =0) should be determined according to the formula (see Figure 5.8a).

$$c_{av} = \frac{1}{2H}[\gamma_s K_s H_s^2 \tan \phi'_s + (H - H_s)n' q_u] \quad (5.4)$$

where

H = total height of the cut

γ_s = unit weight of sand

H_s = height of the sand layer

K_s = a lateral earth pressure coefficient for the sand layer (≈1)

ϕ'_s=5 effective angle of friction of sand
q_u= unconfined compression strength of clay
n' = a coefficient of progressive failure (ranging from 0.5 to 1.0; average value 0.75)

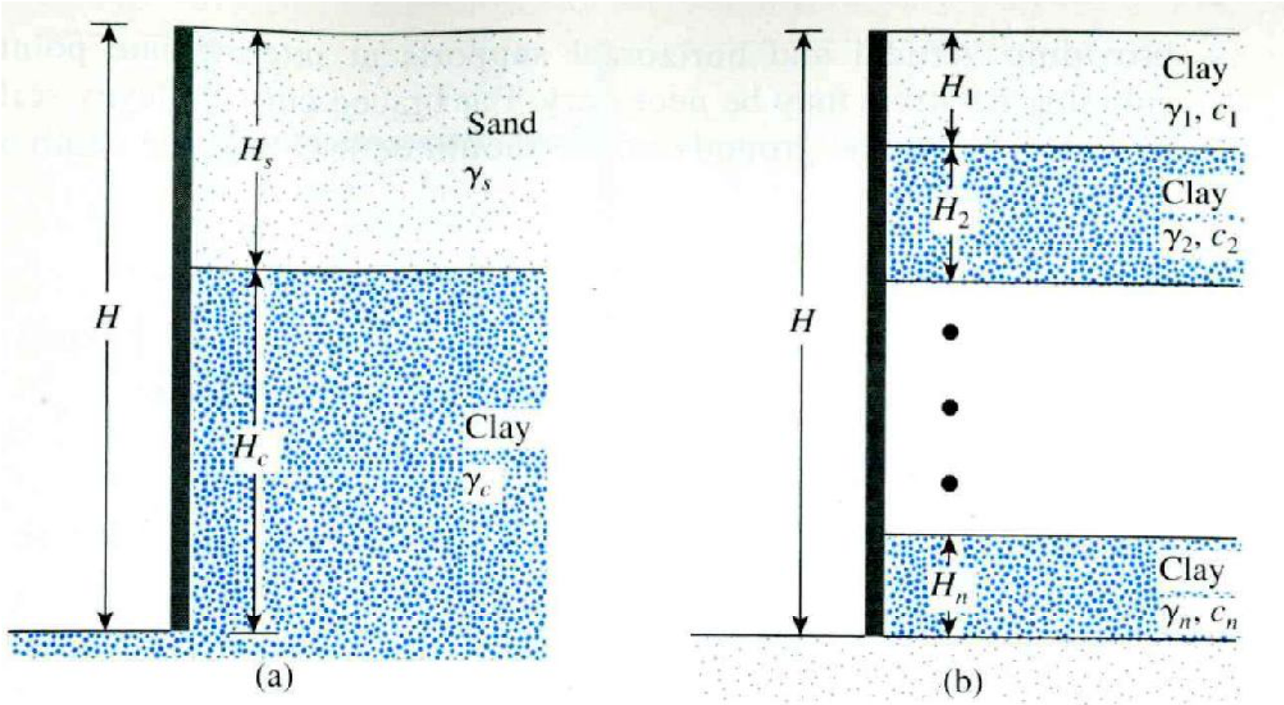

Figure 5.8 Layered soils in braced cuts

The average unit weight of the layers may be expressed as

$$\gamma_a = \frac{1}{H}[\gamma_s H_s + (H - H_s)\gamma_c] \qquad (5.5)$$

where γ_c = saturated unit weight of clay layer.

Once the average values of cohesion and unit weight are determined, the pressure envelopes in clay can be used to design the cuts.

Similarly, when several clay layers are encountered in the cut (Figure 5.8b), the average undrained cohesion becomes

$$c_{av} = \frac{1}{H}(c_1 H_1 + c_2 H_2 + \cdots + c_n H_n) \qquad (5.6)$$

where
$c_1, c_2, \ldots, c_n$ = undrained cohesion in layers 1, 2, … , n
$H_1, H_2, \ldots, H_n$ = thickness of layers 1, 2, … , n

The average unit weight is now

$$\gamma_a = \frac{1}{H}(\gamma_1 H_1 + \gamma_2 H_2 + \gamma_3 H_3 + \cdots + \gamma_n H_n) \qquad (5.7)$$

5.4 Design of Various Components of a Braced Cut Struts

In construction work, struts should have a minimum vertical spacing of about 2.75 m (9 ft) or more. Struts are horizontal columns subject to bending. The load-carrying capacity of columns depends on their *slenderness ratio,* which can be reduced by providing vertical and horizontal supports at intermediate points. For wide cuts, splicing the struts may be necessary. For braced cuts in clayey soils, the depth of the first strut below the ground surface should be less than the depth of tensile crack, z_c. From Eq. (5.7),

$$\sigma'_a = \gamma z K_a - 2c'\sqrt{K_a}$$

where K_a = coefficient of Rankine active pressure.

For determining the depth of tensile crack,

$$\sigma'_a = 0 = \gamma z_c K_a - 2c'\sqrt{K_a}$$

or

$$z_c = \frac{2c'}{\sqrt{K_a}\gamma}$$

With $\phi = 0$, $K_a = \tan^2(45 - \phi/2) = 1$, so

$$z_c = \frac{2c}{\gamma}$$

A simplified conservative procedure may be used to determine the strut loads. Although this procedure will vary, depending on the engineers involved in the project, the following is a step-by-step outline of the general methodology (see Figure 5.9):

Step 1. Draw the pressure envelope for the braced cut. (See Figures 5.5, 5.6, and 5.7.) Also, show the proposed strut levels. Figure 5.9a shows a pressure envelope for a sandy soil; however, it could also be for a clay. The strut levels are marked *A, B, C,* and *D.* The sheet piles (or soldier beams) are assumed to be hinged at the strut levels, except for the top and bottom ones. In Figure 5.9a, the hinges are at the level of struts *B* and *C.* (Many designers also assume the sheet piles or soldier beams to be hinged at all strut levels except for the top.)

Step 2. Determine the reactions for the two simple cantilever beams (top and bottom) and all the simple beams between. In Figure 5.9b, these reactions are A, B_1, B_2, C_1, C_2, and D.

Step 3. The strut loads in the figure may be calculated via the formulas

$$P_A = (A)(s)$$
$$P_B = (B_1 + B_2)(s)$$
$$P_C = (C_1 + C_2)(s) \qquad (5.8)$$

and

$$P_D = (D)(s)$$

where

P_A, P_B, P_C, P_D = loads to be taken by the individual struts at levels A,B, C, and D, respectively

A, B_1, B_2, C_1, C_2, D = reactions calculated in Step 2 (note the unit: force/unit length of the braced cut)

s = horizontal spacing of the struts (see plan in Figure 5.9a)

Step 4. Knowing the strut loads at each level and the intermediate bracing conditions allows selection of the proper sections from the steel manual

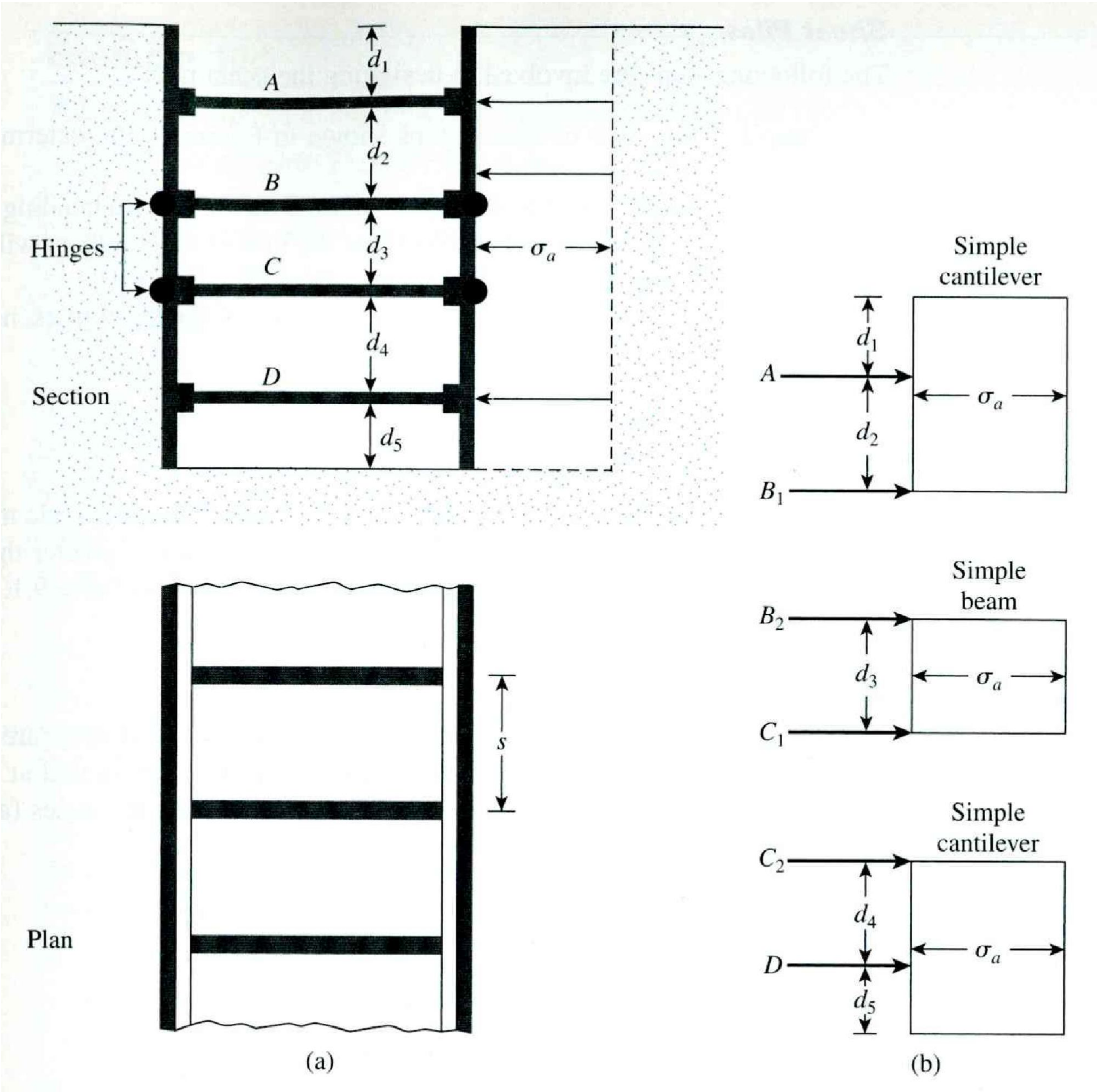

Figure 5.9 Determination of strut loads: (a) section and plan of the cut; (b) method for determining strut loads

Sheet Piles

The following steps are involved in designing the sheet piles:

Step 1. For each of the sections shown in Figure 15.11b, determine the maximum bending moment.

Step 2. Determine the maximum value of the maximum bending moments (M_{max}) obtained in Step 1. Note that the unit of this moment will be, for example, kN-m/m length of the wall.

Step 3. Obtain the required section modulus of the sheet piles, namely,

$$S = \frac{M_{max}}{\sigma_{all}} \qquad (5.9)$$

where σ_{all} = allowable flexural stress of the sheet-pile material.

Step 4. Choose a sheet pile having a section modulus greater than or equal to the required section modulus from a table such as Table 4.1.

Wales

Step1. Wales may be treated as continuous horizontal members if they are spliced properly. Conservatively, they may also be treated as though they are pinned at the struts. For the section shown in Figure 5.9a, the maximum moments for the wales (assuming that they are pinned at the struts) are,

$$\text{At level } A, \quad M_{max} = \frac{(A)(s^2)}{8}$$

$$\text{At level } B, \quad M_{max} = \frac{(B_1 + B_2)s^2}{8}$$

$$\text{At level } C, \quad M_{max} = \frac{(C_1 + C_2)s^2}{8}$$

and

$$\text{At level } D, \quad M_{max} = \frac{(D)(s^2)}{8}$$

where A, B_1, B_2, C_1, C_2, and D are the reactions under the struts per unit length of the wall (see Step 2 of strut design).

Step 2. Determine the section modulus of the wales:

$$S = \frac{M_{max}}{\sigma_{all}}$$

The wales are sometimes fastened to the sheet piles at points that satisfy the lateral support requirements.

Example 5.1:

The cross section of a long braced cut is shown in Figure 10.10a.

a. Draw the earth-pressure envelope.
b. Determine the strut loads at levels *A, B,* and *C*.
c. Determine the section modulus of the sheet pile section required.
d. Determine a design section modulus for the wales at level *B*.

(*Note:* The struts are placed at 3 m, center to center, in the plan.) Use

$$\sigma_{all} = 170 \times 10^3 \text{ kN/m}^2$$

Solution

Part a

We are given that $\gamma = 18 \text{ kN/m}^2$, $c = 35 \text{ kN/m}^2$, and $H = 7$ m. So,

$$\frac{\gamma H}{c} = \frac{(18)(7)}{35} = 3.6 < 4$$

Thus, the pressure envelope will be like the one in Figure 10.7. The envelope is plotted in Figure 10.10a with maximum pressure intensity, σ_a, equal to $0.3\gamma H = 0.3(18)(7) = \mathbf{37.8 \text{ kN/m}^2}$.

Part b

To calculate the strut loads, examine Figure 10.10b. Taking the moment about B_1, we have $\Sigma M_{B_1} = 0$, and

$$A(2.5) - \left(\frac{1}{2}\right)(37.8)(1.75)\left(1.75 + \frac{1.75}{3}\right) - (1.75)(37.8)\left(\frac{1.75}{2}\right) = 0$$

or

$$A = 54.02 \text{ kN/m}$$

Also, Σ vertical forces = 0. Thus,

$$\tfrac{1}{2}(1.75)(37.8) + (37.8)(1.75) = A + B_1$$

or

$$33.08 + 66.15 - A = B_1$$

So,

$$B_1 = 45.2 \text{ kN/m}$$

Due to symmetry,

$$B_2 = 45.2 \text{ kN/m}$$

and

$$C = 54.02 \text{ kN/m}$$

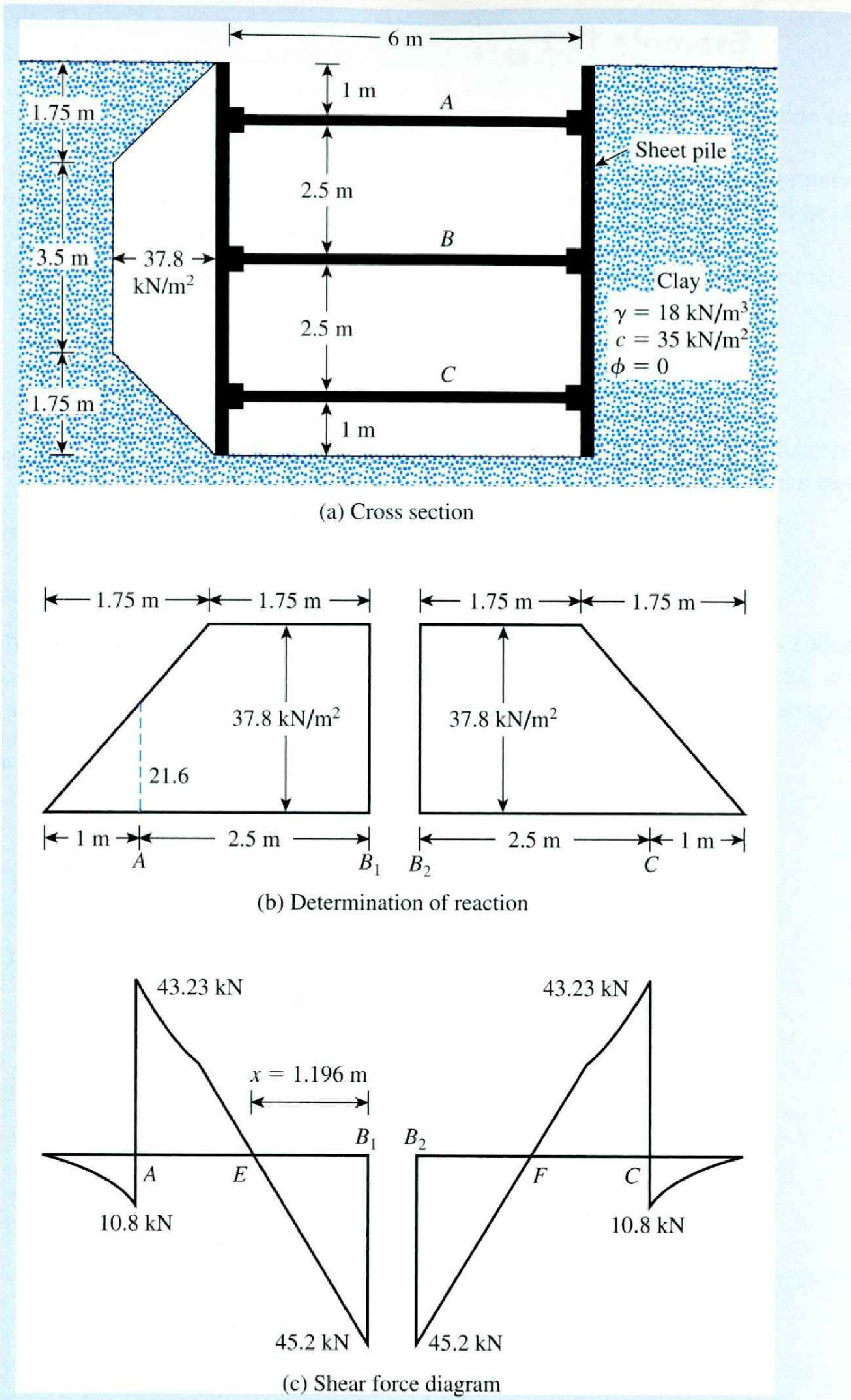

Figure 10.10 Analysis of a braced cut

Hence, the strut loads at the levels indicated by the subscripts are

$$P_A = 54.02 \times \text{horizontal spacing}, s = 54.02 \times 3 = \mathbf{162.06\ kN}$$
$$P_B = (B_1 + B_2)3 = (45.2 + 45.2)3 = \mathbf{271.2\ kN}$$

and

$$P_C = 54.02 \times 3 = \mathbf{162.06\ kN}$$

Part c

At the left side of Figure 10.10b, for the maximum moment, the shear force should be zero. The nature of the variation of the shear force is shown in Figure 10.10c. The location of point E can be given as

$$x = \frac{\text{reaction at } B_1}{37.8} = \frac{45.2}{37.8} = 1.196 \text{ m}$$

Also,

$$\text{Magnitude of moment at } A = \frac{1}{2}(1)\left(\frac{37.8}{1.75} \times 1\right)\left(\frac{1}{3}\right)$$
$$= 3.6 \text{ kN-m/meter of wall}$$

and

$$\text{Magnitude of moment at } E = (45.2 \times 1.196) - (37.8 \times 1.196)\left(\frac{1.196}{2}\right)$$
$$= 54.06 - 27.03 = 27.03 \text{ kN-m/meter of wall}$$

Because the loading on the left and right sections of Figure 10.10b are the same, the magnitudes of the moments at F and C (see Figure 10.10c) will be the same as those at E and A, respectively. Hence, the maximum moment is 27.03 kN-m/meter of wall.

The section modulus of the sheet piles is thus

$$S = \frac{M_{max}}{\sigma_{all}} = \frac{27.03 \text{ kN-m}}{170 \times 10^3 \text{ kN/m}^2} = \mathbf{15.9 \times 10^{-5} m^3/m \text{ of the wall}}$$

Part d

The reaction at level B has been calculated in part b. Hence,

$$M_{max} = \frac{(B_1 + B_2)s^2}{8} = \frac{(45.2 + 45.2)3^2}{8} = 101.7 \text{ kN-m}$$

and

$$\text{Section modulus, } S = \frac{101.7}{\sigma_{all}} = \frac{101.7}{(170 \times 1000)}$$
$$= \mathbf{0.598 \times 10^{-3}\ m^3}$$

■

Example 10.2

Refer to the braced cut shown in Figure 10.11, for which $\gamma = 17\ \text{kN/m}^3$, $\phi' = 35°$, and $c' = 0$. The struts are located 4 m on center in the plan. Draw the earth-pressure envelope and determine the strut loads at levels *A*, *B*, and *C*.

Solution

For this case, the earth-pressure envelope shown in Figure 10.5 is applicable. Hence,

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

From Equation (10.1)

$$\sigma_a = 0.65\,\gamma H K_a = (0.65)(17)(9)(0.271) = 26.95\ \text{kN/m}^2$$

Figure 10.12a shows the pressure envelope. Refer to Figure 10.12b and calculate B_1:

$$\sum M_{B_1} = 0$$

$$A = \frac{(26.95)(5)\left(\frac{5}{2}\right)}{3} = 112.29\ \text{kN/m}$$

$$B_1 = (26.95)(5) - 112.29 = 22.46\ \text{kN/m}$$

Now, refer to Figure 10.12c and calculate B_2:

$$\sum M_{B_2} = 0$$

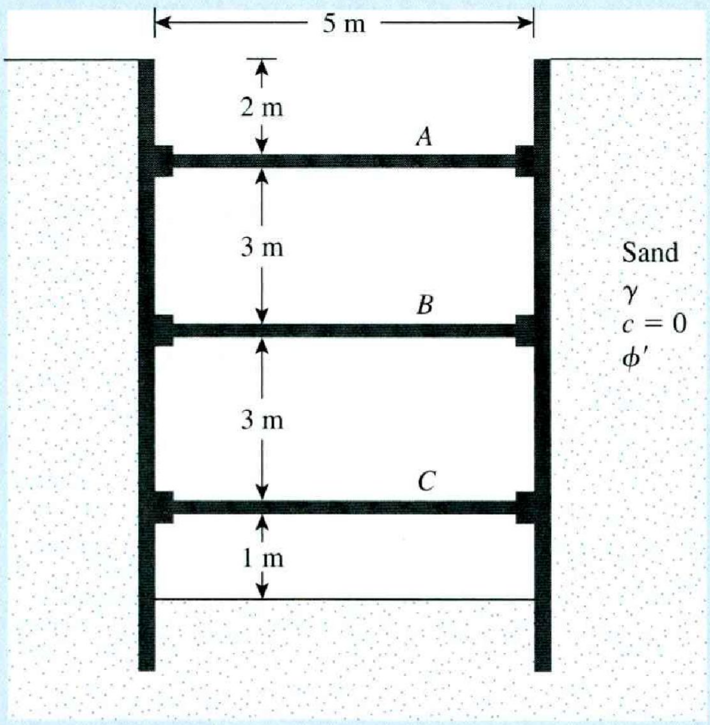

Figure 10.11

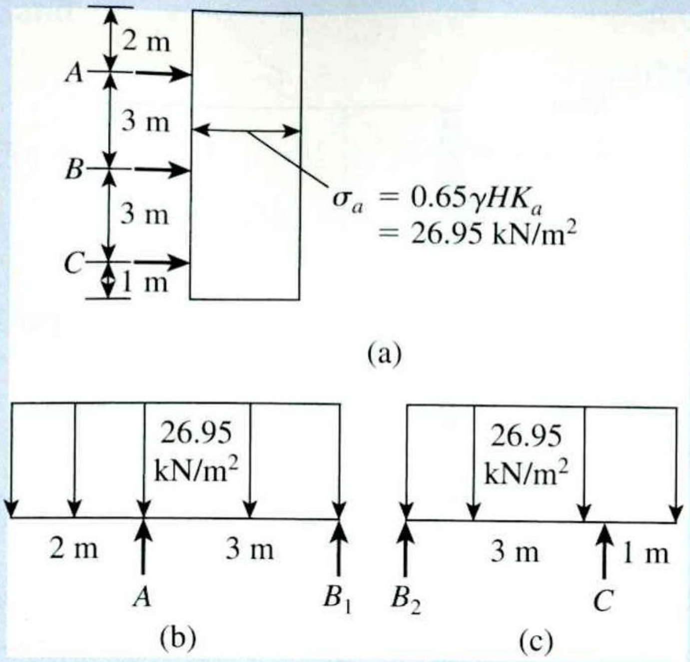

Figure 10.12 Load diagrams

$$C = \frac{(26.95)(4)\left(\frac{4}{2}\right)}{3} = 71.87 \text{ kN/m}$$

$$B_2 = (26.95)(4) - 71.87 = 35.93 \text{ kN/m}$$

The strut loads are

At A, (112.29)(spacing) = (112.29)(4) = **449.16 kN**

At B, $(B_1 + B_2)$(spacing) = (22.46 + 35.93)(4) = **233.56 kN**

At C, (71.87)(spacing) = (71.87)(4) = **287.48 kN**