Technical Supplement 14R

Design and Use of Sheet Pile Walls in Stream Restoration and Stabilization Projects

Issued August 2007

Cover photo: Piles made of wood, steel, or concrete may be needed to stabilize streambanks where bridges, roads, and property boundaries are restrictive.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

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Purpose

This technical supplement provides an introduction to the use of sheet pile, types of walls, sheet pile materials, classical method of design for wall stability, structural design, specification, and installation of sheet pile for stream restoration and stabilization projects.

This technical supplement describes typical applications for cantilever sheet pile wall in stream restoration and stabilization projects, types of sheet pile material, loads applied to the sheet pile, failure modes, design for cantilever wall stability, structural design of the piles, and some construction considerations. It does not address stream stability; hydraulic analyses of the streamflow; geotechnical analyses and slope stability of the stream slopes; or the ecological, aesthetic, or geomorphic consequences of the use of sheet pile.

Introduction

Sheet pile may be used in a variety of applications for stream restoration and stabilization. It is typically used to provide stability to a stream, stream slopes, or other constructed structures in high risk situations. Typical applications of sheet pile include toe walls, flanking and undermining protection, grade stabilization structures, slope stabilization, and earth retaining walls. While sheet pile can be combined with soil bioengineering techniques, it does have some ecologic and geomorphic disadvantages. Stream restoration and stabilization may require the use of structural measures to provide lateral or vertical stability to the stream. Structural measures include concrete retaining walls, drop structures, and sheet pile walls. These measures result in a statically stable stream within the stabilized area and are useful in arresting unacceptable lateral stream migration and local vertical instability. Structural measures may be used when vegetation and other soil bioengineering practices are not stable under the stress or duration of the design event or wherever the consequences of any movement of the banks are unacceptable.

Applications

Sheet pile walls may be used in a variety of applications for stream bank stabilization and restoration projects such as:

- toewall for scour protection (fig. TS14R–1)
- flanking and undermining protection (fig. TS14R–2)
- streambed grade stabilization (fig. TS14R–3)
- bank slope stability (fig. TS14R–4)
- bank retaining walls (fig. TS14R–5)

Figure TS14R–1 Toewall for scour protection cross section

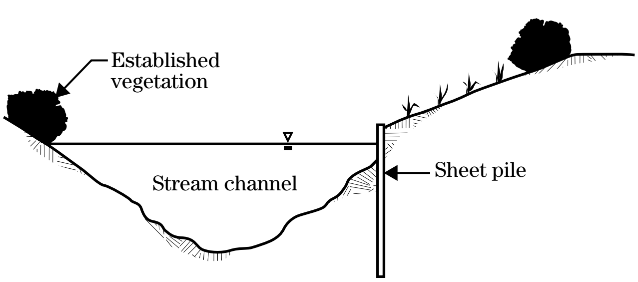


Figure TS14R–2 Flanking and undermining protection profile

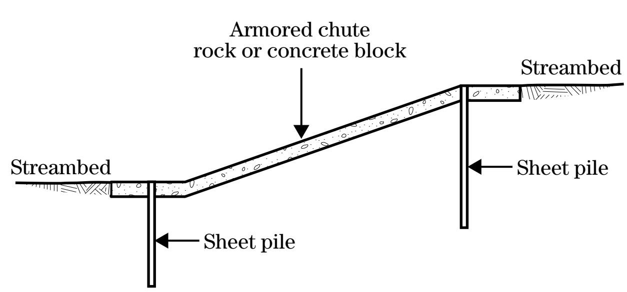


Figure TS14R–3 Streambed grade stabilization profile

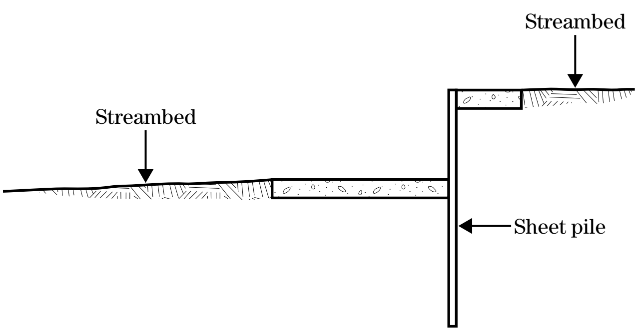


Figure TS14R–4 Bank slope stability cross section

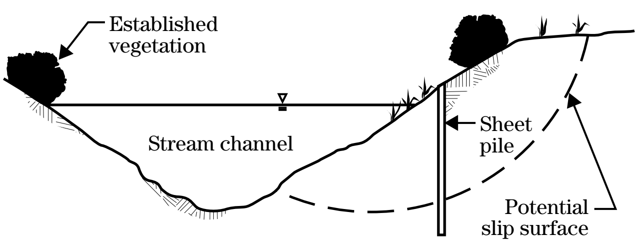
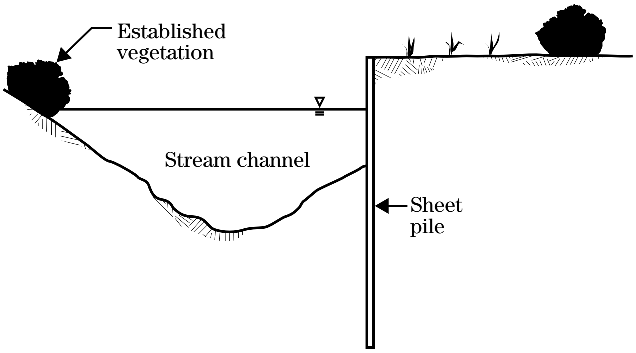


Figure TS14R–5 Bank retaining wall cross section



Types of sheet pile walls

Sheet pile walls may be cantilever or anchored walls. Figure TS14R–6 illustrates both a cantilever sheet pile wall and an anchored sheet pile wall. Cantilever walls derive support from adequate embedment below the stream channel. Steel cantilever walls are limited to wall heights of 15 to 20 feet, while vinyl cantilever walls are limited to 6 to 10 feet. An anchored wall is typically required when the wall height exceeds that suitable for a cantilever wall. Anchored sheet pile walls derive support from embedment in the soil and the anchor force(s) applied to the piling wall.

Materials

Steel

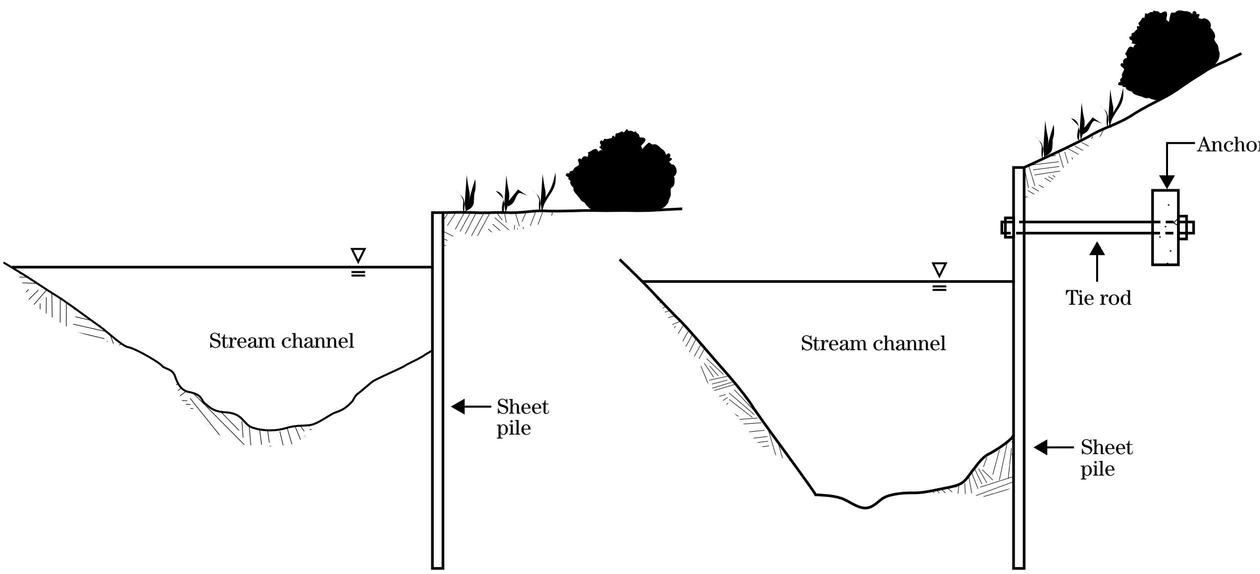
Steel sheet pile is available in various shapes (types), sizes, weights, and steel grades. Z-type piles and American Society for Testing and Materials International (ASTM) A572, Grade 50 are the most common.

Sheet pile may be hot-rolled or cold-rolled piles (fig. TS14R–7 (U.S. Army Corps of Engineers (USACE), 1994c). Hot-rolled piles are formed into the final shape with the interlocks, while the steel is in the molten state. Cold-rolled piles are fabricated into the final shape from flat plate steel. The interlocks for hot-rolled piles are stronger than cold-formed pile interlocks and may allow easier and straighter driving in hard driving conditions and allow less soil migration though the interlocks. Typically, less seepage and material loss are allowed through hot-rolled interlocks. Cold-rolled piles are usually acceptable for stream restoration and stabilization projects. Material specifications often allow either hot-rolled or cold-rolled piles.

Concrete

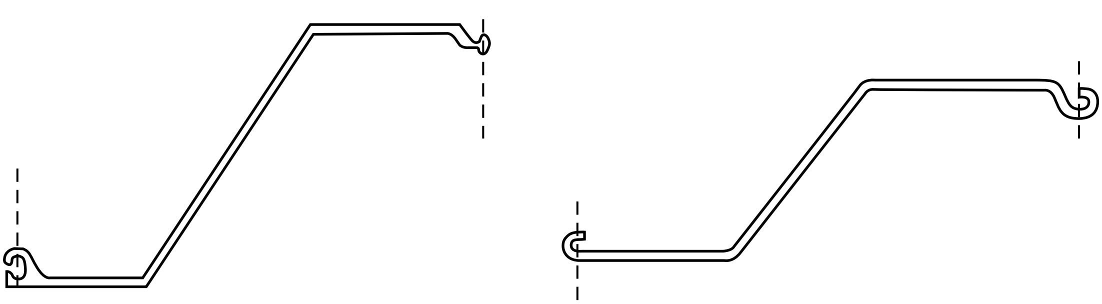
Concrete piles are precast and often prestressed, with a wall thickness of 6 to 12 inches and widths of 30 to 48 inches. The joints may be tongue-and-groove or grouted (fig. TS14R–8 (USACE 1994c)).

Figure TS14R–6 Sheet pile



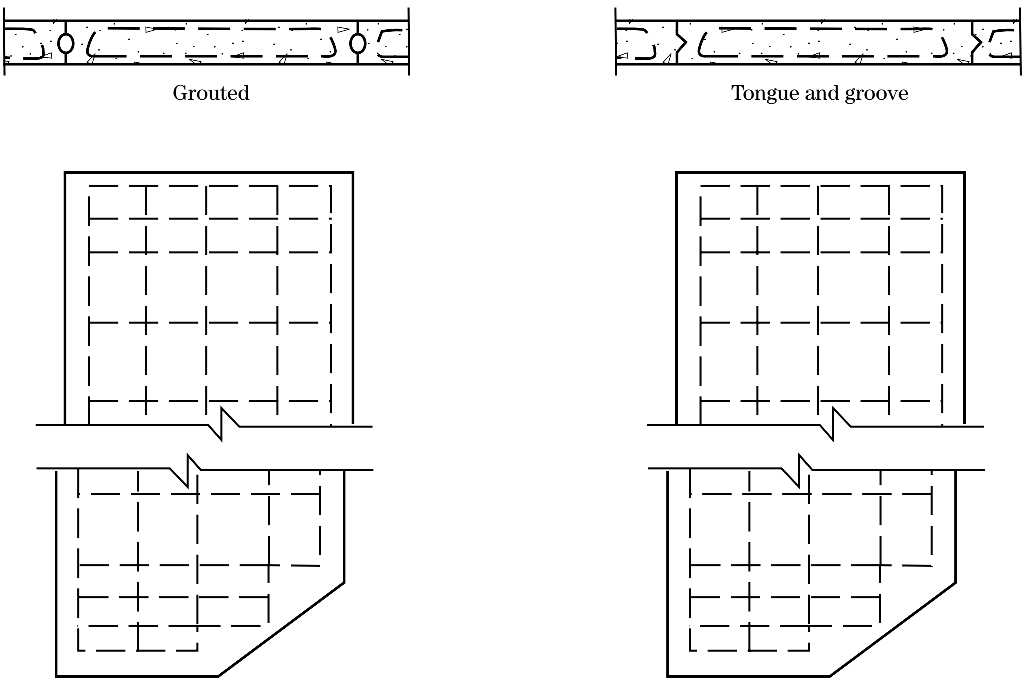
Cantilever wall **Anchored wall**

Figure TS14R–7 Sheet pile section



a. Hot-rolled Z-section **b. Cold-rolled Z-section**

Figure TS14R–8 Concrete piles



Wood

Wood piles may be either independent sheets or tongue-and-groove interlocking sheets (fig. TS14R–9 (USACE 1994c)). Wood piles are used on short wall heights and often anchored with wood walers and vertical wood piles. All wood components should be treated to reduce rot or damage due to wood-destroying insects or water borers.

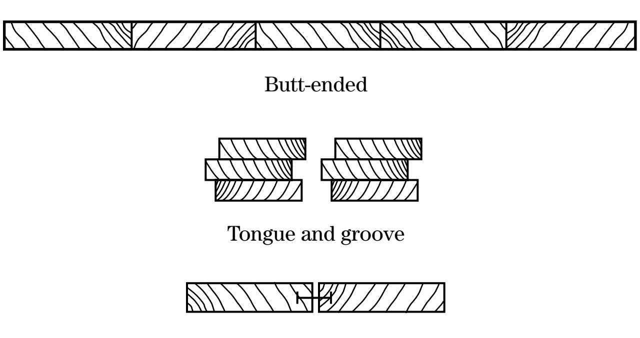
Vinyl

Vinyl sheet pile is available in sections of similar shape to Z-shaped steel sheet pile. Vinyl has lower strength and modulus of elasticity than steel and is, therefore, limited to lower wall heights or anchored walls. Vinyl sheet pile may be manufactured by monoextrusion of all virgin material or coextrusion of recycled material, coextruded with a virgin material coating to provide resistance to ultraviolet light.

Fiber reinforced polymer

Sheet piling may also be manufactured of a synthetic fiber-reinforced polymer (FRP). This type of sheet pile is also referred to as fiberglass or composite sheet pile. A FRP product consists of fiber reinforcement and a polymer resin matrix. The fiber reinforcement typically consists of glass reinforcing fibers. Because of the method of manufacturing, the mechanical properties (strength, modulus of elasticity) may vary with orientation. Due to the potential strength of FRP sheet pile and its resistance to corrosion, FRP could be considered for applications requiring wall heights higher than allowed for vinyl sheet pile or for areas with high corrosion potential for steel. The required strength, modulus of elasticity, and anisotropic nature of the material must be considered in the design.

Figure TS14R–9 Wood pile sheets



Soil properties

The shear strength of soils may vary depending on the rate that load is added to the soil, duration of the load, whether a previous load has been exerted on the soil (in particular for overconsolidated clays), and the permeability of the soil. Shear strength parameters are often characterized as undrained and drained parameters. The terms undrained and drained are not a description of the water level in the soils, but rather a description of the pore pressure condition in the soil when it is loaded. An undrained condition (also called short-term, quick, total stress, or unconsolidated-undrained) assumes that pore pressures will develop due to a change in load. The assumption is that the pore pressures that develop are not known and must be implicitly considered in the methods used to analyze soils for this condition.

A drained condition (also called long term, slow, effective stress, or consolidated-drained) implies that either no significant pore pressures are generated from the applied load or that the load is applied so slowly that the pressure dissipates during the slowly applied loading.

Coarse-grain soils

Coarse-grain soils include sands, gravels, and nonplastic silts of high enough permeability that excess pore pressures do not develop as a result of a change in loading. Soils with a permeability of 1×10^{-4} centimeters per second or greater are often assumed to have permeability rates high enough so that excess pore pressures do not develop. The shear strength of coarse-grain soils is estimated from a consolidated-drained (CD) or consolidated-undrained condition with pore pressure measurements (CU´) shear tests. The shear strength may also be estimated from *in situ* tests such as standard penetration tests or cone penetration tests. The drained shear strength applies to both short-term and long-term load conditions. Typical soil properties for coarse-grain materials are shown in table TS14R–1.

Fine-grain soils

Fine-grain soils such as clays and plastic silts are more complex. They have a low permeability, and shear strength of these materials varies with duration of load. They have the potential to develop excess pore pressure due to changes in loading. If a soil has low permeability and experiences a fast change in load, it will exhibit undrained shear strength parameters. If the load is maintained for a sufficient period of time, the soil will exhibit drained shear stress parameters. Analyses in fine-grain soils should consider both undrained and drained conditions, with the most critical condition governing the design.

For overconsolidated clay soils that contain fissures and slickensides, the design of a sheet pile wall should consider the fully softened shear strength. If the wall is being placed to stabilize a recent slide, the residual shear strength should be considered. Typical soil properties for fine-grain materials are shown in table TS14R–1. Tables TS14R–2 and TS14R–3 provide the description of coarse-grain soil density and fine-grain soil consistency. Figure TS14R–10 illustrates the empirical correlation between effective phi angle and PI (USACE 1994c) A more detailed treatment of soil properties is provided in NEH654 TS14A.

Table TS14R–1 Estimated soil properties

Soil type 1/	Moist unit weight lb/ft^3	Sat. unit weight lb/ft^3	Undrained shear strength properties		Drained shear strength properties		Angle of wall friction (steel pile) δ	Wall/soil adhesion 3/ lb/ft^2
			Cohesion lb/ft^2	Angle of internal friction ϕ	Cohesion lb/ft^2	Angle of internal friction ϕ		
Loose sand	95–125	120–130	0	28	0	28	0.5 × ϕ	0
Medium dense sand	110–130	125–135	0	32	0	32	0.5 × ϕ	0
Dense sand	110–140	130–140	0	38	0	38	0.5 × ϕ	0
Very soft clay	85–100	85–100	0–250	0	0	2/	0.5 × ϕ	0–250
Soft clay	100–120	100–120	250–500	0	0	2/	0.5 × ϕ	250–500
Medium clay	110–125	110–125	500–1,000	0	0	2/	0.5 × ϕ	500–750
Stiff clay	115–130	115–130	1,000–2,000	0	50–100	2/	0.5 × ϕ	750–950
Very stiff clay	120–140	120–140	2,000–4,000	0	100	2/	0.5 × ϕ	950
Hard clay	>130	>130	>4,000	0	100	2/	0.5 × ϕ	950

Compiled from USACE, EM 1110–2–2504, Design of Sheet Pile Walls; Pile Buck, Inc. Steel Sheet Piling Design Manual; and NAVFAC DM –7.2, Foundations and Earth Structures
1/ See tables TS14R–2 and TS14R–3 for qualitative descriptions of soil types.
2/ See figure TS14R–10 (USACE 1994c).
3/ Wall/soil adhesion is typically 0 for drained (long-term) conditions.

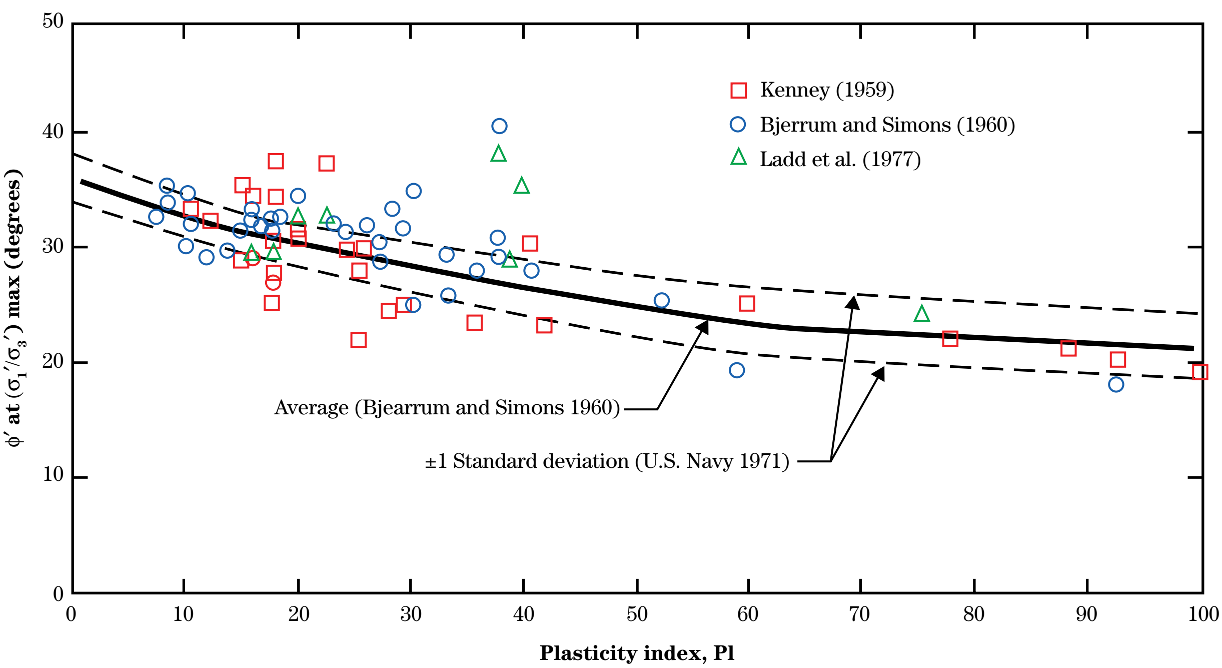
Table TS14R–2 Description of coarse-grain soil density

Density description	Evaluation/description
Very loose	A 1/2-in rod can be pushed easily by hand into soil
Loose	Soil can be excavated with a spade. A 2-in square wooden peg can easily be driven to a depth of 6 in
Medium dense	Soil is easily penetrated with a 1/2-in rod driven with a 5-lb hammer
Dense	Soil requires a pick for excavation A 2-in square wooden peg is hard to drive to a depth of 6 in
Very dense	Soil is penetrated only a few centi-meters with a 1/2-in rod driven with a 5-lb hammer

Table TS14R–3 Description of fine-grain soil consistency

Saturated consistency	Evaluation/description
Very soft	Thumb will penetrate greater than 1 in. Soil is extruded between fingers
Soft	Thumb will penetrate about 1 in. Soil molded by light finger pressure
Medium	Thumb will penetrate about 1/4 in. Soil molded by strong finger pressure
Stiff	Indented with thumb
Very stiff	Indented by thumb nail
Hard	Thumbnail will not indent

Figure TS14R–10 Empirical correlation between effective phi angle and PI



Loads

Lateral earth pressure

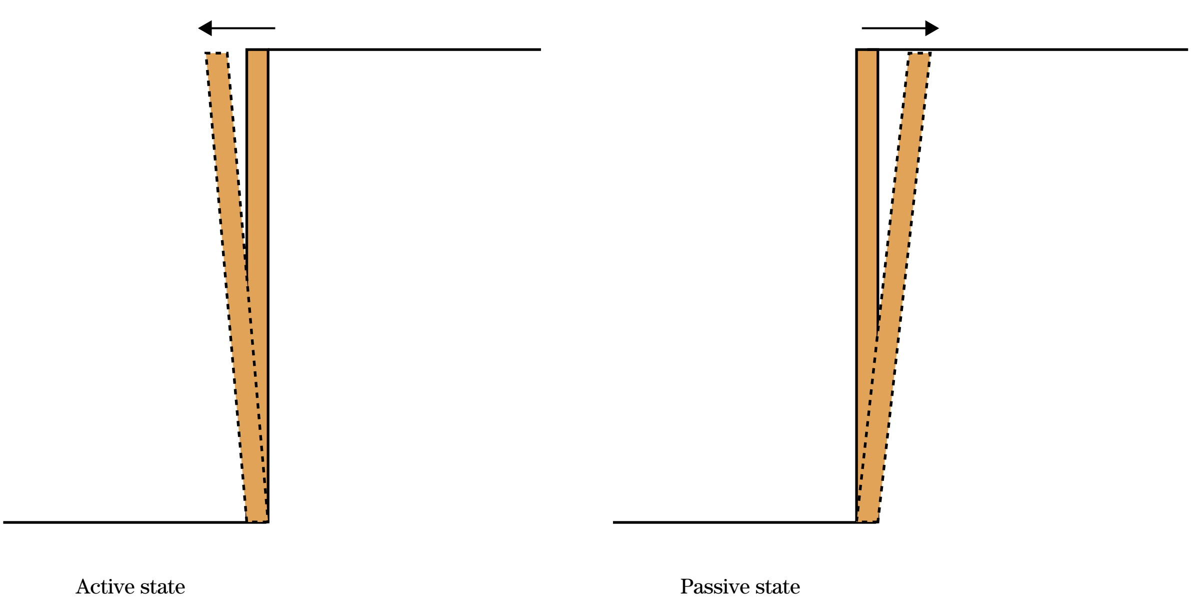
The lateral (horizontal) earth pressure is a function of the soil properties (cohesion, phi angle, and unit weight), height of overburden, and the elevation of the water table. Earth pressures varies from an initial state referred to as at-rest, K_o, to a minimum limit state referred to as active, K_A, to a maximum limit state referred to as passive, K_P. The classical method of sheet pile design assumes development of active and passive lateral earth pressures.

Active earth pressure develops when the pile moves or rotates away from the soil allowing the soil to expand laterally (horizontally) in the direction of the pile movement (fig. TS14R–11). Active earth pressure is the driving force in sheet pile stability analysis. In general, a lateral movement of approximately 1 inch is required to fully mobilize the shear resistance for each 20 feet of wall height.

Passive earth pressure develops when the pile moves or rotate towards the soil, tending to compress the soil laterally (horizontally) in the direction of the pile movement (fig. TS14R–11). Passive earth pressure is the resisting force in sheet pile stability analysis. In general, a lateral movement of approximately 1 inch is required to fully mobilize the shear resistance for each 2 feet of wall height.

More rigorous analysis may be conducted, assuming that the soil behaves as a spring, with the maximum resistance equal to the active or passive lateral earth pressure, as appropriate.

Figure TS14R–11 Active and passive rotation



Water loads

A difference in water level on either side of the wall creates unbalanced hydrostatic pressure, adding to the pressure forcing the wall outward (fig. TS14R–12). The difference in water level may be because of a ground water table, which is higher in the bank than in the stream, a higher water level upstream of an inchannel sheet pile, or from a high streamflow which saturates the bank, followed by rapid drawdown when the water level in the stream drops faster than the water can drain from the bank.

Surcharge

Surface surcharge (fig. TS14R–13) also exerts lateral pressure on the wall, forcing the wall outward. Typical surcharge loadings may be due to equipment (parked or traveling), storage areas, construction materials, vehicles, and others. Surcharge loads are often estimated to be 100 to 200 pounds per square foot. Other surcharge loads include spoil, snow, or ice.

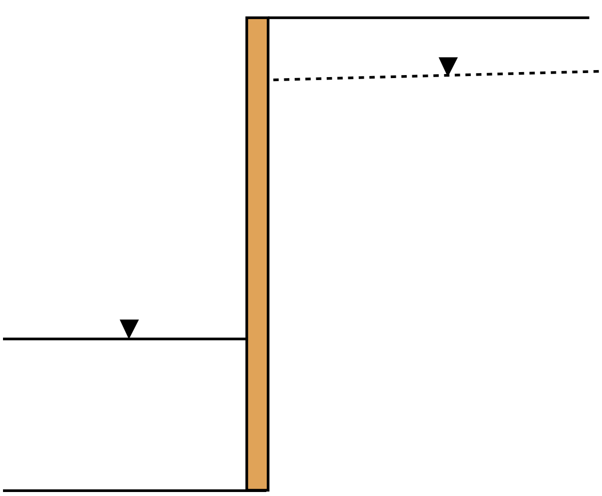
Wall stability

Both anchored and cantilever sheet pile must be analyzed against overturning. Wall penetration must be great enough to prevent deep-seated failure (fig. TS14R–14 (USACE 1994c)) or rotational failure (fig. TS14R–15 (USACE 1994c)). Deep-seated failure should be assessed by a slope stability analysis conducted by a geotechnical engineer.

The rotational stability of a cantilever wall or an anchored wall may be evaluated using methods presented in the Retaining Wall Design Guide (U.S. Department of Agriculture Forest Service (USDA FS) 1994) or the Steel Sheet Piling Design Manual (Pile Buck, Inc. 1987), with some simplifying assumptions, or the USACE computer program CWALSHT (USACE 1994b).

Penetration depths determined by the Retaining Wall Design Guide or Steel Sheet Piling Design Manual are typically increased by 30 percent to provide a factor of safety against overturning. An example calculation is provided later in this technical supplement.

Figure TS14R–12 Differential water load



Active state

Figure TS14R–13 Surface surcharge loading

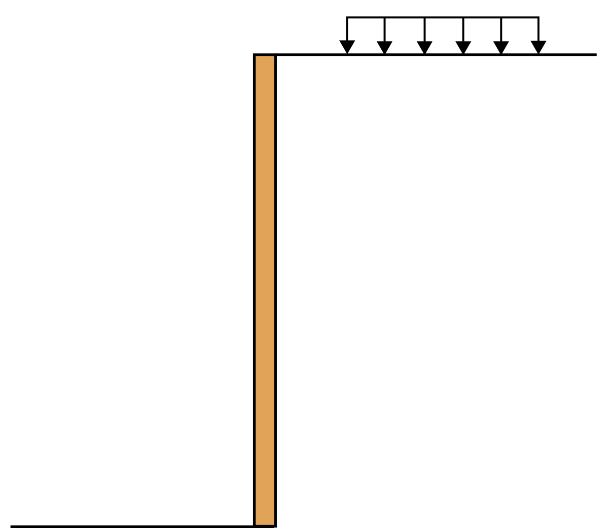


Figure TS14R–14 Deep-seated failure

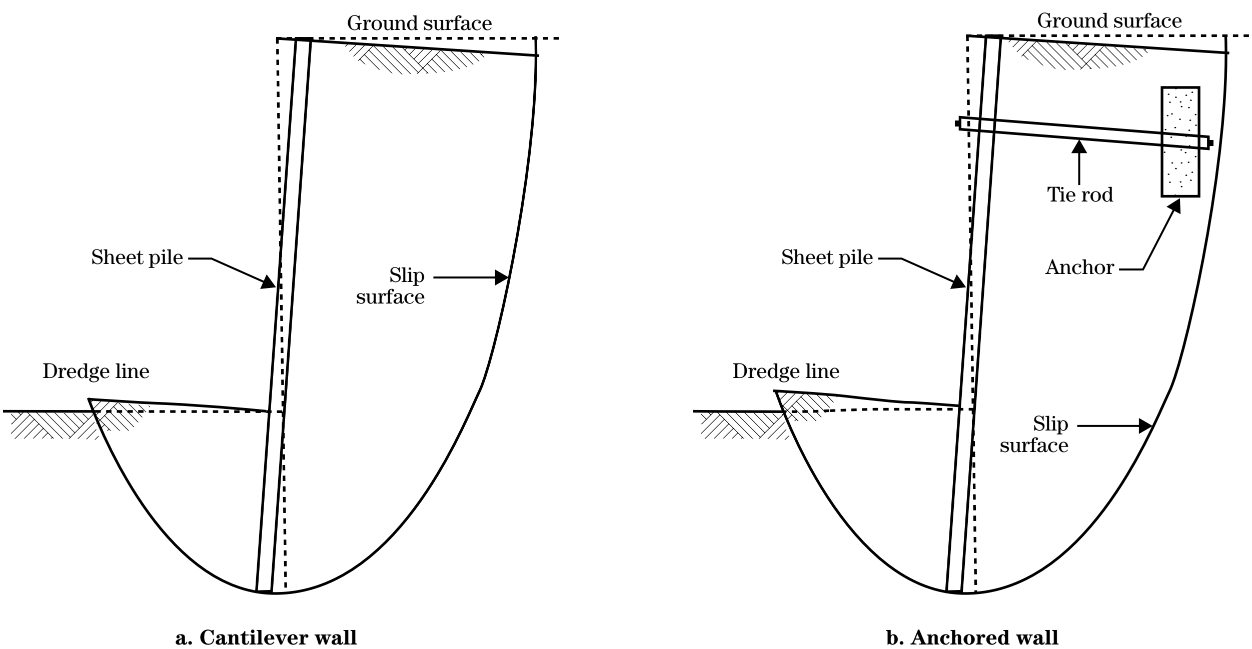
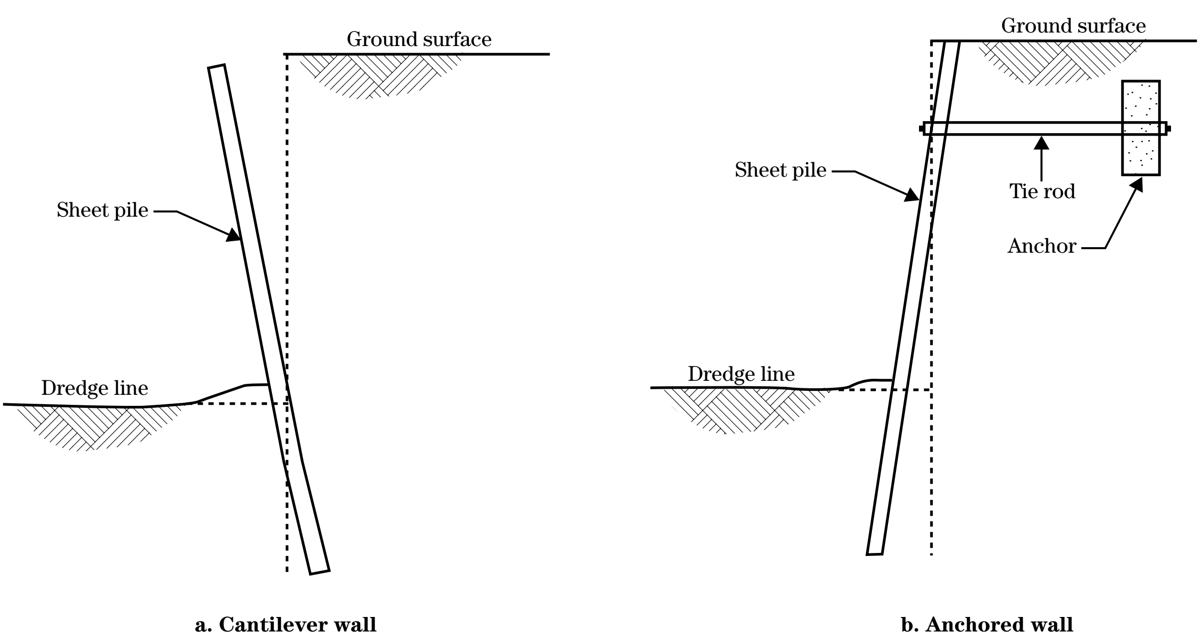


Figure TS14R–15 Wall rotational failure



CWALSHT calculates the required depth of penetration based on the acceptable factor of safety for passive soil pressures. Factors of safety are applied to both active and passive pressures. A factory of safety for active pressures may be applied; however, it is considered sufficient to use a value of 1.0 unless wall deformations are restricted. The following factors of safety are recommended by the USACE for retaining walls:

- Usual loads—2.0 for undrained (short-term) conditions and 1.5 for drained (long-term) conditions
- Unusual loads—1.75 for undrained (short-term) conditions and 1.25 for drained (long-term) conditions
- Extreme loads—1.5 for undrained (short-term) conditions and 1.10 for drained (long-term) conditions

Usual loads are considered to be loads frequently experienced by the system in performing its primary function such as retaining soil or a differential water load at the design storm. Usual loads may be long term or intermittent. Unusual loads may be construction or operational loads of an infrequent and short-term nature such as surcharge from construction equipment adjacent to the wall. Extreme loads are worst case loads such as water loads above the design storm. The system should be designed to withstand extreme loads without failure.

CWALSHT will compute both the active and passive lateral earth pressures from the input listed below and conduct a sheet pile design or analysis:

- wall height
- water table elevations
- anchor location (if anchored wall)
- soil properties
- moist unit weight
- saturated unit weight
- undrained shear strength parameters (as applicable)
- drained shear strength parameters (as applicable)
- soil/pile properties
- angle of wall friction
- wall/soil adhesion

An example using CWALSHT is provided at the end of this technical supplement.

Structural design

Sheet pile failure may also be caused by overstressing the pile (fig. TS14R–16 (USACE 1994c)).

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 1.0 for both active and passive pressures (USACE 1994c). Therefore, the design bending moment, shear, and associated deflection for the sheet pile are based on a factor of safety of 1.0 for both active and passive soil pressures.

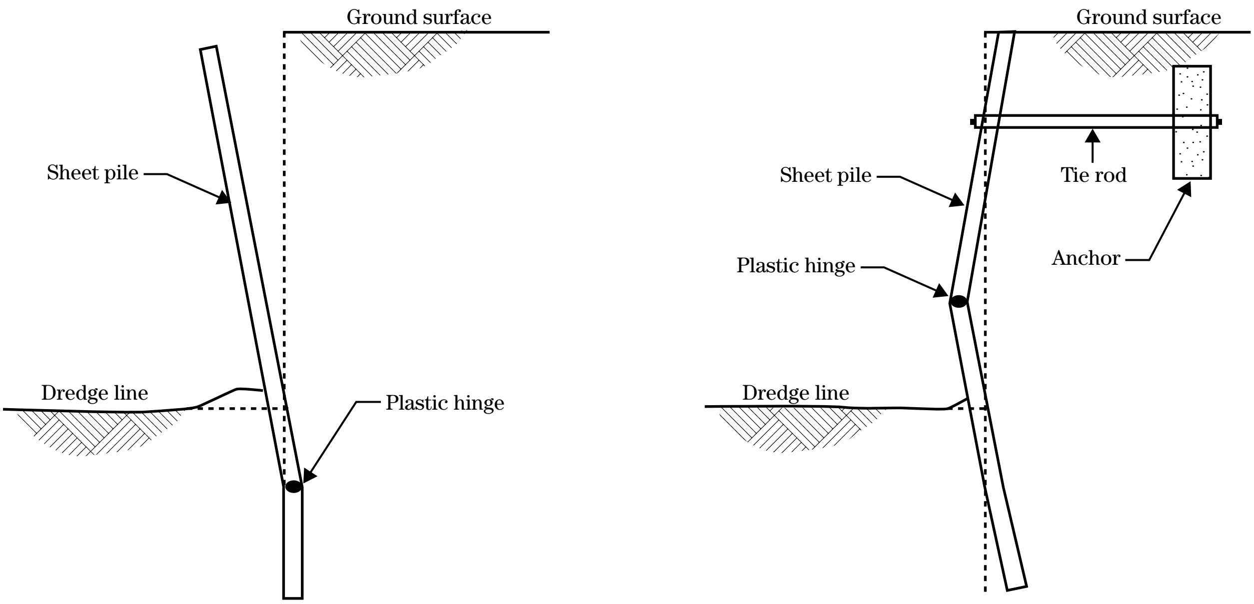
Moment—The maximum moment may be evaluated using methods presented in the Retaining Wall Design Guide or Steel Sheet Piling Design Manual. The moment along the length of the pile may be evaluated with CWALSHT.

Shear—The shear along the length of the pile may be evaluated with CWALSHT.

Deflection—A scaled deflection is calculated in the CWALSHT design mode. An estimate of the actual deflection may be determined by dividing the scaled deflection by the modulus of elasticity, E, of the pile material and the moment of inertia, I, of the pile section. The deflection along the length of a particular pile section may be evaluated with the CWALSHT analysis mode.

No firm guidelines exist for acceptable deflection, and values ranging from 1 to 5 inches are typically considered acceptable. It is recommended that the deflection be limited to 1 to 3 inches for stream restoration and stabilization projects.

Figure TS14R–16 Overstressed pile



a. Cantilever wall **b. Anchored wall**

Sheet design

Steel—The minimum section modulus per foot of wall is:

$$S_{min} = \frac{M_{max}}{f_b} \qquad \text{(eq. TS14R–1)}$$

The minimum shear area per foot of wall is:

$$A_{v,min} = \frac{V_{max}}{f_v} \qquad \text{(eq. TS14R–2)}$$

The allowable stress, f_b, for steel sheet piling is typically:

Bending and axial load:

$$f_b = 0.5f_y \quad \text{(usual loads)} \qquad \text{(eq. TS14R–3)}$$

$$f_b = 0.5f_y \times (1.33) \quad \text{(unusual loads)} \qquad \text{(eq. TS14R–4)}$$

$$f_b = 0.5f_y \times (1.75) \quad \text{(extreme loads)} \qquad \text{(eq. TS14R–5)}$$

Shear:

$$f_v = 0.33f_y \quad \text{(usual loads)} \qquad \text{(eq. TS14R–6)}$$

$$f_v = 0.33f_y \times (1.33) \quad \text{(unusual loads)} \qquad \text{(eq. TS14R–7)}$$

$$f_v = 0.33f_y \times (1.75) \quad \text{(extreme loads)} \qquad \text{(eq. TS14R–8)}$$

where:

f_y = yield strength of the pile material

Concrete—Reinforced concrete and prestressed concrete piles should be designed in accordance with the appropriate ACI Code.

Wood—Wood piles should be designed in accordance with the **National Design Specification for Wood Construction (NDS)** (American Wood Council 2005).

Vinyl and fiber reinforced polymer—The allowable stress should be limited to half the yield stress of the material.

Anchor design—Anchors may consist of concrete, steel member, or sheet pile deadmen attached to the pile with tie rods, tiebacks with grouted anchors, or various configurations of steel or concrete piles attached to the sheet pile by a wale or through a tie rod. Design of anchors and tie rods is described in Design of Sheet Pile Walls (USACE 1994c).

Construction considerations

Piling—Cold-rolled steel sheet pile sections have a weaker interlock than hot-rolled sections and may unlock while being driven in hard conditions, resulting in misalignment. A minimum pile thickness of a fourth inch is typically recommended for driveability. In tough driving conditions, such as dense to very dense sands, very stiff to hard clay soils, or soils containing significant amounts of gravel, a thicker pile should be considered. In areas where corrosion of the steel pile is a concern, a thicker pile than required structurally should be considered to allow for corrosion throughout the design life.

Equipment—Sheet pile is typically installed by driving, jetting, or trenching. Jetting is often not allowed for walls designed to retain soil. Hammers for driving may be steam, air, diesel-drop, single action, double action, differential action, or vibratory. Vibratory hammers work well in sand, silt, or softer clay soils. Harder driving conditions such as stiff clay may require an impact hammer.

Access for a crane is often required to operate the hammer. Short piles or piles in easier driving conditions may be installed with a backhoe or hammer attached to a back/track hoe. A temporary guide structure or template is recommended to ensure that the piles are driven in the correct alignment. Use of a protective cap is required with impact hammers. Protective shoes may be used on the tip of a pile in hard driving conditions.

When driving vinyl pile in stiff clays or dense sands, a steel mandrel is often driven with the vinyl pile and extracted upon completion of driving. The purpose of the mandrel is to support the vinyl pile only during driving.

Pile driving and installation—Piles should be driven with the proper size hammer for the size of pile, depth of penetration, and soil conditions. When impact hammers are used, the hammer should be appropriately sized and a protective cap utilized to prevent excessive damage to the pile. In some conditions, large impact hammers are not appropriate for driving smaller pile sections and have caused excessive damage to the pile. A smaller impact hammer may work better in these situations.

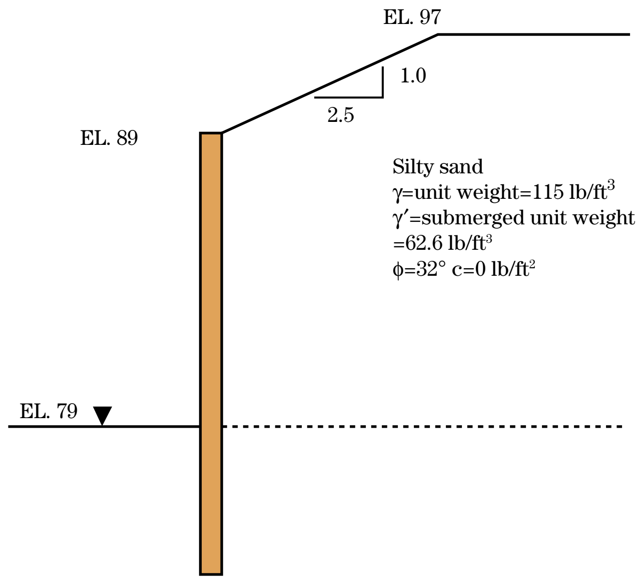
Alignment—Piles should be maintained in alignment during driving. Sheet pile should not be driven more than an eighth inch per foot out of plumb in the plane of the wall or perpendicular to the plane of the wall.

Conclusion

Sheet pile may be used in a variety of applications for stream restoration and stabilization. Typical applications of sheet pile are in high risk situations where no additional bank or bed movement is acceptable. Sheet pile applications include toe walls, flanking and undermining protection, grade stabilization structures, slope stabilization, and earth retaining walls. Sheet pile is often combined with soil bioengineering techniques to provide stability to a stream, stream slopes, or other manmade structures. It is particularly useful in open channel environments that are characterized by high velocities and shear stresses. Its use has distinct advantages because of accepted design techniques established contracting and construction procedures. However, the use of sheet pile does have certain cost, aesthetic, ecologic and geomorphic drawbacks. It is important to balance these potential drawbacks against the need to provide static protection.

Steel sheet pile wall example calculation

Given: A steel sheet pile will be installed to provide support to the lower streambank and prevent further erosion of the bank toe.



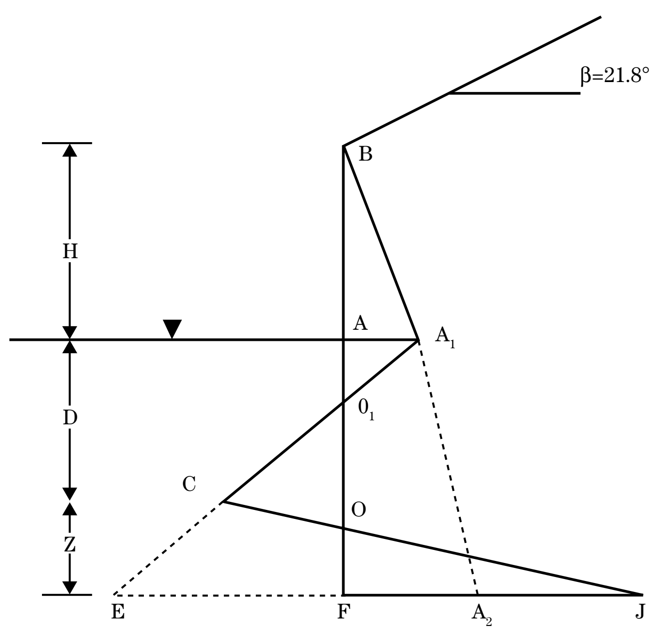
Determine:

Required embedment depth

Design embedment depth

Minimum recommended steel sheet pile wall properties

Solution:



Net soil pressure

Steel sheet pile wall example calculation—Continued

$$\beta = \tan^{-1}\frac{1}{2.5} = 21.8^{\circ} \qquad \text{(eq. TS14R–9)}$$

Using Rankine equations for lateral earth pressure coefficients.

$$K_A = \cos\beta \frac{\cos\beta - \sqrt{\cos^2\beta - \cos^2\phi}}{\cos\beta + \sqrt{\cos^2\beta - \cos^2\phi}} \qquad \text{(eq. TS14R–10)}$$

$$= \cos 21.8 \frac{\cos 21.8 - \sqrt{\cos^2 21.8 - \cos^2 32}}{\cos 21.8 + \sqrt{\cos^2 21.8 - \cos^2 32}} = 0.39$$

$$K_P = \cos\beta \frac{\cos\beta + \sqrt{\cos^2\beta - \cos^2\phi}}{\cos\beta - \sqrt{\cos^2\beta - \cos^2\phi}} \qquad \text{(eq. TS14R–11)}$$

$$= \cos 21.8 \frac{\cos 21.8 + \sqrt{\cos^2 21.8 - \cos^2 32}}{\cos 21.8 - \sqrt{\cos^2 21.8 - \cos^2 32}} = 2.2$$

Less conservative methods of estimating K_A and K_P, such as Coulomb (1776) equations, are acceptable. These equations are described in the Steel Sheet Piling Design Manual (Pile Buck, Inc. 1987) and other foundation engineering references.

Determine wall pressures:

$$P_{A1} = \gamma H K_a = 115 \times 10 \times 0.39 = 448.5 \text{ lb/ft}^2 \qquad \text{(eq. TS14R–12)}$$

$$\begin{aligned} P_{A2} &= P_{A1} + \gamma' D K_A \qquad \text{(eq. TS14R–13)} \\ &= 448.5 + (62.6)D(0.39) \\ &= 448.5 + 24.4D \end{aligned}$$

$$\begin{aligned} P_E &= \gamma' D\left(K_p - K_A\right) - P_{A1} \\ &= 62.6D(2.2 - 0.39) - 448.5 \\ &= 113.3D - 448.5 \end{aligned}$$

$$\begin{aligned} P_J &= \gamma' D(K_P - K_A) + \gamma H K_P \\ &= 62.6D(2.2 - 0.39) + 115 \times 10 \times 2.2 \qquad \text{(eq. TS14R–14)} \\ &= 113.3D + 2{,}530 \end{aligned}$$

To be stable, the sum of forces must be zero, and the sum of moments at any point must be zero.

$$\sum F = 0 \text{ by areas} \qquad \text{(eq. TS14R–15)}$$

$$\text{Area}\left(BAA_1\right) + \text{Area}\left(AA_1A_2F\right) + \text{Area}\left(ECJ\right) - \text{Area}\left(EA_1A_2\right) = 0 \qquad \text{(eq. TS14R–16)}$$

or

Steel sheet pile wall example calculation—Continued

$$\frac{1}{2}HP_{A1}+\left(P_{A1}+P_{A2}\right)\frac{D}{2}+\left(P_E+P_J\right)\frac{Z}{2}-\left(P_E+P_{A2}\right)\frac{D}{2}=0 \quad \text{(eq. TS14R–17)}$$

Solve this equation for Z:

$$Z=\frac{\left(P_E-P_{A1}\right)D-HP_{A1}}{P_E+P_J} \quad \text{(eq. TS14R–18)}$$

$$\sum M=0 \text{ at point F} \quad \text{(eq. TS14R–19)}$$

$$\sum M_F=\frac{1}{2}HP_{A1}\left(D+\frac{H}{3}\right)+P_{A1}\frac{D^2}{2}+\left(P_E+P_J\right)\frac{Z^2}{6}-\left(P_E+P_{A2}\right)\frac{D^2}{6}+\left(P_{A2}-P_{A1}\right)\frac{D^2}{6}=0 \quad \text{(eq. TS14R–20)}$$

These two equations may be solved by trial and error.

Assume a depth of penetration, D.

Solve for Z.

Substitute Z into the ΣM_F. Continue adjusting D and Z until $\Sigma M_F = 0$.

Try D = 20 feet

$$P_{A1}=448.5\text{ lb/ft}^2 \quad \text{(eq. TS14R–21)}$$

$$P_{A2}=448.5+\left(24.4\times 20\right)=936 \quad \text{(eq. TS14R–22)}$$

$$P_E=113.3\times 20-448.5=1{,}817 \quad \text{(eq. TS14R–23)}$$

$$P_J=113.3\times 20+2{,}530=4{,}796 \quad \text{(eq. TS14R–24)}$$

$$Z=\frac{\left(P_E-P_{A1}\right)D-HP_{A1}}{P_E+P_J}=\frac{\left(1817-448\right)20-10\times 448}{1{,}817+4{,}796}=3.46 \quad \text{(eq. TS14R–25)}$$

$$\Sigma M_F=\frac{1}{2}\times 10\times 448\left(20+\frac{10}{3}\right)+448\frac{20^2}{2}+\left(1{,}817+4{,}796\right)\frac{3.46^2}{6}-\left(1{,}817+936\right)\frac{20^2}{6}+\left(936-448\right)\frac{20^2}{6} \quad \text{(eq. TS14R–26)}$$

$$\sum M_F=4{,}185 \quad \text{(eq. TS14R–27)}$$

Try D = 20.5 feet

$$P_{A1}=448.5\text{ lb/ft}^2 \quad \text{(eq. TS14R–28)}$$

$$P_{A2}=448.5+\left(24.4\times 20.5\right)=948 \quad \text{(eq. TS14R–29)}$$

$$P_E=113.3\times 20.5-448.5=1{,}874 \quad \text{(eq. TS14R–30)}$$

$$P_J=113.3\times 20.5+2530=4852 \quad \text{(eq. TS14R–31)}$$

Steel sheet pile wall example calculation—Continued

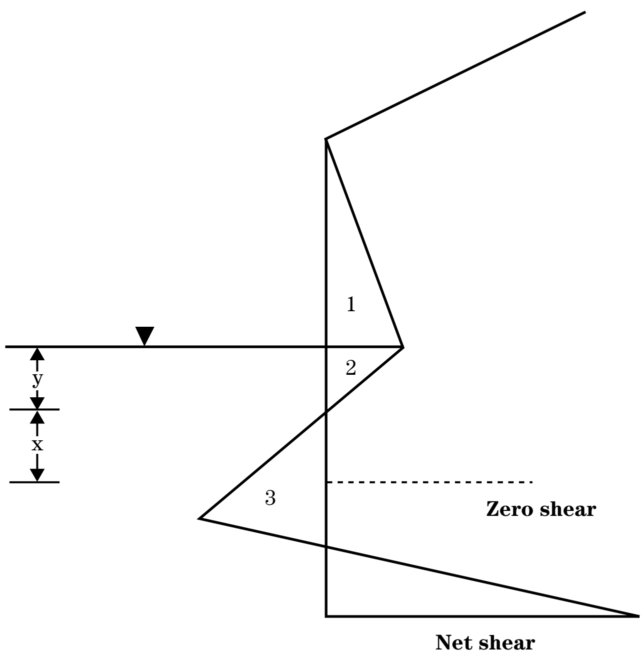
$$Z = 3.68 \qquad \text{(eq. TS14R–32)}$$

$$\sum M_F = 164 \text{ ft-lb} \qquad \text{(eq. TS14R–33)}$$

The required depth is 20.5 feet.

To determine the design embedment depth, increase D by 30 percent for a factor of safety.

$$D = 20.5 \times 1.30 = 26.65 \text{ ft} \qquad \text{(eq. TS14R–34)}$$



The design embedment depth is 26.5 feet.

Locate the point of zero shear.

$$y = \frac{P_{A1}}{\gamma'(K_P - K_A)} = \frac{448.5}{62.6(2.2 - 0.39)} = 3.96 \qquad \text{(eq. TS14R–35)}$$

$$P_1 = \frac{1}{2} P_{A1} H = \frac{1}{2} \times 448 \times 10 = 2,240 \text{ lb/ft of wall} \qquad \text{(eq. TS14R–36)}$$

Steel sheet pile wall example calculation—Continued

$$P_2 = \frac{1}{2} P_{A1} y = \frac{1}{2} \times 448 \times 3.96 = 887 \text{ lb/ft of wall} \quad \text{(eq. TS14R–37)}$$

Solve for X

$$\frac{1}{2} \gamma' (K_P - K_A) x^2 = P_1 + P_2 \quad \text{(eq. TS14R–38)}$$

$$x^2 = \frac{2(P_1 + P_2)}{\gamma'(K_P - K_A)} = \frac{2(2{,}240 + 887)}{62.6(2.2 - 0.39)} = 55 \text{ ft} \quad \text{(eq. TS14R–39)}$$

$$x = 7.42 \text{ ft} \quad \text{(eq. TS14R–40)}$$

Solve for the maximum moment (occurs at the point of zero shear)

$$P_3 = \frac{1}{2} \gamma' (K_P - K_A) x^2 = P_1 + P_2 = 2{,}240 + 887 = 3{,}127 \quad \text{(eq. TS14R–41)}$$

$$M_{max} = P_1 l_1 + P_2 l_2 - P_3 l_3 \quad \text{(eq. TS14R–42)}$$

$$l_1 = \frac{H}{3} + y + x = \frac{10}{3} + 3.96 + 7.42 = 14.71 \quad \text{(eq. TS14R–43)}$$

$$l_2 = \frac{2y}{3} + x = \frac{2(3.96)}{3} + 7.42 = 10.06 \quad \text{(eq. TS14R–44)}$$

$$l_3 = \frac{x}{3} = \frac{7.42}{3} = 2.47 \quad \text{(eq. TS14R–45)}$$

$$\begin{aligned} M_{max} &= 2{,}240(14.71) + 887(10.06) - 3{,}127(2.47) \\ &= 34{,}149 \text{ ft-lb} \end{aligned} \quad \text{(eq. TS14R–46)}$$

The minimum section modulus of 50 kilopounds per square inch steel per foot of wall is:

$$S_{min} = \frac{M_{max}}{f_b} \quad \text{(eq. TS14R–47)}$$

$$f_b = 0.5 f_y = 0.5 \times 50{,}000 = 25{,}000 \text{ lb/in}^2 \quad \text{(eq. TS14R–48)}$$

$$S_{min} = \frac{34{,}149 \text{ ft-lbs} \times 12 \text{ in/ft}}{25{,}000 \text{ lb/in}^2} = 16.39 \text{ in}^3\text{/ft of wall} \quad \text{(eq. TS14R–49)}$$

Steel sheet pile wall CWALSHT program

The steel sheet pile should be Grade 50 steel with a minimum section modulus of 16.4 cubic inches per foot of wall.

Given: The steel sheet pile is described in the previous example.

Determine:

Design embedment depth

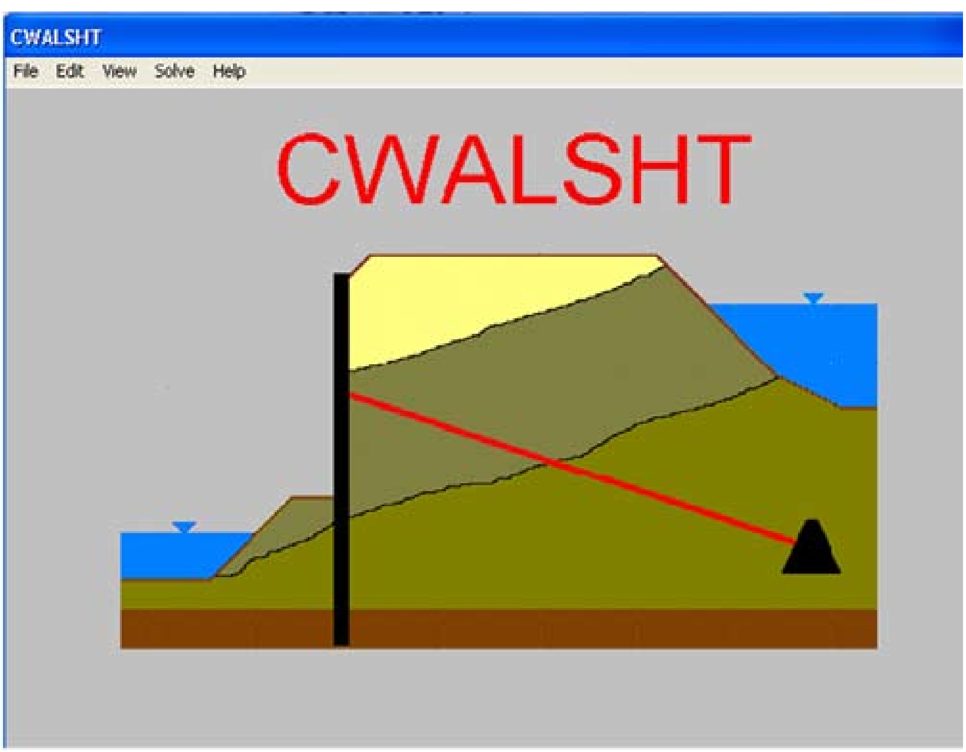
Maximum moment and shear in the pile

Minimum recommended steel sheet pile wall properties

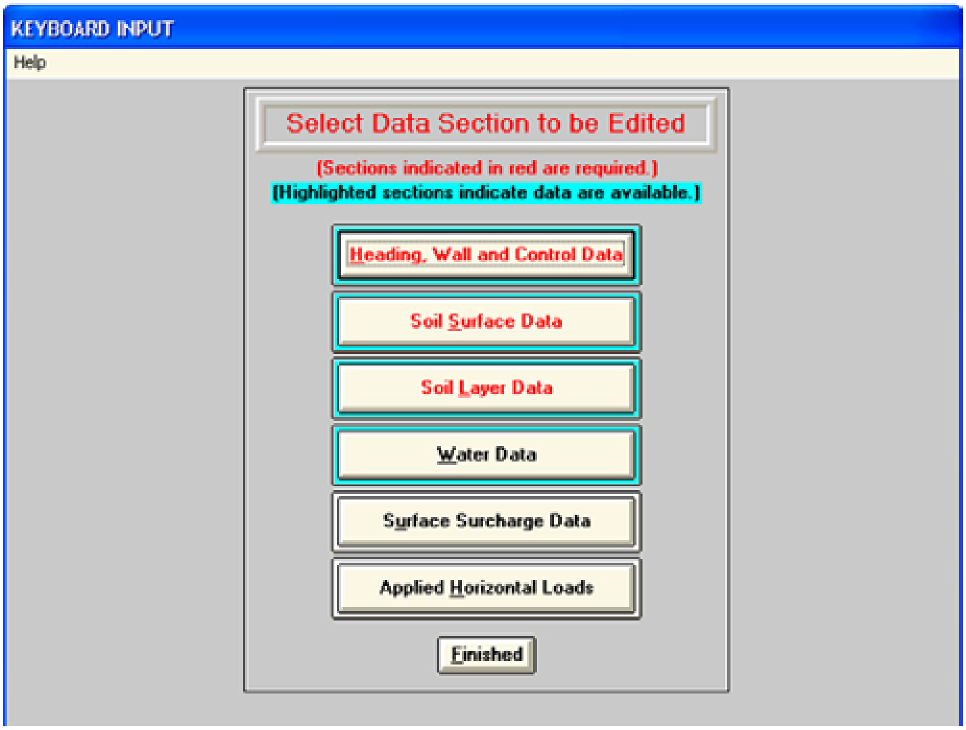
Estimate the deflection of the top of the pile

Solution:

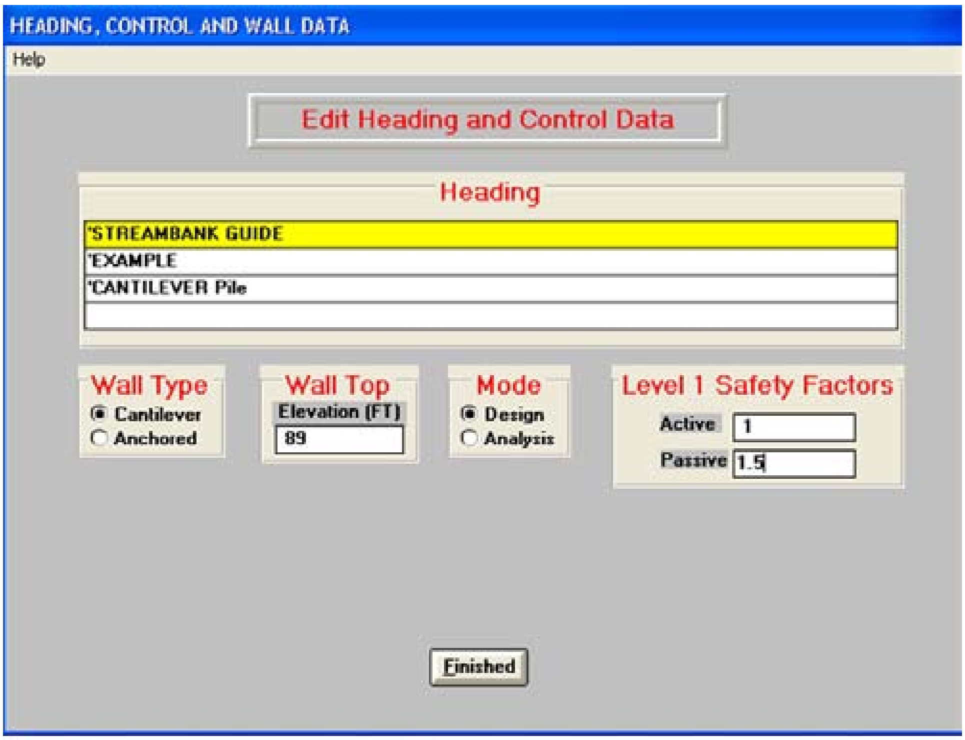
Using CWALSHT, enter the data for the analysis.



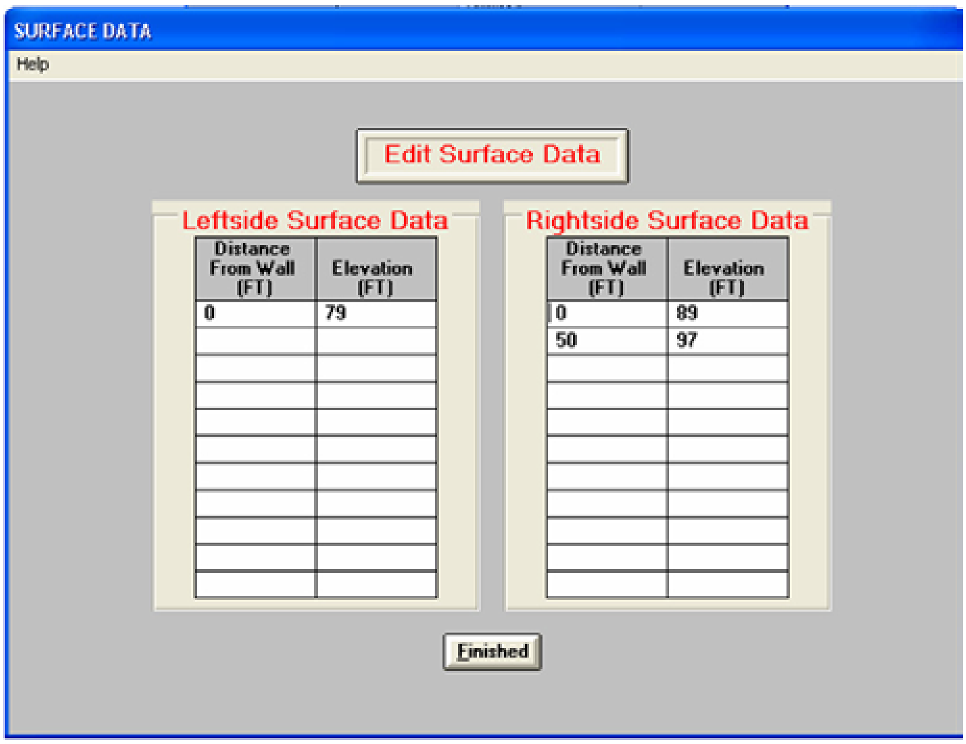
A factor of safety of 1.5 on the passive soil pressure is recommended for this usual load condition. Since the soils are silty sand with a moderate permeability, they will exhibit drained (long-term, effective) behavior.

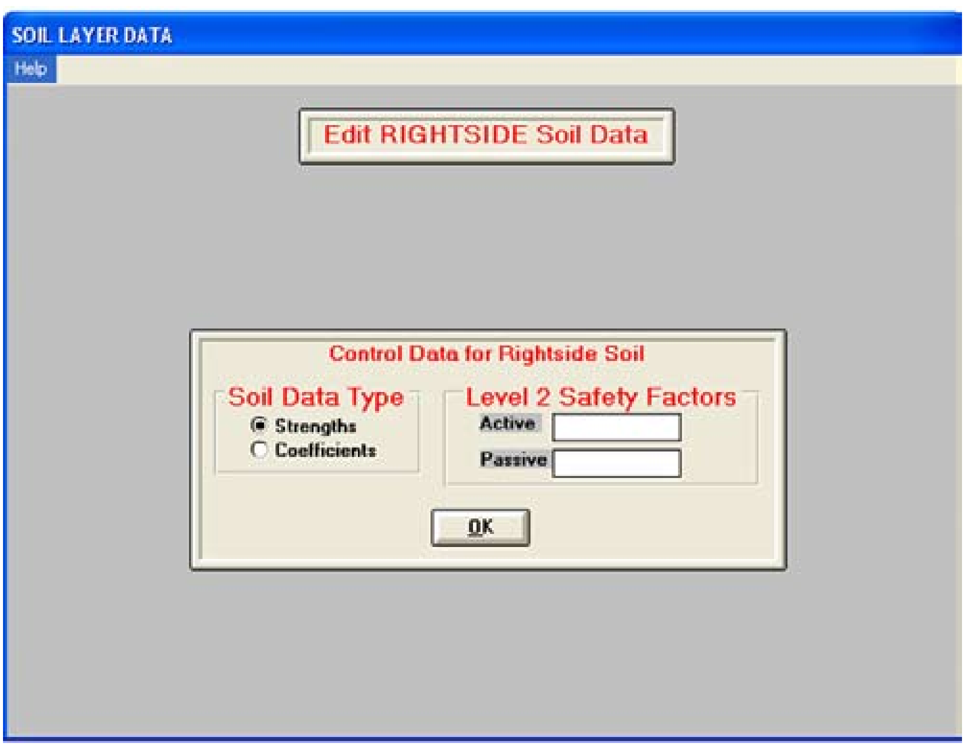


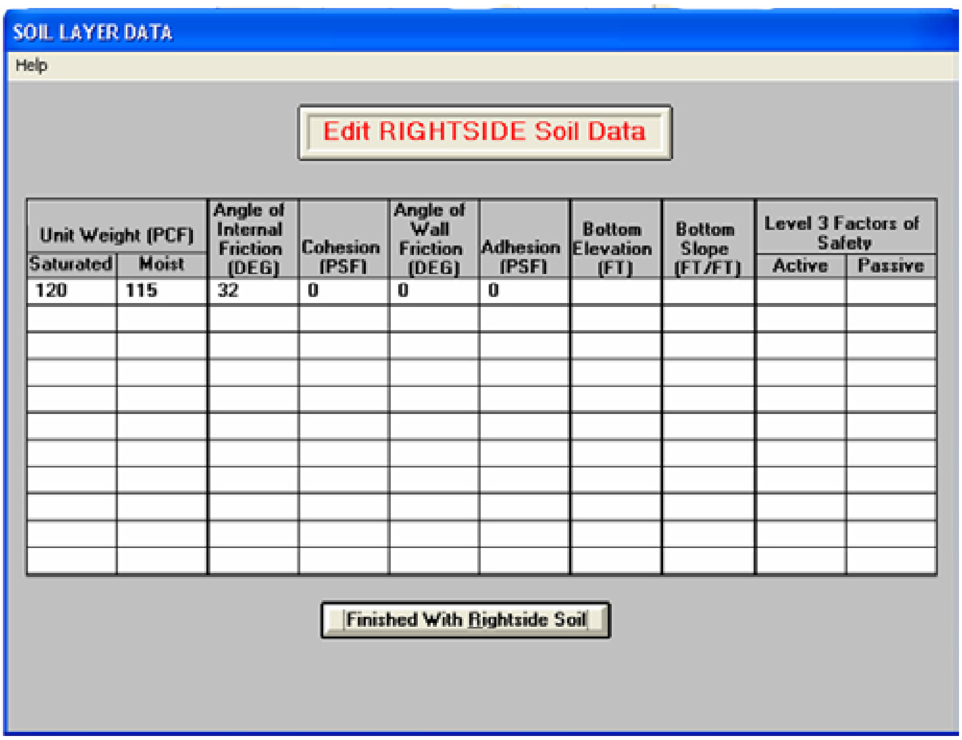
Enter the surface data for both the left side and right side. CWALSHT requires the pile to be loaded from the right side.

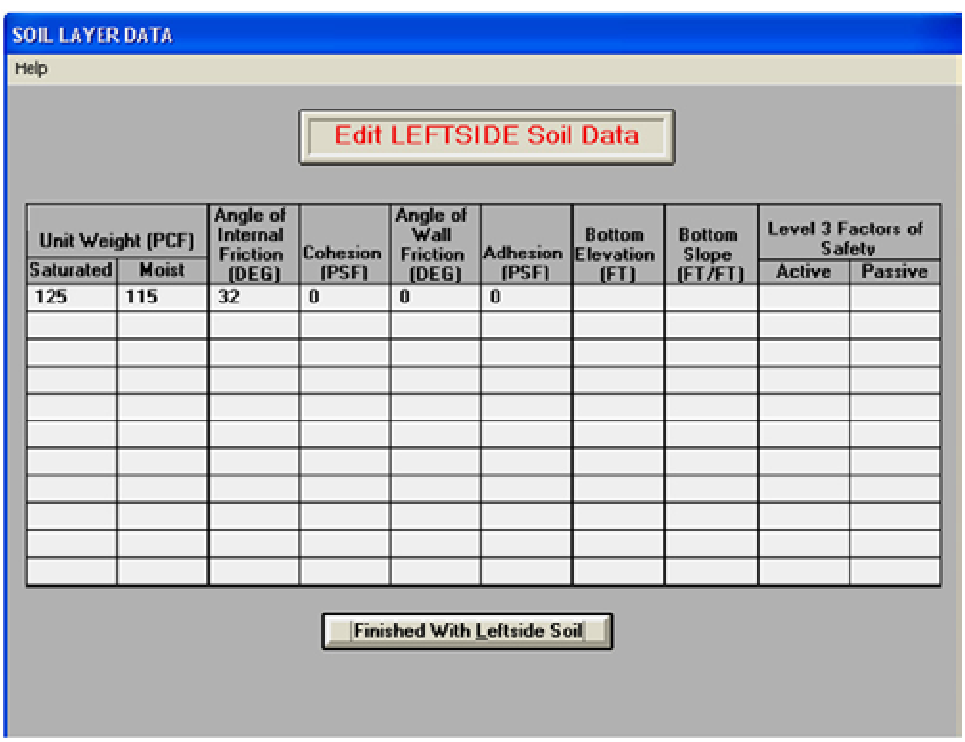


Enter the soils data for both the left and right side. The level 1 factors of safety input previously will apply to the soils data unless level 2 factors are input to override level 1.

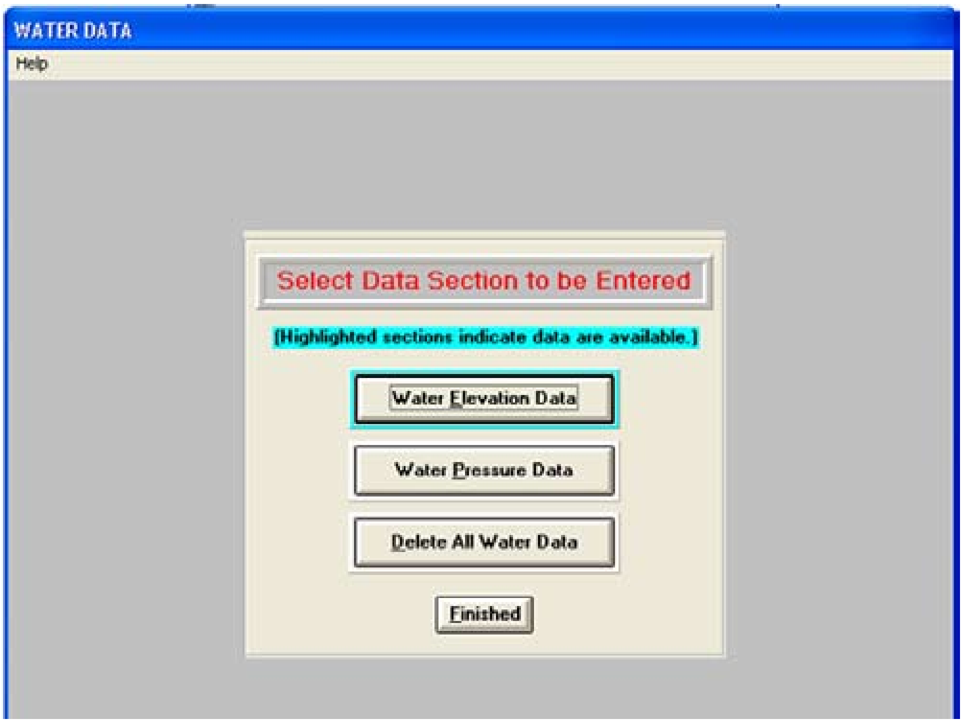


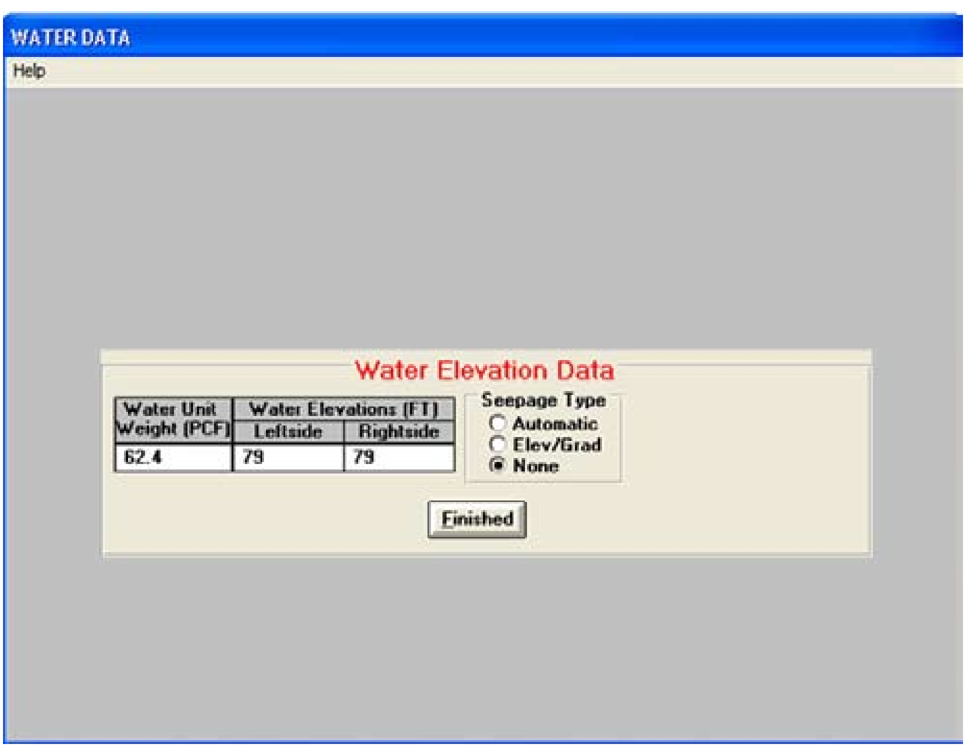



SOIL LAYER DATA
Help
Edit RIGHTSIDE Soil Data
Unit Weight (PCF)
Saturated
Moist
Angle of Internal Friction (DEG)
Cohesion (PSF)
Angle of Wall Friction (DEG)
Adhesion (PSF)
Bottom Elevation (FT)
Bottom Slope (FT/FT)
Level 3 Factors of Safety
Active
Passive
120
115
32
0
0
0
Finished With Rightside Soil


SOIL LAYER DATA
Help
Edit LEFTSIDE Soil Data
Unit Weight (PCF)
Saturated
Moist
Angle of Internal Friction (DEG)
Cohesion (PSF)
Angle of Wall Friction (DEG)
Adhesion (PSF)
Bottom Elevation (FT)
Bottom Slope (FT/FT)
Level 3 Factors of Safety
Active
Passive
125
115
32
0
0
0
Finished With Leftside Soil

Enter the water elevation data.





The data input for this problem is complete. The problem may be solved with the ***sweep*** search, fixed wedge method, or both may be run separately.

The fixed surface method will be used and the solution continued and completed. The output may be viewed to determine the required depth of the pile (fig. TS14R–17).

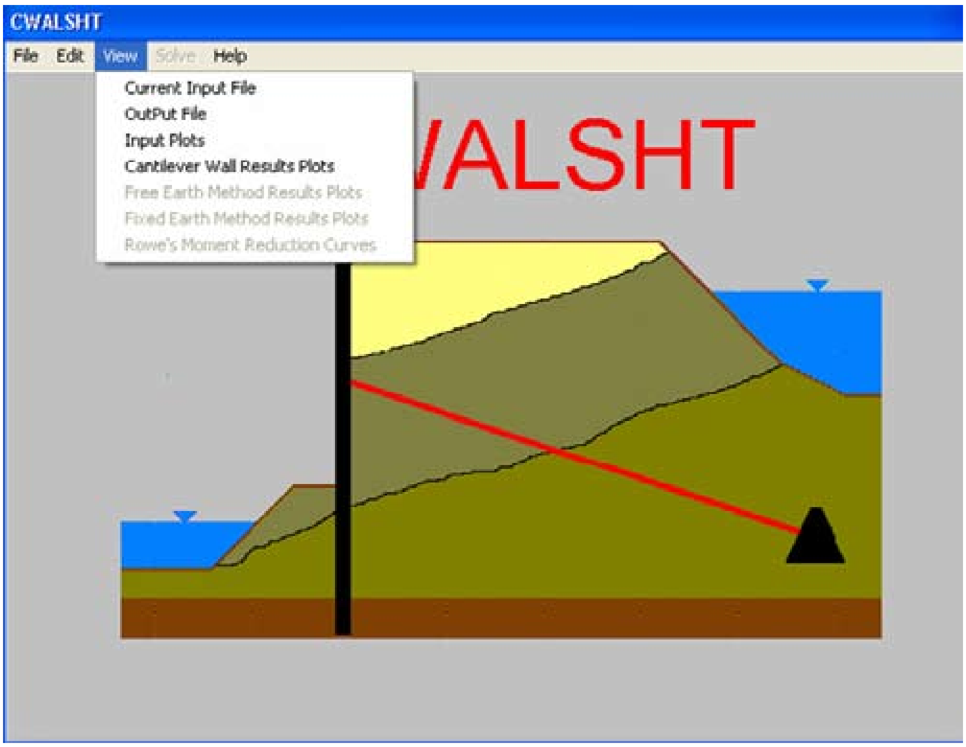


Figure TS14R–17 CWALSHT output file

```
II.--SUMMARY
           RIGHTSIDE SOIL PRESSURES DETERMINED BY FIXED SURFACE WEDGE METHOD.
           LEFTSIDE SOIL PRESSURES DETERMINED BY COULOMB COEFFICIENTS
           AND THEORY OF ELASTICITY EQUATIONS FOR SURCHARGE LOADS.
      WALL BOTTOM ELEV. (FT)      : 61.47
           PENETRATION (FT)       : 17.53
      MAX. BEND. MOMENT (LB-FT)   : 2.5262E+04
           AT ELEVATION (FT)      : 69.22
      MAX. SCALED DEFL. (LB-IN3)  : 9.6124E+09
           AT ELEVATION (FT)      : 89.00
                  NOTE:  DIVIDE SCALED DEFLECTION MODULUS OF
                         ELASTICITY IN PSI TIMES PILE MOMENT
                         OF INERTIA IN IN4 TO OBTAIN DEFLECTION
                         IN INCHES.
```

So the design embedment depth using a factor of safety on passive soil pressure is 17.53 feet.

The maximum moment and shear should be determined using a factor of safety of 1.0 in the CWALSHT program. The results are:

```
II.--SUMMARY
           RIGHTSIDE SOIL PRESSURES DETERMINED BY FIXED SURFACE WEDGE METHOD.
           LEFTSIDE SOIL PRESSURES DETERMINED BY COULOMB COEFFICIENTS
           AND THEORY OF ELASTICITY EQUATIONS FOR SURCHARGE LOADS.
      WALL BOTTOM ELEV. (FT)      : 65.72
           PENETRATION (FT)       : 13.28
      MAX. BEND. MOMENT (LB-FT)   : 1.9080E+04
           AT ELEVATION (FT)      : 71.81
      MAX. SCALED DEFL. (LB-IN3)  : 5.1147E+09
           AT ELEVATION (FT)      : 89.00
                  NOTE:  DIVIDE SCALED DEFLECTION MODULUS OF
                         ELASTICITY IN PSI TIMES PILE MOMENT
                         OF INERTIA IN IN^4 TO OBTAIN DEFLECTION
                         IN INCHES.

      PROGRAM CWALSHT-DESIGN/ANALYSIS OF ANCHORED OR CANTILEVER SHEET PILE WALLS
                                 BY CLASSICAL METHODS
DATE: 14-DECEMBER-2004 TIME: 14:08:44
                            ****************************
                            *  COMPLETE OF RESULTS FOR *
                            *   CANTILEVER WALL DESIGN *
                            ****************************
           I.--HEADING
           ,STREAMBANK GUIDE
           ,EXAMPLE
           ,CANTILEVER Pile
```

Figure TS14R–17 CWALSHT output file—Continued

II.--RESULTS

ELEVATION (FT)	BENDING MOMENT (LB-FT)	SCALED SHEAR (LB)	NET DEFLECTION (LB-IN^3)	PRESSURE (LB/FT^2)
89.00	0.0000E+00	0.	5.1147E+09	0.00
88.00	6.4623E+00	19.	4.7876E+09	38.77
87.00	5.1698E+01	78.	4.4606E+09	77.55
86.00	1.7448E+02	174.	4.1336E+09	116.32
85.00	4.1358E+02	310.	3.8070E+09	155.09
84.00	8.0778E+02	485.	3.4811E+09	193.87
83.00	1.3958E+03	698.	3.1567E+09	232.64
82.00	2.2166E+03	950.	2.8347E+09	271.41
81.00	3.3087E+03	1241.	2.5165E+09	310.26
80.00	4.7111E+03	1570.	2.2041E+09	348.96
79.00	6.4616E+03	1936.	1.8999E+09	383.19
78.00	8.5600E+03	2231.	1.6069E+09	205.14
77.00	1.0863E+04	2345.	1.3288E+09	22.60
76.88	1.1153E+04	2346.	1.2956E+09	0.00
76.00	1.3188E+04	2276.	1.0694E+09	-160.07
75.00	1.5353E+04	2024.	8.3278E+08	-342.67
74.00	1.7176E+04	1590.	6.2264E+08	-525.27
73.00	1.8473E+04	974.	4.4211E+08	-707.87
72.00	1.9063E+04	175.	2.9340E+08	-890.47
71.00	1.8762E+04	-807.	1.7750E+08	-1073.07
70.00	1.7388E+04	-1971.	9.3872E+07	-1255.67
69.00	1.4758E+04	-3318.	4.0106E+07	-1438.27
68.00	1.0690E+04	-4848.	1.1635E+07	-1620.87
67.36	7.2451E+03	-5923.	3.5387E+06	-1737.81
67.00	5.0536E+03	-6126.	1.4035E+06	612.96
66.00	3.2402E+02	-2244.	3.7195E+03	7150.96
65.72	0.0000E+00	0.	0.0000E+00	8970.81

NOTE: DIVIDE SCALED DEFLECTION MODULUS OF ELASTICITY IN PSI TIMES PILE MOMENT OF INERTIA IN IN^4 TO OBTAIN DEFLECTION IN INCHES.

The maximum moment estimated by the CWALSHT program is 19,080 feet-pounds and maximum shear of 6,126 pounds at elevation 77.

The difference in the analysis completed by hand calculations, and the CWALSHT analysis is due to the method of estimating the active and passive earth pressure.

The minimum section modulus of 50 kilopounds per square inch steel per foot of wall is:

$$S_{min} = \frac{M_{max}}{f_b} \qquad \text{(eq. TS14R–50)}$$

$$f_b = 0.5f_y = 0.5 \times 50,000 = 25,000 \text{ lb/in}^2 \qquad \text{(eq. TS14R–51)}$$

$$S_{min} = \frac{19,080 \text{ ft-lb/ft of wall} \times 12 \text{ in/ft}}{25,000 \text{ lb/in}^2} = 9.15 \text{ in}^3\text{/ft of wall} \qquad \text{(eq. TS14R–52)}$$

A CZ–67 pile will provide a section modulus of 10.69 cubic inches per foot of wall. The thickness of a CZ–67 is 0.217 inches. A minimum thickness of 0.25 inches is recommended. A CZ–84 provides a thickness of 0.276 inches and section modulus of 13.62 cubic inches per foot of wall.

The minimum shear area per foot of wall is:

$$A_{v,min} = \frac{V_{max}}{f_v} \qquad \text{(eq. TS14R–53)}$$

$$f_v = 0.33f_y = 0.33 \times 50,000 = 16,500 \text{ lb/in}^2 \qquad \text{(eq. TS14R–54)}$$

$$A_{v,min} = \frac{6,126 \text{ lb/ft of wall}}{16,500 \text{ lb/in}^2} = 0.37 \text{ in}^2\text{/ft of wall} \qquad \text{(eq. TS14R–55)}$$

$$A_v \text{ of Z} - \text{shaped piles} = t_w \times \frac{h}{w}$$

$$A_v \text{ of u} - \text{shaped piles} = 2t_w \times \frac{h}{w}$$

$$\begin{aligned} A_v \text{ of CZ} - 84 &= t_w \times \frac{h}{w} \\ &= 0.276 \times \frac{7.88}{\left(\frac{21.65}{12}\right)} \\ &= 1.2 \text{ in}^2\text{/ foot of wall} > 0.37 \end{aligned} \qquad \text{(eq. TS14R–56)}$$

The steel sheet pile should be Grade 50 steel with a minimum section modulus of 13.6 cubic inches per foot of wall.

The deflection of the top of the pile may be determined by using the analysis mode of CWALSHT and inputting the actual pile properties or by dividing the scaled deflection provided by the design mode by the modulus of elasticity of the steel and the moment of inertia per foot of pile.

$$\text{Deflection} = \frac{\text{Scaled deflection}}{(E \times I)}$$

$$= 5.1147E + \frac{9}{(29{,}000{,}000 \times 53.63)} \qquad \text{(eq. TS14R–57)}$$

$$= 3.28 \text{ in}$$