

tar, wrapped with fabric of tough and durable quality, and coated again with paint or tar. Protection of tie rods with concrete cover is not considered desirable due to the likelihood of cracks in the concrete thus permitting penetration of moisture.

Table 12-1 FACTORS AFFECTING THE RATE OF DETERIORATION OF STEEL SHEETPIILING

	Harbor bulkheads (in./yr)	Beach bulkheads (in./yr)	Groins and jetties (in./yr)
Geographical location			
South (south of Welmington, N.C.)	0.0062	0.017	0.018
North (north of Pt. Pleasant, N.J.)	0.0023	0.0075	0.011
Zone relative to tidal planes			
8 ft above mean high water	0.0049	0.020	0.010
5 ft to 8 ft above mean high water		0.022	
2 ft to 5 ft above mean high water		0.0081	
Mean high water	0.0027	0.0074	0.0055
Mean tide level	0.0024	0.001	0.024
Mean low water	0.0035	0.002	0.028
Mean low water to ground line	Average of 4 values = 0.0036		
Below ground line	Average of 4 values = 0.0016		
Exposure to salt spray			
Heavy spray	0.0083	0.016	0.016
Moderate spray	0.0041	(beach bulkheads, groins, and jetties are considered to be subjected to heavy spray)	
Light spray or none	0.0024		
Paint protection			
None	0.0045	0.018	0.020
At least painted once	0.0027	0.011	0.010

12-5 Design of Sheetpiling Walls

The design procedure of sheetpiling walls generally comprises the following steps:

1. *Assemble the general information.* In addition to the topographical survey, the controlling dimensions must be included in the general information. The controlling dimensions are the elevation of top of wall, the dredge line (the elevation of ground surface in front of the wall), the maximum water level, the mean tide level (normal pool), and the low water level.

2. *Analyse the subsoil conditions.* The shear strength of each soil stratum should be determined by standard penetration tests (for granular soils) and unconfined compression strength (for cohesive soils). If considerable dredging is done, the effective pressure on the soil is reduced. This reduction in pressure tends to allow reduction in shear strength (Sec. 1-5). In such a case, unconfined compression tests may give unsafe results, and laboratory tests should be made to predict the anticipated conditions.
A soil profile should be drawn for the most unfavorable conditions revealed by the soil borings. The borings should be carried to a very dense or hard layer or bedrock. The contemplated sheetpiling wall and the type of backfill material should also be shown in the profile.
3. *Select the type of wall.* Sections 12-2 and 12-3.
4. *Compute earth pressure and surcharge pressure.* Section 12-6.
5. *Determine the piling penetration.* Sections 12-7, 12-8, and 12-9.
6. *Determine the bending stress and design the piling.* Sections 12-7, 12-8, and 12-10.
7. *Design the tie rods.* Section 12-11.
8. *Design the anchorage.* Sections 12-3, 12-14, and 12-15.

12-6 Lateral Pressure Acting on Sheetpiling Walls

A sheetpiling wall may be subjected to some or all of the following types of lateral pressure.

Earth pressure: active and passive pressure

Lateral pressure due to surcharge load

Unbalanced water pressure and seepage pressure

Mooring pull, ship impact, etc.

Earthquake force, wave pressure, etc.

The procedure for calculation of earth pressure, unbalanced water pressure and seepage pressure are presented below. The lateral pressures due to other loads were discussed in Chapter 4.

A. Earth pressure acting on sheetpiling walls. The actual earth pressure acting on sheetpiling walls cannot be calculated by the classical theories (Rankine, Coulomb, and wedge theories). The classical theories are all based on the condition that the wall yields laterally, by sliding or by rotation about the bottom of the wall, to such an extent that the shear strength of the soil is fully mobilized. This condition is generally satisfied for ordinary retaining walls. The sheetpiling walls, however are supported differently, and they are more flexible, consequently they do not yield in the same manner as the ordinary retaining walls. An anchored sheetpiling wall, due to the elastic

deflection of the wall, will bulge, or yield considerably more at a point between the tie rod level and the dredge line than other portions of the wall. This large yield tends to relieve the magnitude of pressure on that portion of the wall. The pressure distribution is further influenced by the amount of elongation of the tie rod and the depth of sheet pile penetration.

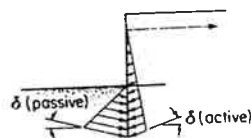
The earth pressure against sheetpiling walls can be determined by theories which take into account of the conditions of yield of the wall (Hansen, J. Brinch, 1953). Although the procedure is more laborious than the classical method it is recommended for larger projects. In practice, several empirical and semiempirical methods have been developed all of which use the classical earth pressure theories. The Coulomb theory has been employed to determine the active and passive earth pressures against the sheetpiling. Since this theory gives misleadingly large values for passive earth pressure, it should be used conservatively. For more accurate design, the wedge theory may be used for passive pressure calculations. The values of ϕ (angle of internal friction of soil) and δ (angle of wall friction) recommended for earth pressure calculations are shown in Table 12-2. The corresponding coefficients of earth pressure K_a and K_p for the condition of horizontal ground surface are also shown in the same table.

Table 12-2 UNIT WEIGHTS OF GRANULAR SOILS AND COEFFICIENTS OF EARTH PRESSURE

Type of soil	Unit wt of moist soil*		Unit wt of submerged soil*		Coefficient of active earth pressure			Coefficient of passive earth pressure		
	γ		γ'		K_a			K_p		
	Min	Max	Min	Max	For backfill	For soils in place	Friction angles†	For soils in place	Friction angles†	
							ϕ δ		ϕ δ	
Clean sand:										
dense	110	140	65	78		0.20	38 20	9.0	38 25	
medium	110	130	60	68		0.25	34 17	7.0	34 23	
loose	90	125	56	63	0.35	0.30	30 15	5.0	30 20	
Silty sand:										
dense	110	150	70	88		0.25	34 17	7.0	34 23	
medium	95	130	60	68		0.30	30 15	5.0	30 20	
loose	80	125	50	63	0.50	0.35	26 13	3.0	26 18	

* In pounds per cubic foot.

† These angles, expressed in degrees, are ϕ , the angle of internal friction, and δ , the angle of wall friction, and are used in estimating the coefficients under which they are listed. After Terzaghi, 1954.



B. Unbalanced water pressure and seepage pressure. Sheetpiling walls are widely used for water front construction. When the tide or river level is at the lowest stage, the sheetpiling is subjected to the maximum earth pressure. During a rain storm or a rapidly receding high water, the water level behind the wall may be several feet higher than that in front of the wall and the difference in water level introduces additional pressure on the piling. Furthermore, the receding water percolates downward through the soil behind the sheetpiling and then upward in front of the piling. The upward seepage reduces the effective weight of the soil and consequently reduces its passive resistance. Therefore, it is necessary to evaluate the unbalanced water pressure and the effect of seepage pressure in the cases where conditions of unequal water level may exist.

The height of water head lagging behind a rapidly receding tide or river stage depends primarily upon the type of backfill used. In coarse sand and gravel, the lag may be negligible. In fine or silty sand, the lag may be several feet. If the backfill is clay or silt, full hydrostatic pressure should be assumed below the highest possible position of water level.

If a sheetpiling is driven in granular soil with fairly uniform coefficient of permeability, the seepage water follows the paths indicated by the arrows shown in Fig. 12-7(a). This diagram is known as a flownet.* The unbalanced

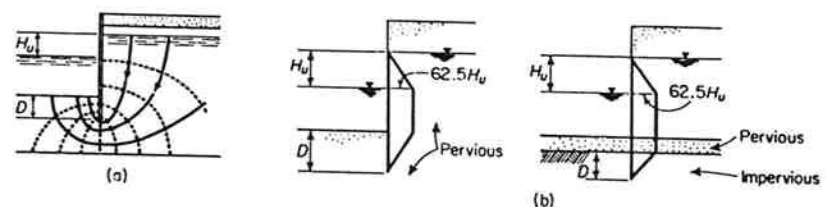


Fig. 12-7 Unbalanced water pressure: (a) flow net; (b) unbalanced water pressure; (c) average reduction of effective unit weight of passive wedge due to seepage pressure exerted by the upward flow of water. After Terzaghi (1954).

water pressure may be approximately established by the diagram *acde* in Fig. 12-7(b), where γ_w = the unit weight of water. If the permeability of soil varies widely in the vertical direction, the distribution of unbalanced water pressure must be determined by construction of a flow net.

The effective weight of soil below a static water table is the bouyant or

* See standard textbook of soil mechanics, e.g., Donald W. Taylor, *Fundamentals of Soil Mechanics*. (New York: John Wiley & Sons, Inc., 1948).

submerged weight. Under the action of upward seepage, the submerged unit weight is reduced approximately by the following amount,

$$\Delta'_v = 20 \frac{H_u}{D} \quad (12-1)$$

where Δ'_v = reduction in submerged unit weight of soil, pcf; the effective unit weight to be used in the computation of passive pressure is $(\gamma' - \Delta'_v)$;

H_u = unbalanced water head, ft;

D = as shown in Fig. 12-7(b).

The relationship between Δ'_v and H_u/D is shown in Fig. 12-7(c).

The effect of downward seepage in the soil behind the piling is very small and may be neglected.

12-7 Design of Cantilever Sheetpiling Walls

A. General principle of design of cantilever sheetpiling. The action of earth pressure against a cantilever sheetpiling can be best illustrated by a simple case shown in Fig. 12-8(a). In this case, the sheetpiling is assumed to be perfectly rigid. When a horizontal force P is applied at the top of the piling, the upper portion of the piling tilts in the direction of P , and the lower portion

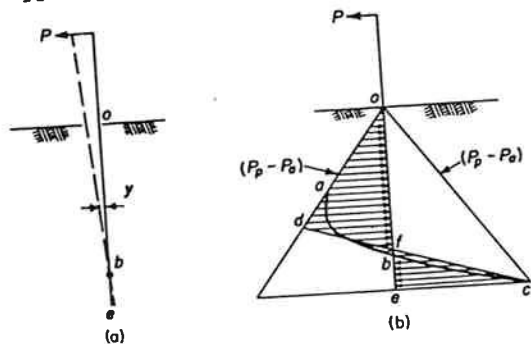


Fig. 12-8 Example illustrating earth pressure on cantilever sheetpiling.

moves in the opposite direction, as shown by a dotted line in the figure. Thus, the piling rotates about a stationary point b . The upper portion ob is subjected to a passive earth pressure from the soil on the left side of the piling, and the lower portion eb is subjected to a passive earth pressure from the soil on the right side of the piling. At point b , the piling does not move and therefore it is subjected to equal and opposite earth pressures (at-rest pressures from both sides) with a net pressure equal to zero. The earth pressure is represented by the diagram $oabc$ in Fig. 12-8(b). The lines oa and oc represent

the net passive resistance which is equal to the passive earth pressure minus the active earth pressure acting in opposite directions. For the purpose of design, the curve of abc is replaced by a straight line dc . Point d is located at such a position on the line oa that the sheetpiling is in static equilibrium under the action of force P and the earth pressure represented by the areas odf and fce . The position of point d can be determined by a trial-and-error method.

This discussion leads to the conclusion that a cantilever sheetpiling derives its stability from passive earth pressure on both sides of the piling. However, the distribution of earth pressure is different between sheetpiling in granular soils and sheetpiling in cohesive soils. And, the pressure distribution is likely to change with time for sheetpilings in clay. Therefore, the design procedures for sheetpiling in both types of soils are discussed separately in the following.

B. Design of cantilever sheetpiling in granular soils. A cantilever sheetpiling to be driven to granular soils may be designed by the conventional method in accordance with the principles just discussed, or by an approximate method based on further simplifying assumptions. These methods are illustrated in Fig. 12-9 where the subsoil is assumed to consist of one layer of

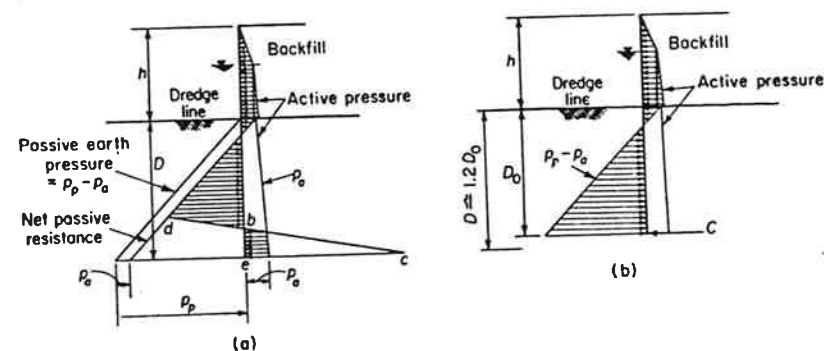


Fig. 12-9 Design of cantilever sheetpiling in granular soils: (a) conventional method; (b) simplified method.

soils throughout the piling penetration. For the cases where two or more layers are penetrated, the earth pressure distributions are different but the basic design concept remains the same.

In either design method, the earth pressure should be calculated by using appropriate values for γ (unit weight), ϕ (angle of internal friction), and δ (angle of wall friction). For ordinary projects, the values shown in Table 12-2 may be used. Note that the earth pressure coefficients listed in the table are for the case of horizontal ground surface. If the soil layers or the ground surface is sloping or irregular, the earth pressure should be determined by the wedge theory, Sec. 5-4, in which the surface of rupture is assumed to

be a spiral surface. Since the application of the wedge theory is laborious, the Coulomb theory is often used instead. The passive pressure obtained by the Coulomb theory should be used conservatively because it is somewhat greater than the actual values.

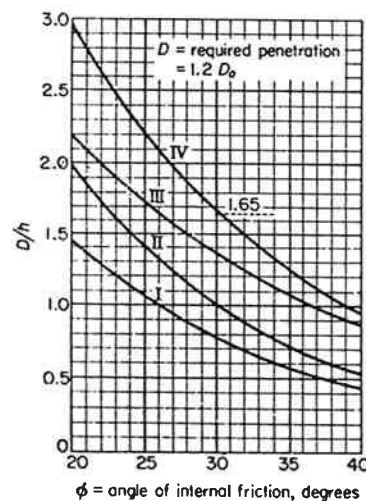
The conventional method of design generally consists of the following steps:

1. Sketch a profile of the piling with a trial depth of penetration. Approximate depth of penetration may be taken as follows:

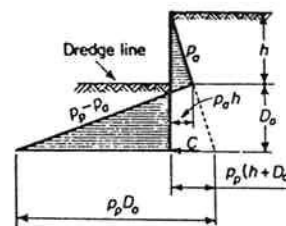
Soil	Depth of penetration*
Dense	$0.75h$
Firm	$1.0h$
Loose	$1.5h$
Very loose	$2.0h$

* h = height of piling above the dredge line.

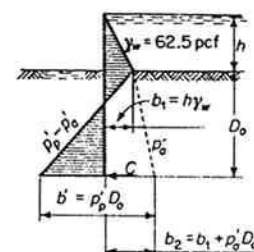
2. Determine the passive earth pressure in front of the piling. This is the gross passive resistance due to the weight of soil. Buoyant weight should be used for soil below water level.
3. Determine the active earth pressure due to surcharge load, the backfill, and the soil layers below.
4. Determine the net passive resistance which is equal to the gross passive pressure (step 2) minus the active earth pressure (step 3).
5. Determine the maximum net passive resistance ce which is equal to the passive pressure due to the backfill and soil below, minus the active earth pressure at the foot of the piling due to the soil in front of the sheetpiling.
6. Draw a trial line cd and check the statical equilibrium of the entire sheetpiling under the action of the lateral forces. The position of point d is correct if the total moment is zero about any point of the piling. When it is impossible to maintain equilibrium with any location of point d , the trial penetration is too small.
7. Add 20 to 40 per cent to the calculated depth of penetration. This will give a safety factor of 1.5 to 2.0 approximately. An alternate and more desirable method is the use of a reduced value of passive earth pressure for design. In this method, the maximum allowable earth pressure is limited to $\frac{1}{2}$ to $\frac{3}{8}$ the ultimate passive resistance.
8. Compute the maximum bending moment which occurs at the point of zero shear prior to increasing the depth by 20 to 40 per cent.



Charts for Depth of penetration



Case I Water below bottom of piling



Case III Piling subjected to hydrostatic pressure only

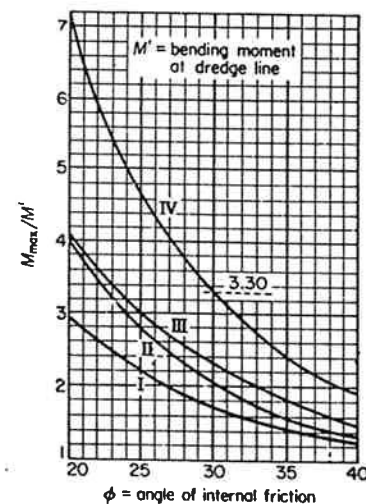
Example

For case IV with $h = 10$ ft

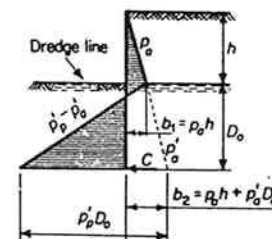
$$\phi = 30^\circ \quad \gamma' = 70 \text{ pcf} \quad p_o = 23.2 \text{ pcf}$$

$$\frac{D}{h} = 1.65 \quad D = 1.65 \times 10 = 16.5 \text{ ft}$$

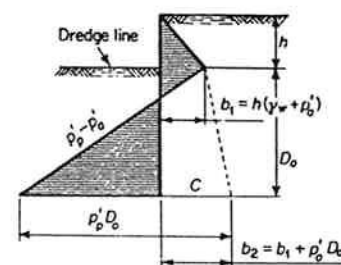
$$M = (62.5 + 23.2) \frac{10^3}{6} = 14,700 \text{ ft-lb}$$



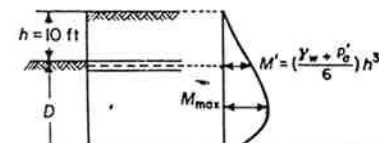
Charts for Bending Moment



Case II Water level at dredge line



Case IV Water level at ground surface



A simplified method of design of cantilever sheetpiling in granular soils is illustrated in Fig. 12-9(b). This method begins with the same steps 1 through 4 as described above; however, the passive resistances are simplified by assuming a right triangle on the left side of the piling and by substitution with a concentrated force C on the right side. These simplifications result in a small error but save in the computation work. The total depth of penetration D may be taken approximately at about 20 per cent higher than D_0 calculated by this method.

In practice, the values of γ , φ , and δ are only estimated from the results of standard penetration tests. Consequently, refinement on the design values is seldom justified. For most cases, the charts shown in Fig. 12-10 will give sufficiently satisfactory results. These charts are constructed on the basis that

$$\begin{aligned}\gamma &= 115 \text{ pcf} && \text{(above water)} \\ \gamma' &= 70 \text{ pcf} && \text{(below water)} \\ \delta &= 0\end{aligned}$$

C. Design of cantilever sheetpiling in cohesive soils. Sheetpiling may be driven in clay, and subsequently, the clay in front of the piling is dredged out; or driven in clay and backfilled with granular soil. The earth pressure acting on the piling is different between these two types.

Furthermore, the strength of clay changes with time and consequently the earth pressure changes with time also. The design must be made for the condition immediately after installation or for a critical condition after changes take place. Immediately after the sheetpiling is installed and the backfill and other loads are applied, the earth pressure may be calculated on the assumption that the angle of friction of clay φ is zero; and the cohesive strength c is equal to half the unconfined compression strength q_u . This case is referred to as the initial earth pressure which may be determined by the classical earth pressure theory.

Figure 12-11 illustrates a case where the sheetpiling is driven into cohesive soil, and the soil in front of the piling is dredged out. From the Rankine theory, Sec. 4-3, the passive earth pressure due to soil in front (on the left side) of the piling is equal to

$$(q_u + \gamma_e Z)$$

and is shown by line gi , where Z = depth below the dredge line. The active earth pressure due to the soil behind (or on the right side) of the piling is equal to

$$(\gamma_e Z - q_u)$$

and is shown by line jk , where Z = depth below the original ground surface. The negative earth pressure; as shown by the dotted line, is usually ignored

because the soil may develop cracks in the upper portion. The net passive resistance is constant throughout the pile penetration D , and is equal to

$$(2q_u - \gamma_e h)$$

For the lower end of the piling where it moves toward the right side, the net maximum passive resistance ce is equal to

$$(2q_u + \gamma_e h)$$

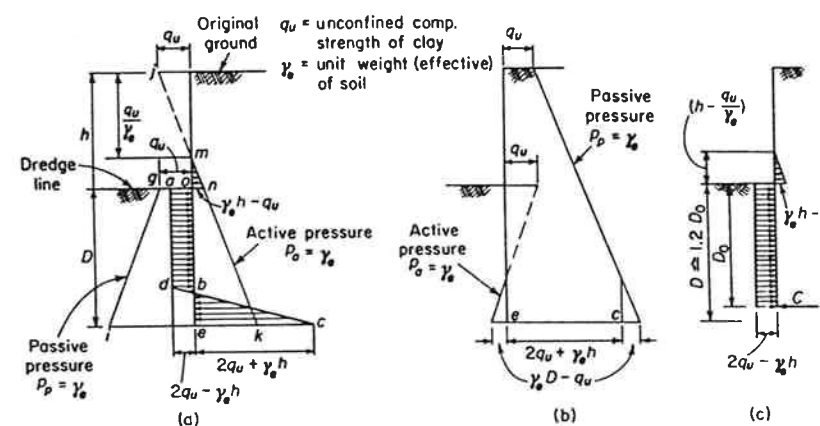


Fig. 12-11 Initial earth pressure for design of cantilever sheetpiling entirely in cohesive soil.

which is derived from Fig. 12-11(b). Based on the discussion of the general principle for cantilever piling, the earth pressure diagram is $mnoadbce$, where point d and the depth of penetration D are so chosen to satisfy the static equilibrium of the lateral forces. Similar to the simplified method for granular soil, the design may be made by the use of the pressure diagram shown in Fig. 12-11(c).

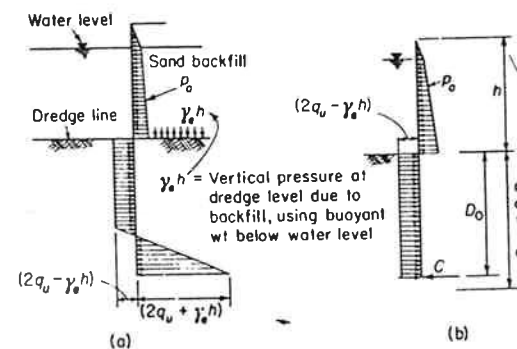


Fig. 12-12 Initial earth pressure for design of cantilever sheetpiling: (a) in cohesive soil; (b) backfilled with granular soil.