H = depth below ground level (ft)

k_a = active earth pressure coefficient

= $\tan^2 (45° - \phi_f/2)$

ϕ_f = angle of internal friction which usually ranges from 26° to 30° for medium to dense soils

Active Earth Pressure for Cohesive Soils:

$$p_a = \gamma_s H - 2c \text{ (psf)} \quad (4.3.1.2\text{-}2)$$

where:

γ_s = total unit weight of soil (pcf)

H = depth below ground level (ft)

c = cohesion = $Q_u/2$

Q_u = undrained unconfined compressive strength in (psf)

In the absence of test data, cohesion, c, may be estimated to range between 20 to 25 percent of the effective overburden pressure.

Pressures given by this formula may be negative in the upper portion of the wall, depending on the value of cohesion. In such cases, minimum active pressure shall not be less than those for a cohesionless soil with an active earth pressure coefficient, k_a, of 0.25.

Cohesive Soils—Tension cracks and fissures, etc. in cohesive soils can destroy the cohesion. Cohesion is also lost from exposure to weather, pore pressure dissipation, erosion, remolding, and other construction activities. Hence, a minimum active pressure coefficient of 0.25 has been specified.

Active Earth Pressure for Mixed Soils:

$$p_a = k_a \gamma_s H - 2c\sqrt{k_a} \text{ (psf)} \quad (4.3.1.2\text{-}3)$$

where the symbols have the same meaning as described above.

Minimum pressures shall not be less than those corresponding to an active earth pressure coefficient of 0.25.

4.3.1.3—At-Rest Pressures

Where ground movement is prevented, lateral pressures shall correspond to the at-rest values given by:

$$p_o = k_o \gamma_s H \text{ (psf)} \quad (4.3.1.3\text{-}1)$$

where:

γ_s = unit weight of soil (psf)

H = depth below ground level (ft)

k_o = at-rest earth pressure coefficient, given empirically as follows:

Cohesionless soils: $k_o = 1 - \sin \phi_f$

Cohesive soils: $k_o = 0.95 - \sin \phi_f$

C4.3.1.3

Many published empirical formulas are available for at-rest earth pressure coefficients. The selected value should be consistent with local practice. Soil type and stress history have a significant effect on these coefficients. Hydrostatic pressures should be added below the water table.

ϕ_f = effective angle of internal friction

Where free ground water can exist, earth pressures should be determined for the buoyant unit weight of the soil below the water table and separate hydrostatic pressures added to the submerged soil pressures to determine the total earth pressure.

Mixed Soils—The above commentary for cohesive soils is also applicable to the case of mixed soils.

For most normally consolidated clays, ϕ ranges between 20° and 28°. In overconsolidated and compacted clays, k_o values can be higher and design values shall be based on appropriate values from standard textbooks.

4.3.1.4—Passive Pressures

Passive Pressure—Cohesionless Soils:

$$p_p = k_p \gamma_s H \text{ (psf)} \quad (4.3.1.4\text{-}1)$$

where:

γ_s = unit weight of soil (psf)

H = depth below ground level (ft)

k_p = passive earth pressure coefficient

= $(1 + \sin\phi_f)/(1 - \sin\phi_f)$ for zero angle of wall friction. For values of k_p including the effect of wall friction, refer to charts in standard textbooks or NAVFAC DM-7.

Passive Pressure—Cohesive Soils:

$$p_p = \gamma_s H + 2c \text{ (psf)} \quad (4.3.1.4\text{-}2)$$

where:

γ_s = unit weight of soil (psf)

H = depth below ground level (ft)

c = $Q_u/2$ (psf)

Q_u = undrained unconfined compressive strength in (psf)

Passive Pressure—Mixed Soils:

$$p_p = k_p \gamma_s H + 2c\sqrt{k_p} \text{ (psf)} \quad (4.3.1.2\text{-}3)$$

where:

γ_s = unit weight of soil (psf)

H = depth below ground level (ft)

c = $Q_u/2$ (psf)

k_p = passive earth pressure coefficient

= $(1 + \sin\phi_f)/(1 - \sin\phi_f)$ for zero angle of wall friction. For values of k_p including the effect

C4.3.1.4

Cohesionless Soils—Passive pressure coefficients for various geometries and angles of internal friction and wall friction can be obtained from charts given in many soil mechanics textbooks and handbooks. In computing the passive pressures below the water table, use buoyant unit weight of the soil and add hydrostatic pressure. The angle of internal friction for the soil should be estimated conservatively. Charts are available in textbooks that relate the angle of internal friction to the relative density or standard penetration test values. Seepage gradients will reduce the passive pressure.

Cohesive Soils—The formula given for the passive pressure is for undrained conditions. Pore pressure dissipation can reduce the passive resistance significantly. For long duration exposure, passive pressures should also be evaluated for the drained effective friction angles using the formulas for cohesionless soils and the design based on the lower pressures. Ground water table conditions must also be considered in the analysis of earth pressures.

Mixed Soils—The above commentary for cohesionless and cohesive soils is also applicable to the mixed soils. Hydrostatic pressures in cohesionless layers interbedded in cohesive layers can cause uplift and heaving and reduce passive pressures significantly. The design should consider relief of uplift pressures, as appropriate.

of wall friction, refer to charts in standard textbooks or NAVFAC DM-7.

Q_u = undrained unconfined compressive strength in (psf)

Passive resistance in top 1 ft should be neglected. Design values of cohesion shall be selected conservatively with a minimum factor of safety of 1.5. Effect of soil disturbance at the excavated subgrade shall also be considered. If duration of exposure is sufficient for pore pressure dissipation, design values in cohesive and mixed soils shall be based on effective strength parameters, neglecting the undrained cohesion.

Full passive pressures will be mobilized where ground movements will cause strains of 0.02H to 0.04H for medium to dense cohesionless soils, and 0.02H to 0.04H or more for hard to soft cohesive soils. Where smaller movements are anticipated, computed passive pressures shall be reduced appropriately.

4.3.2—Braced Excavations

For braced retaining structures with two or more levels of bracings, design shall be based on apparent earth pressure diagrams given by empirical methods or any other acceptable earth pressure distribution developed for this purpose. The apparent earth pressure diagrams in Figures 4.3.2-1 and 4.3.2-2 are reproduced from the *LRFD Bridge Design Specification*. Figure 4.3.2-2 shall be used when:

$$\text{stability number} = \gamma H/S_u > 6.0$$

Using Figures 4.3.2-1 and 4.3.2-2, reaction at the bracing levels shall be determined by assuming simple hinges at the bracing points and a fictitious hinge below the cut level. Penetration of sheathing shall be sufficient so that enough passive soil resistance can be developed. The lower hinge point shall depend on the strength of soil, depth of cut, duration, and the type of retention system. For normal soils, this depth would be in the range of 2 to 6 ft below the excavation level and may be assumed at the point of zero net pressure. Wall elements may be designed for the same pressures, assuming hinges at support points.

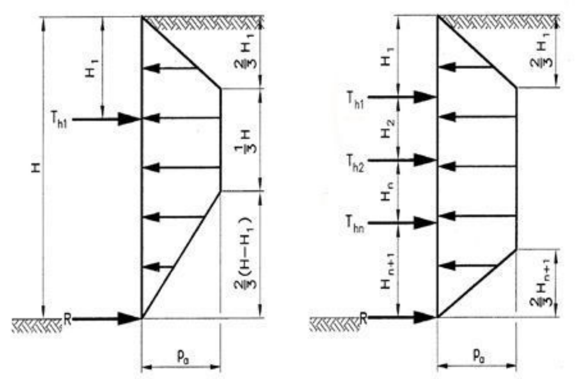
Alternate design methods based on active and passive pressures and staged excavations with continuous wall elements may also be used provided the continuity of wall elements, soil–structure interaction, and deflections during the various stages of excavation are considered.

C4.3.2

Bracing should be designed for various stages of the excavation, corresponding to the cuts necessary to install the braces at each level. The uppermost stage is analyzed for a cantilever condition, using active pressures. The next stage with a single brace is also analyzed using active pressures and passive pressures. The braced case empirical diagrams are generally used for conditions of two or more levels of bracing.

The location of the hinge point for determining reactions at bracing levels may be estimated from the position of net zero pressure (where the passive pressure equals the active or the empirical design pressure). The wall elements must have sufficient embedment below the assumed hinge position to obtain passive reaction greater than the required toe reaction.

The design of braces should include allowances for thermal changes from ambient temperatures, misalignments, and impact from construction activities.



(a) Wall with one level of ground anchors

(b) Walls with multiple levels of ground anchors

Figure 4.3.2-1—Apparent Earth Pressure Distributions for Anchored Walls Constructed from the Top Down in Cohesionless Soils

Notes:

a. $p_a = k_a \gamma_s' H$ for one anchor level

b. $p_a = k_a \gamma_s' H^2/(1.5H - 0.5H_1 - 0.5H_{n+1})$ for multiple anchor levels

c. $k_a = \tan^2(45° - \phi_f/2)$ for $\beta = 0$

d. $k_a = \dfrac{\sin^2(\theta+\phi_f')}{\Gamma[\sin^2\theta \sin(\theta-\delta)]}$ for $\beta \neq 0$

e. $\mathrm{T} = \left[1 + \sqrt{\dfrac{\sin(\phi_f'+\delta)\sin(\phi_f'-\beta)}{\sin(\theta-\delta)\sin(\theta+\beta)}}\right]^2$

f. Surcharge and water pressures must be added to |these earth pressure diagrams.

Notation:

H = final wall height (ft)
k_a = active earth pressure coefficient
ϕ_f = angle of internal friction (degrees)
ϕ_f' = effective angle of internal friction (degrees)
θ = angle of back of wall to the horizontal (degrees)
δ = friction angle between fill and wall (degrees)
γ_s' = effective soil unit weight (kcf)
γ_s = total soil unit weight (kcf)
T = horizontal load in ground anchor (kip/ft)
R = reaction to be resisted by subgrade (kip/ft)
β = slope of backfill surface behind retaining wall: (+) for slope up from wall, (-) for slope down from wall (degrees)

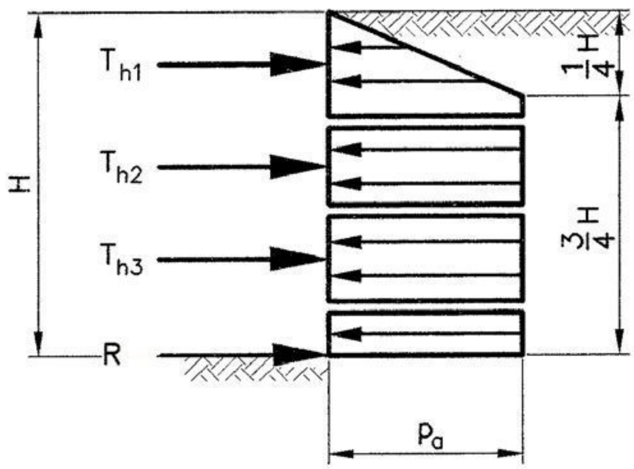


Figure 4.3.2-2—Apparent Earth Pressure Distribution for Anchored Walls Constructed from the Top Down in Soft to Medium Stiff Cohesive Soils

Notes:

a. $p_a = 0.2\gamma_s H$ to $0.4\gamma_s H$ for stiff to hard soils

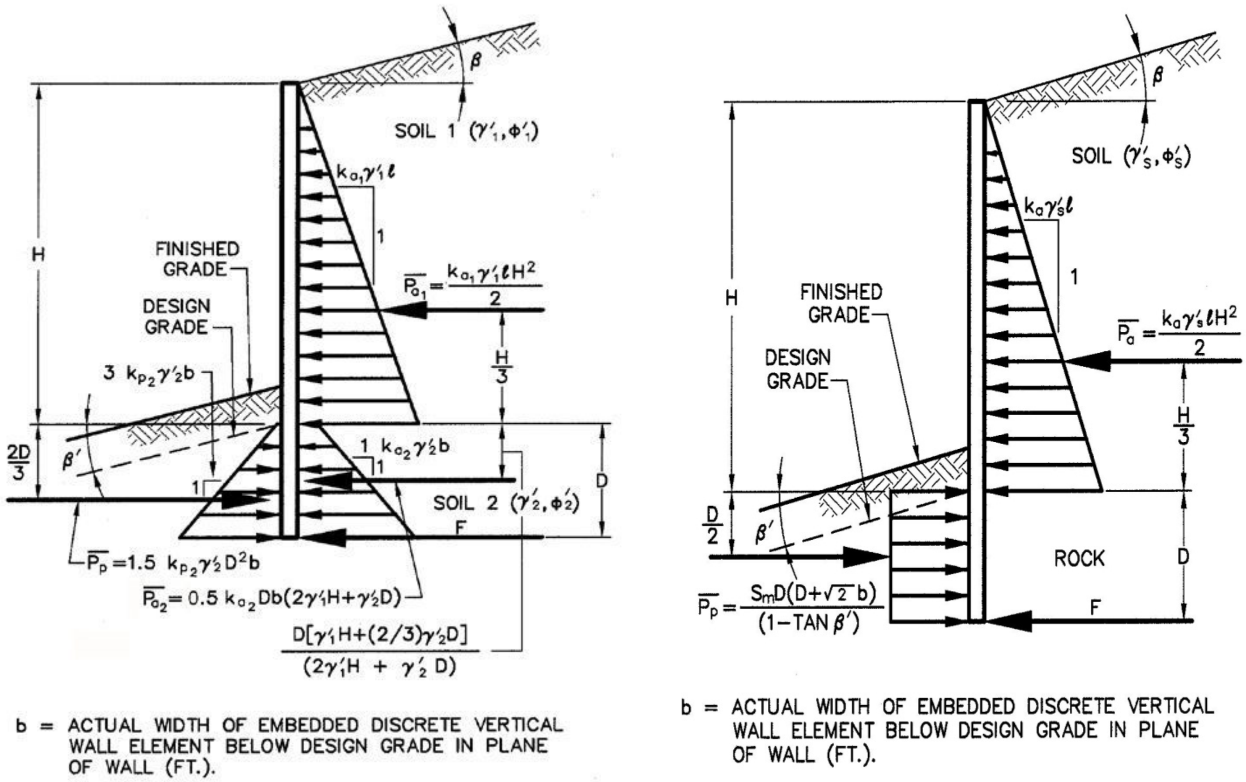
b. $p_a = k_a \gamma_s H$ for soft to medium stiff soils

c. $k_a = 1 - \frac{4S_u}{\gamma_s H} + 2\sqrt{2}\frac{d}{H}\left(\frac{1-5.14S_{ub}}{\gamma_s H}\right) \geq 0.22$

d. Surcharge and water pressures must be added to these earth pressure diagrams.

Notation:

k_a = active earth pressure coefficient
S_u = undrained strength of retained soil (ksf)
S_{ub} = undrained strength of soil below excavation base (ksf)
γ_s = effective soil unit weight (kcf)
H = final wall height (ft)
T = horizontal load in ground anchor (kip/ft)
R = reaction to be resisted by subgrade (kip/ft)



a) Embedment in Granular Soil

b) Embedment in Rock

Figure 4.3.2-3—Unfactored Simplified Earth Pressure Distributions for Permanent Non-Gravity Cantilevered Walls with Discrete Vertical Wall Elements

Notes:

a. For temporary walls embedded in granular soil or rock, see above figure, determine passive resistance, and use diagrams in Figure 4.3.2-5 to determine active earth pressure of retained soil.

b. Surcharge and water pressures must be added to the indicated earth pressures.

c. Forces shown are per vertical wall element.

d. Pressure distributions below the exposed portion of the wall are based on an effective element width of $3b$, which is valid for $l \geq 5b$. For $l < 5b$, refer to Figures 4.3.2-4 and 4.3.2-6 for continuous wall elements to determine pressured distributions on embedded portions of the wall.

e. Refer to Reference 5 for determination of k_a and k_p.

Notation:

γ_s' = effective unit weight of soil (kcf)

b = vertical element width (ft)

l = spacing between vertical wall elements (c/c) (ft)

S_m = shear strength of rock mass (ksf)

p_p = passive resistance per vertical wall element (ksf)

p_a = active earth pressure per vertical wall element (ksf)
β = ground surface slope behind wall: (+) for slope up from wall, (−) for slope down from wall (degrees)
β′ = ground surface slope in front of wall: (+) for slope up from wall, (−) for slope down from wall (degrees)
k_a = active earth pressure coefficient
k_p = passive earth pressure coefficient
ϕ_f = angle of internal friction (degrees)

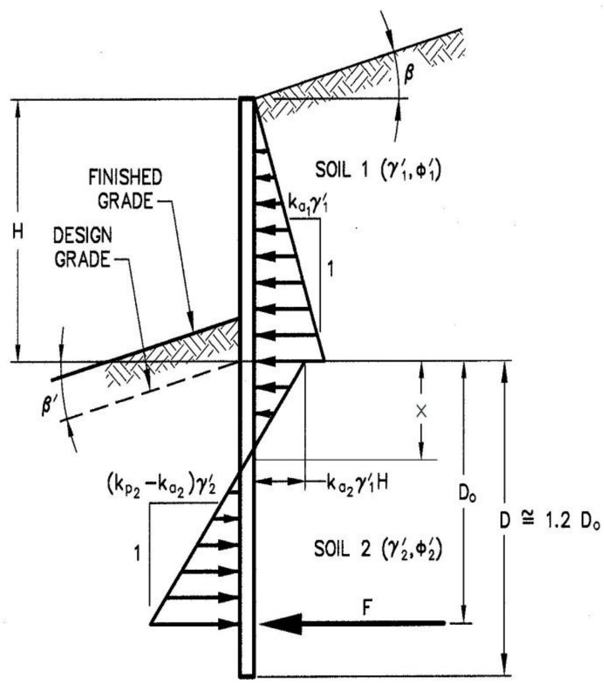
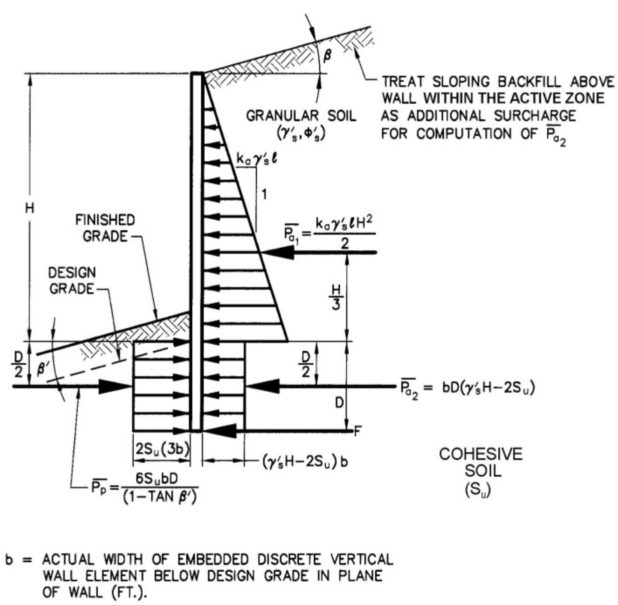


Figure 4.3.2-4—Unfactored Simplified Earth Pressure Distribution and Design Procedures for Permanent Non-Gravity Cantilevered Walls with Continuous Vertical Wall Elements Embedded in Granular Soil Modified after Teng (1962)

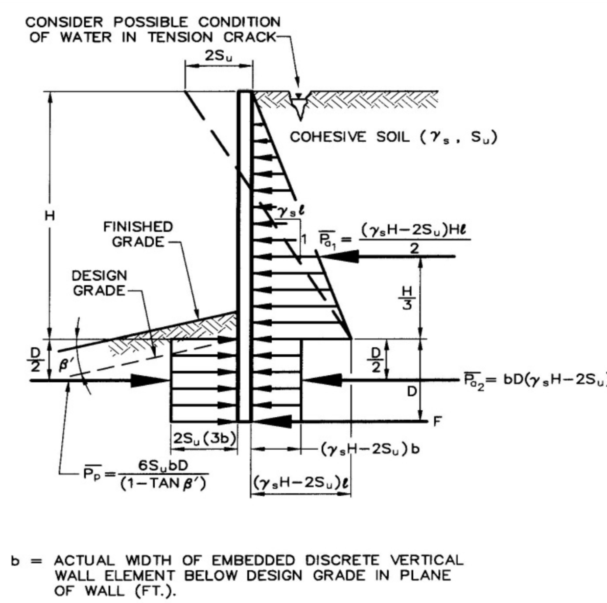
Notes:
a. Surcharge and water pressures must be added to the above earth pressures.
b. Forces shown are per horizontal foot of vertical wall element.

1. Determine the active earth pressure on the wall due to surcharge loads, the retained soil, and differential water pressure above the design grade (refer to AASHTO *Standard Specifications for Highway Bridges* for determination of k_a).

2. Determine the magnitude of active pressure at the design grade ($p^* = k_{a2}\gamma_1' H$) due to surcharge loads, retained soil, and differential water pressure, using the earth pressure coefficient k_{a2}.
3. Determine the value of x = $p^*/\left[\left(k_{p2} - k_{a2}\right)\gamma_2'\right]$ for the distribution of net passive pressure in front of the wall below the design grade (refer to AASHTO *Standard Specifications for Highway Bridges* for determination of k_a and k_p).
4. Sum moments about the point of action of F to determine the embedment (D_0) for which the net passive pressure is sufficient to provide equilibrium.
5. Determine the depth (point α) at which the shear in the wall is zero (i.e., the point at which the areas of the driving and resisting pressure diagrams are equivalent).
6. Calculate the maximum bending moment at the point of zero shear.
7. Calculate the design depth, $D = 1.2D_0$ to $1.4D_0$ for a safety factor of 1.5 to 2.0.



a) Embedment in cohesive soil retaining granular soil



b) Embedment in cohesive soil retaining cohesive soil

Figure 4.3.2-5—Unfactored Simplified Earth Pressure Distributions for Temporary Nongravity Cantilevered Walls with Discrete Vertical Wall Elements

Notes:

a. For temporary walls embedded in granular soil or rock, refer to Figure 4.3.2-3 to determine passive resistance and use diagrams in above figure to determine active earth pressure of retained soil.
b. Surcharge and water pressures must be added to the indicated earth pressures.
c. Forces shown are per vertical wall element.
d. Pressure distributions below the exposed portion of the wall are based on an effective element

width of $3b$, which is valid for $1 \geq 5b$. For $1 < 5b$, refer to Figures 4.3.2-4 and 4.3.2-6 for continuous wall elements to determine pressured distributions on embedded portions of the wall

e. The ratio of total overburden pressure to undrained shear strength, N_s, should be < 3 at wall base.

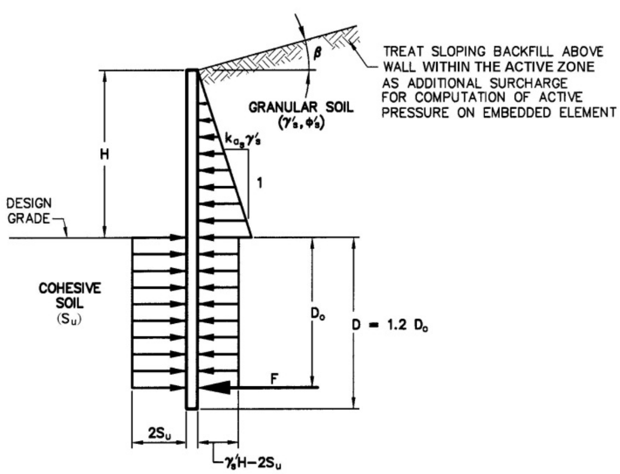
f. The active earth pressure shall not be less than 0.25 times the effective overburden pressure at any depth, or 0.035 ksf/ft of wall height, whichever is greater.

g. In Figure 4.3.2-5(b), a portion of negative loading at the top of the wall due to cohesion is ignored and hydrostatic pressure in a tension crack should be considered, but is not shown in the figure.

h. Refer to Reference 5 for determination of k_a.

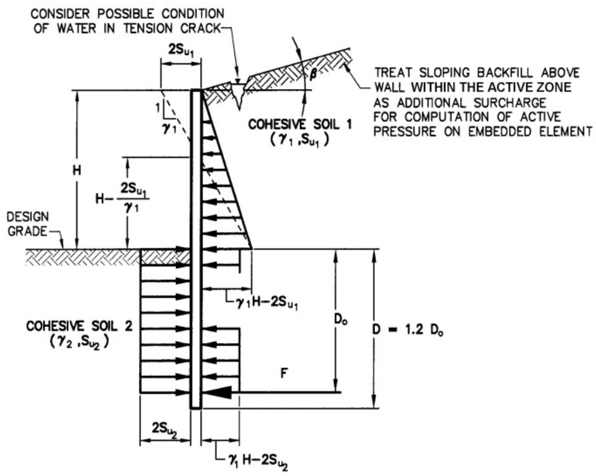
Notation:

γ'_s = effective unit weight of soil (kcf)
b = vertical element width (ft)
l = spacing between vertical wall elements (c/c) (ft)
S_u = undrained shear strength of cohesive soil (ksf)
p_p = passive resistance per vertical wall element (ksf)
p_a = active earth pressure per vertical wall element (ksf)
β = ground surface slope behind wall: (+) for slope up from wall, (—) for slope down from wall (degrees)
β' = ground surface slope in front of wall: (+) for slope up from wall, (—) for slope sown from wall (degrees)
k_a = active earth pressure coefficient
ϕ_f = angle of internal friction (degrees)



a) Embedment in cohesive soil retaining granular soil

Figure 4.3.2-6—Unfactored Simplified Earth Pressure Distributions for Temporary Non-Gravity Cantilevered Walls with Continuous Vertical Wall Elements [modified after Teng (1962)]



b) Embedment in cohesive soil retaining cohesive soil

Figure 4.3.2-6 (cont.)—Unfactored Simplified Earth Pressure Distributions for Temporary Non-Gravity Cantilevered Walls with Continuous Vertical Wall Elements [modified after Teng (1962)]

Notes:

a. For walls embedded in granular soil, refer to Figure 4.3.3-4 and use above diagram for retained cohesive soil when appropriate.
b. Refer to Figure 4.3.2-4 for simplified design procedure.
c. Surcharge and water pressures must be added to the above earth pressure.
d. Forces shown are per horizontal foot of vertical wall element.
e. The ratio of total overburden pressure to undrained shear strength, N_s, should be < 3 at wall base.
f. The active earth pressure shall not be less than 0.25 times the effective overburden pressure at any depth, or 0.035 ksf/ft of wall height, whichever is greater.
g. Refer to Reference 5 for determination of k_a.

Notation:

γ_s' = effective unit weight of soil (kcf)
S_u = undrained shear strength of cohesive soil (ksf)
β = ground surface slope behind wall: (+) for slope up from wall, (-) for slope down from wall (degrees)
k_a = active earth pressure coefficient