Chapter 6
Structural Design

6-1. Forces for Design

Design penetration of the piling is based on a factor of safety for stability applied to soil strengths. To avoid compounding factors of safety, the sheet piling and wales are designed to resist forces produced by soil pressures calculated using a factor of safety of 1 for both active and passive pressures. Consequently, the analyses for soil pressures (Chapter 4) and system stability (Chapter 5) must be repeated with full soil strength properties including consideration of usual, unusual, and extreme loading conditions. The sizes of the sheet piling and wales are determined from the net pressure distributions, depth of penetration, and assumed structural supports as illustrated in Figures 6-1 and 6-2.

a. Cantilever wall. Bending moments and shears are calculated under the assumption that the wall is a cantilever beam fixed at the bottom of the wall, Figure 6-1.

b. Anchored wall.

(1) Structural analysis. Bending moments, shears, and anchor force are calculated under the assumption that the wall is a beam with simple supports at the anchor elevation and at the bottom of the wall (Figure 6-2). With the bottom of the wall at the penetration consistent with a factor of safety of 1, the lateral reaction at the bottom support will be zero and the lateral reaction at the upper support will be the horizontal component of the anchor force.

(2) Total anchor force. When the tie rods are installed perpendicular to the plane of the wall, the design tie rod force will be equal to the lateral reaction at the upper support (Figure 6-2). When the tie rods are inclined, Figures 5-11 and 6-3, the total tie rod force is obtained from

$$T_A = T_{\Delta H} \,/\, \cos(\alpha) \qquad (6\text{-}1)$$

where

$T_{\Delta H}$ = upper simple support reaction

α = angle of tie rod inclination

Tie rod inclination further induces axial force in the sheet piling given by

$$T_{\Delta V} = T_{\Delta H} \tan(\alpha) \qquad (6\text{-}2)$$

The axial component of inclined anchor force and any external axial loads are assumed to be resisted by a vertical reaction at the lower simple support.

6-2. Deflections

When the material and cross section for the piling have been selected, structural deflections are calculated using the assumed support conditions shown in Figures 6-1 and 6-2. It must be emphasized that the deflections thus determined are representative of the relative deformation of the wall. Total system displacements will be comprised of a combination of structural deformations and rotations and translations of the entire wall/soil system.

6-3. Design of Sheet Piling

The structural analyses described in paragraph 6-1 provide values of maximum bending moment (Mmax), maximum shear (Vmax), and anchor force per foot of wall to be sustained by the piling.

a. Materials and allowable stresses for sheet piling.

(1) Steel. Allowable stresses for steel sheet piling for usual load conditions are:

Combined bending and axial load: $f_b = 0.5\, f_y$
Shear: $f_v = 0.33\, f_y$

where f_y is the yield stress of the steel. The 0.5 times f_y for combined bending and axial load represents 5/6 of the American Institute of Steel Construction (AISC) recommended values and reflects the Corps' design procedures for hydraulic steel structures. For unusual loadings the allowable stresses may be increased by 33 percent. For extreme loadings the allowable stresses may be increased by 75 percent.

(2) Prestressed concrete piles. Design must satisfy both strength and serviceability requirements. Strength design should follow the basic criteria set forth in ACI 318 (1983), except the strength reduction factor (ϕ) shall be 0.7 for all failure modes and a single load factor for 1.9 shall be used for all loads. The specified load and strength reduction factors provide a safety factor equal

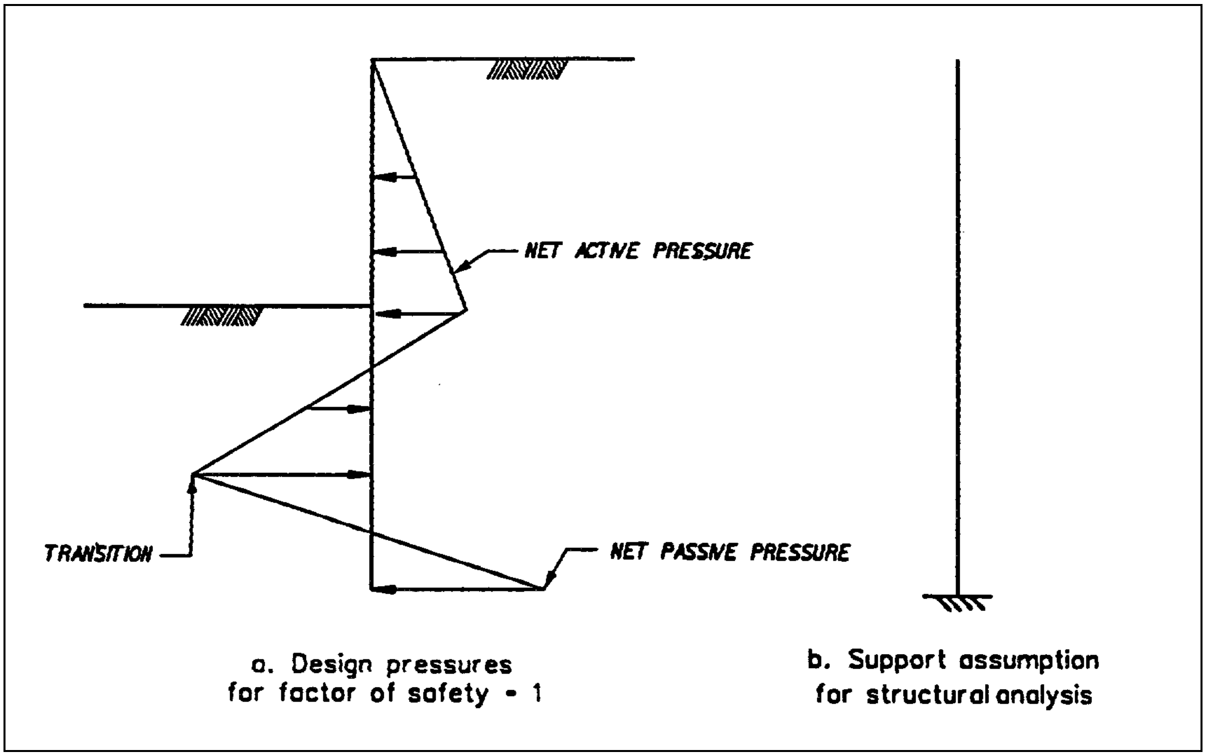

Figure 6-1. Pressures and supports for structural design of cantilever walls

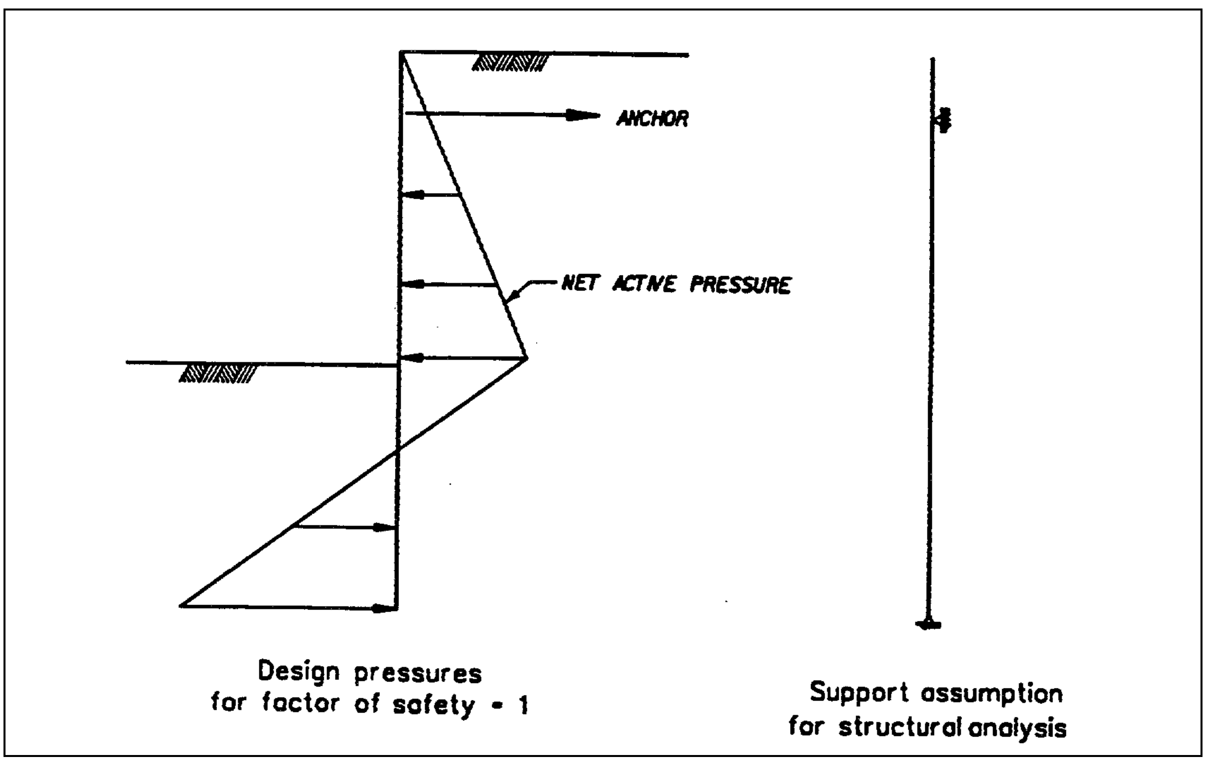

Figure 6-2. Pressures and supports for structural design of anchored walls

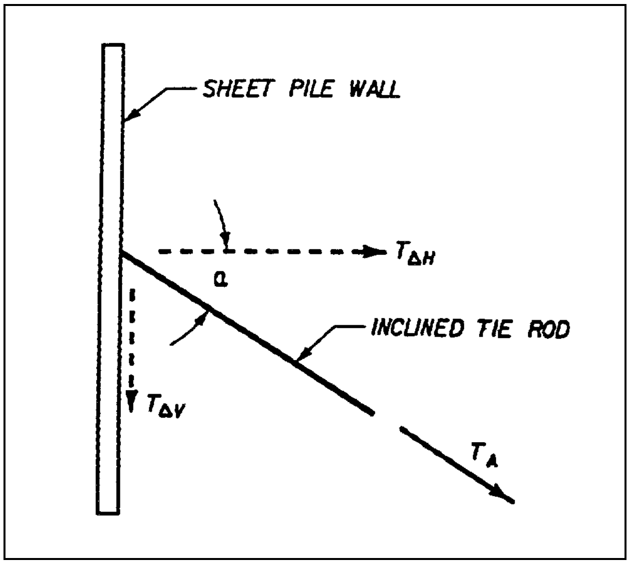

Figure 6-3. Anchor force components for inclined anchors

to 2.7. Control of cracking in prestressed piles is achieved by limiting the concrete compressive and tensile stresses, under service load conditions, to the following values:

Uniform Axial Tension	0
Bending (Extreme Fibers)	
Compression	$0.40\, f'_c$
Tension	0

f'_c = compressive strength of concrete

(3) Reinforced concrete. Reinforced concrete piles shall be designed in accordance with EM 1110-2-2104.

(4) Aluminum. Basic allowable stresses for aluminum piles will be the lesser of the minimum yield strength divided by a factor of safety of 1.95 or the minimum ultimate tensile strength divided by a factor of safety of 2.3. Additional information can be found in the latest edition of the Aluminum Association's "Specifications for Aluminum Structures" (1976).

(5) Wood. Stresses for wood piles should be in accordance with "The National Design Specification for Wood Construction" (National Forest Products Association 1986), depending on species and grade.

(6) Other materials. Sheet piles composed of fiberglass, vinyl, and PVC are usually available as very flexible sections with low moment capacities. Their use should be limited to very low wall heights subjected to light loads. Sectional geometries and material properties should be specified for each application, and conformance of the piling should be verified by a qualified testing laboratory. As a minimum, the designer should specify acceptable values of the following properties determined by the referenced ASTM standards: water absorption (ASTM D 570 (1981)); tensile strength (ASTM D 638 (1989d)); flexural strength and modulus of elasticity (ASTM D 790 (1986b)); compressive strength (ASTM D 695 (1990)); and barcol hardness (ASTM D 2583 (1987)). If a wall of these materials is expected to be exposed to sunlight or extreme heat, the ultraviolet and thermal properties of the material should be investigated and adequate protection provided.

b. Material selection. Selection of the material for the sheet piling should be based on economics, aesthetics, the function of the wall, and the difficulty of installation. Life cycle cost analyses should be performed for various alternatives to select the most viable solution. Steel is the most frequently used material because of its relatively high strength-weight ratio and its availability in a variety of shapes and sizes. Aluminum piling may be advantageous in a corrosive environment where additional thickness of steel is required to compensate for section loss.

c. Required pile cross section for cantilever walls. The sheet pile section must provide the following minimum sectional properties after allowance for possible loss of material due to corrosion, abrasion, or other detrimental effects.

(1) Cantilever walls of materials other than concrete.

(a) Flexure. The minimum section modulus is given by

$$S_{min} = M_{max} / f_b \tag{6-3}$$

where

S_{min} = section modulus per foot of wall

M_{max} = maximum bending moment per foot of wall

f_b = allowable bending stress appropriate to the material and loading condition

(b) Shear. The minimum "shear area" is given by

$$A_{v,\min} = V_{\max} / f_v \quad (6\text{-}4)$$

where

$A_{v,\min}$ = minimum "shear area" per foot of wall

$V_{\max}$ = maximum shear per foot of wall

f_v = allowable shear stress appropriate to the material and loading condition

The shear area for Z-shaped sections may be taken as

$$A_v = t_w \, h / w \quad (6\text{-}5)$$

where

t_w = thickness of the web portion of the Z

h = height of the Z

w = width of the section

For wood piles the shear area may taken as two-thirds of the rectangular area per foot of wall.

(c) Combined loads. Where external effects (e.g. a concrete cap) may produce an axial load in the pile, the minimum section modulus is given by

$$S_{\min} = [M_{\max} + P(y_p + e_p)] / f_b \quad (6\text{-}6)$$

where

P = applied axial load

y_p = lateral deflection at the point of application of P

e_p = eccentricity of the point of application of P from the centroidal axis of the piling (may be positive or negative)

It is recommended that the value of $P(y_p + e_p)$ be less than $M_{\max}/10$ unless it is demonstrated that buckling of the piling is unlikely.

(2) Cantilever concrete walls. Cross sections for walls of prestressed or reinforced concrete shall be proportioned for maximum bending moment, shear and any axial load in accordance with paragraphs 6-3a(2) and (3).

d. Required cross section for anchored walls. The pile section must provide the minimum sectional properties after allowance for loss of material due to corrosion, abrasion, and other deleterious effects.

(1) Moment reduction for anchored walls. Rowe (1952, 1955a and b, 1956, 1957a and b) demonstrated that the Free Earth method overestimates the maximum bending moment in anchored walls with horizontal tie rods. The reduced bending moment for design is given by

$$M_{des} = M_{\max} R_m \quad (6\text{-}7)$$

where

$M_{\max}$ = maximum bending moment predicted by the Free Earth method

R_m = reduction factor depending on wall geometry, wall flexibility, and foundation soil characteristics

(a) Moment reduction factor for granular foundation soils. When the soil below the dredge line is granular, the magnitude of the reduction factor R_m is a function of a flexibility number given by

$$\rho = H^4 / EI \quad (6\text{-}8)$$

where

H = total length of the sheet piling (ft)

E = modulus of elasticity of the pile material (psi)

I = moment of inertia (in^4) per foot of wall

Curves of R_m are given in Figure 6-4 for "loose" and "dense" foundation material and several system geometries.

(b) Moment reduction factor for cohesive foundation soils. Moment reduction factors for piles in homogeneous cohesive soils also depend on the stability number given by

$$S_n = 1.25\ (c/p_v) \quad (6\text{-}9)$$

where

c = cohesive strength of the soil

p_v = effective vertical soil pressure on the retained side of the wall at the elevation of the dredge line

Curves for R_m are given for various combinations of system parameters in Figure 6-4.

(2) Anchored walls of materials other than concrete.

(a) Flexure. The minimum required section modulus is given by

$$S_{min} = [M_{des} + T_{av}(y_m + e_a)]/f_b \quad (6\text{-}10)$$

where

M_{des} = reduced maximum bending moment

T_{av} = axial component of an inclined anchor force

y_m = computed deflection at the elevation of maximum moment

e_a = eccentricity due to anchor connection details (may be positive or negative, see discussion of design of wales, paragraph 6-3e).

(b) Shear. The required shear area of the section is calculated as described in paragraph 6-4c(1)(b).

(c) Combined Loading. When external effects other than an inclined anchor produce axial loading on the sheet piling, the minimum section modulus is given by

$$S_{min} = [M_{max} + T_{av}(y_m + e_a) + P(y_m - y_p + e_p)] / f_b \quad (6\text{-}11)$$

where

M_{max} = maximum bending moment from the Free Earth method (unreduced)

T_{av} = axial component of the anchor force

y_m = computed deflection at the elevation of *Mmax*

e_a = eccentricity of the anchor force

P = additional axial load

y_p = deflection at the point of application of P

e_p = eccentricity of the point of application of P

It is recommended that $T_{av}(y_m + e_a) + P(y_m - y_p + e_p)$ be less than $M_{max}/10$ unless it is demonstrated that buckling is unlikely.

(3) Anchored walls of concrete. Cross sections of prestressed or reinforced concrete walls shall be proportioned in accordance with the requirements specified in paragraphs 6-3.a(2) and (3).

e. Design of tie rods and wales. A majority of failures of anchored walls occur in the tie rods, wales, and anchors. Typical wale and tie rod configurations are shown in Figure 6-5. All connections in these components should be bolted and designed in accordance with the American Institute of Steel Construction (AISC) Specifications for Bolted Connections (Research Council on Structural Connections 1985). Because of the critical nature of the anchorage, the design of the tie rods and wales should be based on the anchor force calculated from the stability analysis with the factor of safety applied to the passive soil pressure as described in Chapter 5.

(1) Tie rod design. Tie rods are commonly steel rods with threaded connections including a turnbuckle

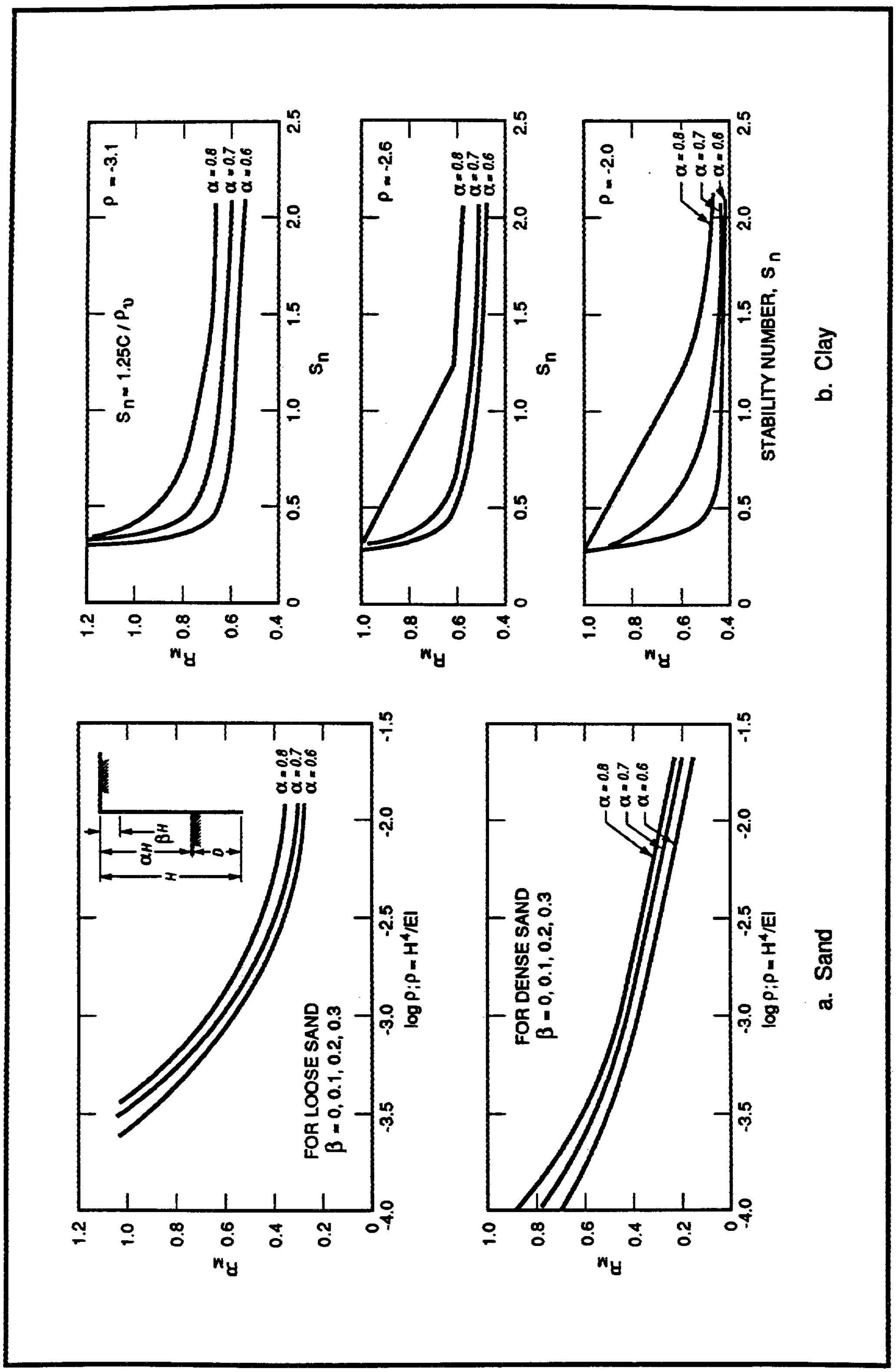

Figure 6-4. Rowe's moment-reduction coefficients (after Bowles 1982)

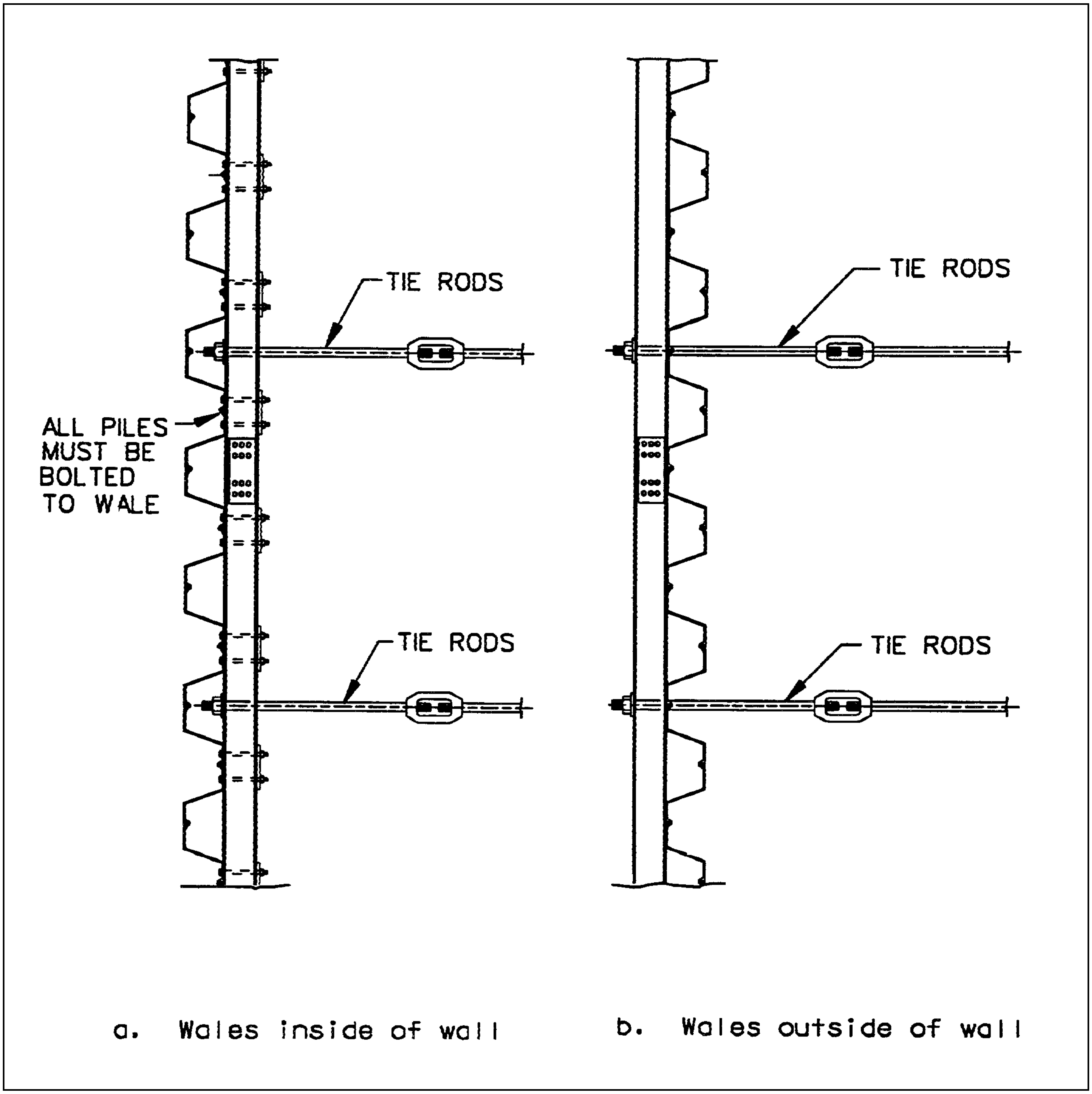

Figure 6-5. Typical wale configurations

for slack removal, Figure 6-5. Upset threads are recommended.

(a) Tie rod area. The force sustained by each tie rod is given by

$$T_{rod} = T_a\ S \qquad (6\text{-}12)$$

where

T_a = anchor force per foot of wall from the stability analysis (see also Figure 6-3)

S = spacing between adjacent tie rods

The minimum required net area for a tie rod is

$$A_{net} = T_{rod}\ /\ f_t \qquad (6\text{-}13)$$

where

A_{net} = available net tension area of the threaded rod

f_t = allowable tensile stress for the rod material according to

Steel rods: $f_t = 0.4\ f_y$

Aluminum rods: f_t is the smaller of minimum yield strength divided by 2.5 or ultimate tension strength divided by 3.0.

(b) Tie rod yield strength. The tie rod yield strength is the product of A_{net} times f_y for steel rods and A_{net} times minimum yield strength for aluminum rods. The design capacity of the anchor wall or deadman, Chapter 5, should be sufficient to develop the tie rod yield strength.

(c) Tie rod support. The tie rod design is based on the assumption that the rod is straight and centrically loaded. The rod must be protected against any influence which tends to induce bending in the rod. Careful attention must be directed to the tie rod-to-wale connection and tie rod-to-anchor connection to eliminate any eccentricities at these points. The tie rod must also be protected against any potential consolidation in the backfill. The geotechnical engineer should evaluate any potential settlement due to consolidation and the tie rod should be encased in a conduit of sufficient diameter to permit backfill consolidation without contact between the rod and conduit.

(2) Design of tendons for grouted anchors. Tendons for grouted anchors may be either rods or cables. Rods used as tendons should be designed according to the preceding strength requirements for tie rods. When cables are used, the size should be evaluated based on manufacturer's specifications for the sum of the anchor force (T_{rod}, Equation 6-12) and any alignment loads.

(3) Design of wales. Wales which transfer the tie rod forces to the sheet piling are usually composed of back-to-back channels as illustrated in Figures 6-5. From a load transfer standpoint, the most desirable position of the wales is on the outside of the piling, Figure 6-5a. When the wales are placed on the inside face, Figure 6-5b, each individual sheet pile must be bolted to the wale. The wale is assumed to act as a continuous flexural member over simple supports at the tie rod locations. The maximum bending moment in the wale may be approximated as

$$M_{max} = T_{ah}\ S^2\ /\ 10 \qquad (6\text{-}14)$$

where

T_{ah} = anchor force per foot of wall

S = distance between adjacent tie rods

Sizing of the wale cross section, wale-to-piling connections, and tie rod-to-wale connections shall be in accordance with the current *Manual of Steel Construction*, "Allowable Stress Design," as published by AISC (1989) with the exception that allowable stresses shall be limited to five-sixths of those specified in the design codes. The design should take into consideration such factors as web crippling and possible torsion, biaxial bending, and shear produced by inclined tie rods.