Estimating the Sizes of Cantilever Retaining Walls

Estimating the Sizes of Cantilever Retaining Walls

The statical analysis of retaining walls and consideration of their stability as to overturning and sliding are based on service-load conditions. In other words, the length of the footing and the position of the stem on the footing are based entirely on the actual soil backfill, estimated lateral pressure, coefficient of sliding friction of the soil, and so on.

On the other hand, the detailed designs of the stem and footing and their reinforcing are determined by the strength design method. To carry out these calculations, it is necessary to multiply the service loads and pressures by the appropriate load factors. From these factored loads, the bearing pressures, moments, and shears are determined for use in the design.

Estimating the Sizes of Cantilever Retaining Walls

Thus, the initial part of the design consists of an approximate sizing of the retaining wall. Although this is actually a trial-and-error procedure, the values obtained are not too sensitive to slightly incorrect values, and usually one or two trials are sufficient.

Various rules of thumb are available with which excellent initial size estimates can be made. In addition, various handbooks present the final sizes of retaining walls that have been designed for certain specific cases. This information will enable the designer to estimate very well the proportions of a wall to be designed. The *CRSI Design Handbook* is one such useful reference. Suggested methods are presented for estimating sizes without the use of a handbook. These approximate methods are very satisfactory as long as the conditions are not too much out of the ordinary.

Estimating the Sizes of Cantilever Retaining Walls

Stem Thickness

Stems are theoretically thickest at their bases because the shears and moments are greatest there. They will ordinarily have total thicknesses somewhere in the range of 7% to 12% of the overall heights of the retaining walls. The shears and moments in the stem decrease from the bottom to the top; as a result, thicknesses and reinforcement can be reduced proportionately. Stems are normally tapered. The minimum thickness at the top of the stem is 8 in., with 12 in. preferable. As will be shown in Section later, it is necessary to have a mat of reinforcing in the inside face of the stem and another mat in the outside face. To provide room for these two mats of reinforcing, for cover and spacing between the mats, a minimum total thickness of at least 8 in. is required.

Estimating the Sizes of Cantilever Retaining Walls

Stem Thickness

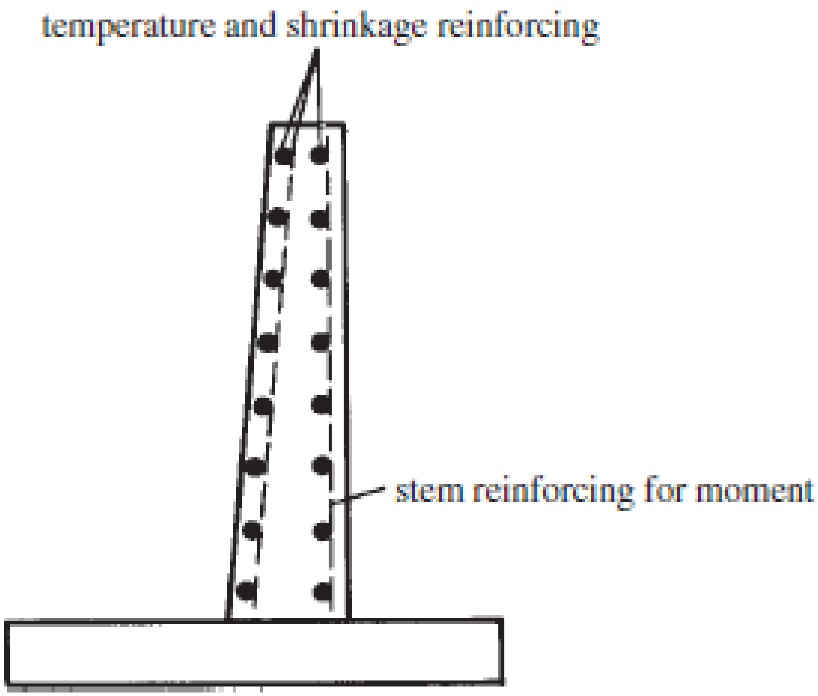

FIGURE 13.12 Cantilever retaining wall with tapered stem.

Estimating the Sizes of Cantilever Retaining Walls

Stem Thickness

The use of the minimum thickness possible for walls that are primarily reinforced in one direction (here it's the vertical bars) doesn't necessarily provide the best economy. The reason is that the reinforcing steel is a major part of the total cost. Making the walls as thin as possible will save some concrete but will substantially increase the amount of reinforcing needed. For fairly high and heavily loaded walls, greater thicknesses of concrete may be economical.

If ρ in the stem is limited to a maximum value of approximately $(0.18f'c/fy)$, the stem thickness required for moment will probably provide sufficient shear resistance without using stirrups. Furthermore, it will probably be sufficiently thick to limit lateral deflections to reasonable values.

Estimating the Sizes of Cantilever Retaining Walls

Stem Thickness

For heights up to about 12 ft, the stems of cantilever retaining walls are normally made of constant thickness because the extra cost of setting the tapered formwork is usually not offset by the savings in concrete. Above 12-ft heights, concrete savings are usually sufficiently large to make tapering economical.

Actually, the sloping face of the wall can be either the front or the back, but if the outside face is tapered, it will tend to counteract somewhat the deflection and tilting of the wall because of lateral pressures. A taper or batter of ¼ in. per foot of height is often recommended to offset deflection or the forward tilting of the wall.

Estimating the Sizes of Cantilever Retaining Walls

Base Thickness

The final thickness of the base will be determined on the basis of shears and moments. For estimating, however, its total thickness will probably fall somewhere between 7% and 10% of the overall wall height. Minimum thicknesses of at least 10 in. to 12 in. are used.

Estimating the Sizes of Cantilever Retaining Walls

Base Length

For preliminary estimates, the base length can be taken to be about 40% to 60% of the overall wall height. A little better estimate, however, can be made by using the method described by Professor Ferguson in his reinforced concrete text. For this discussion, reference is made to Figure 13.13. In this figure, *W* is assumed to equal the weight of all the material within area *abcd*. This area contains both concrete and soil, but the authors assume here that it is all soil. This means that a slightly larger safety factor will be developed against overturning than assumed. When surcharge is present, it will be included as an additional depth of soil, as shown in the figure.

Estimating the Sizes of Cantilever Retaining Walls

Base Length

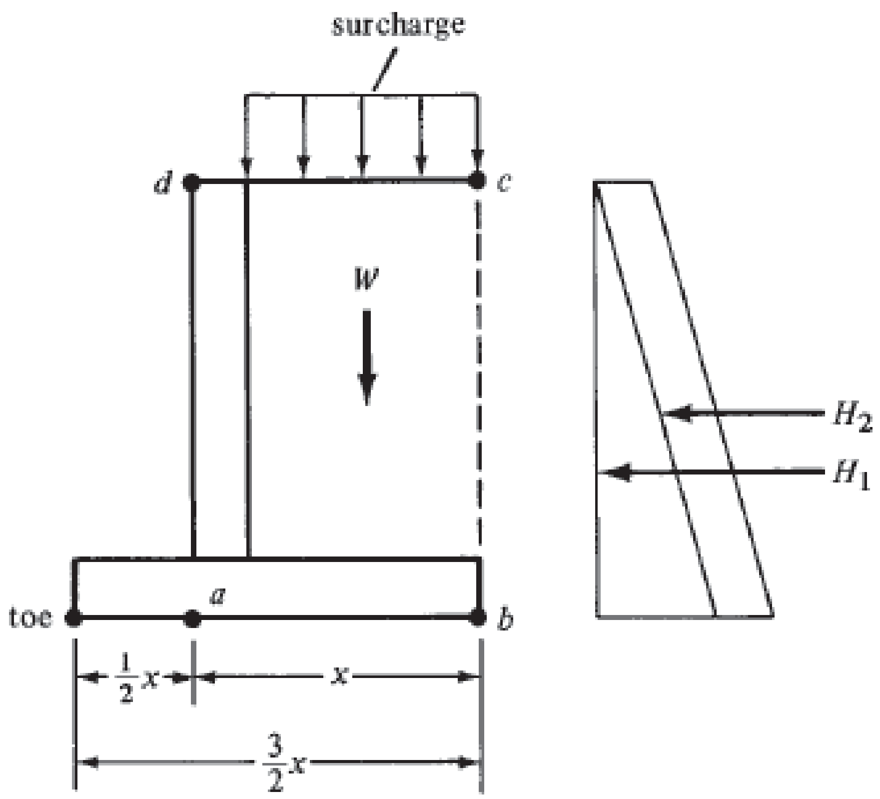

FIGURE 13.13 Forces acting on a cantilever retaining wall.

Estimating the Sizes of Cantilever Retaining Walls

Base Length

If the sum of moments about point *a* due to *W* and the lateral forces H_1 and H_2 equal zero, the resultant force, *R*, will pass through point *a*. Such a moment equation can be written, equated to zero, and solved for *x*. Should the distance from the footing toe to point *a* be equal to one-half of the distance *x* in the figure and the resultant force, *R*, pass through point *a*, the footing pressure diagram will be triangular. In addition, if moments are taken about the toe of all the loads and forces for the conditions described, the safety factor against overturning will be approximately two.

A summary of the preceding approximate first trial sizes for cantilever retaining walls is shown in Figure 13.14. These sizes are based on the dimensions of walls successfully constructed in the past. They often will be on the conservative side.

Estimating the Sizes of Cantilever Retaining Walls

Base Length

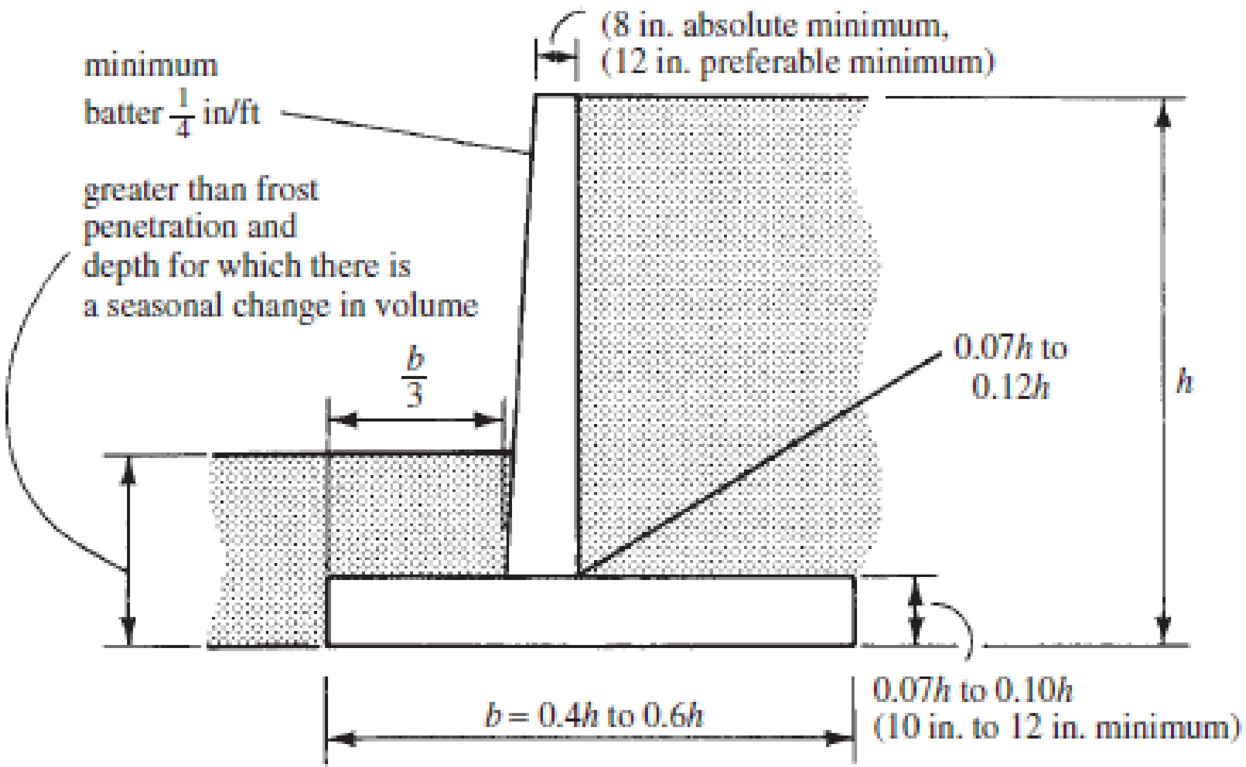

FIGURE 13.14 Rules of thumb for proportioning cantilever retaining walls.

Estimating the Sizes of Cantilever Retaining Walls

Example 13.2

Using the approximate rules presented, estimate the sizes of the parts of the retaining wall shown in next figure. The soil weighs 100 lb/ft³, and a surcharge of 300 psf is present. Assume k_a = 0.32. (For many practical soils such as clays or silts, k_a will be two or more times this large.)

Solution

Stem Thickness

Assume 12 in. thickness at top.

$$\text{Assume bottom thickness} = \boxed{0.07h = (0.07)(21\text{ ft}) = 1.47\text{ ft}} \qquad \underline{\underline{\text{Say 1 ft 6 in.}}}$$

Base Thickness

$\boxed{\text{Assume base } t = 7\% \text{ to } 10\% \text{ of overall wall height.}}$

$$t = (0.07)(21\text{ ft}) = 1.47\text{ ft} \qquad \underline{\underline{\text{Say 1 ft 6 in.}}}$$

$$\text{Height of stem} = 21\text{ ft 0 in.} - 1\text{ ft 6 in.} = \underline{\underline{19\text{ ft 6 in.}}}$$

Estimating the Sizes of Cantilever Retaining Walls

Example 13.2

Solution

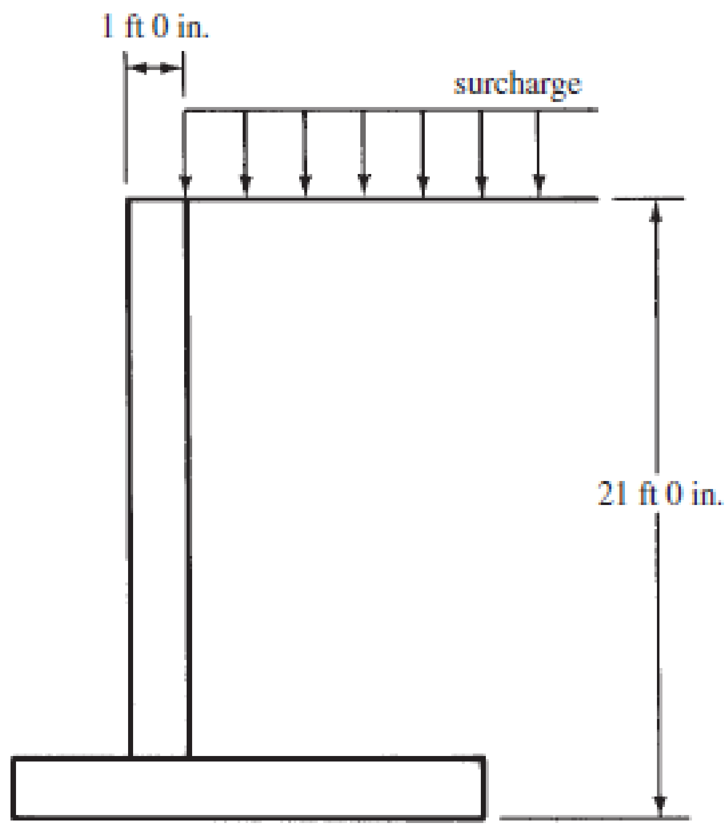

FIGURE 13.15 Cantilever retaining wall for Example 13.2.

Estimating the Sizes of Cantilever Retaining Walls

Example 13.2

Solution

Base Length and Position of Stem

Calculating horizontal forces without load factors, as shown in Figure 13.16.

$$\boxed{p_a = k_a wh = (0.32)(100\text{ pcf})(21\text{ ft}) = 672\text{ lb/ft}^2}$$

$$H_1 = \left(\frac{1}{2}\right)(21\text{ ft})(672\text{ lb/ft}^2) = 7056\text{ lb/ft}$$

$$H_2 = (21\text{ ft})\boxed{(96\text{ psf})} = 2016\text{ lb/ft}$$

$$W = (x)(24\text{ ft})(100\text{ psf}) = 2400x$$

$\Sigma M_a = 0$

$$-(7056\text{ lb/ft})(7.00\text{ ft}) - (2016\text{ lb/ft})(10.5\text{ ft}) + (2400x)\left(\frac{x}{2}\right) = 0$$

$$x = 7.67\text{ ft}$$

$$b = \left(\frac{3}{2}\right)(7.67\text{ ft}) = 11.505\text{ ft}$$

Say 11 ft 6 in.

The final trial dimensions are shown in Figure 13.22.

Estimating the Sizes of Cantilever Retaining Walls

Example 13.2

Solution

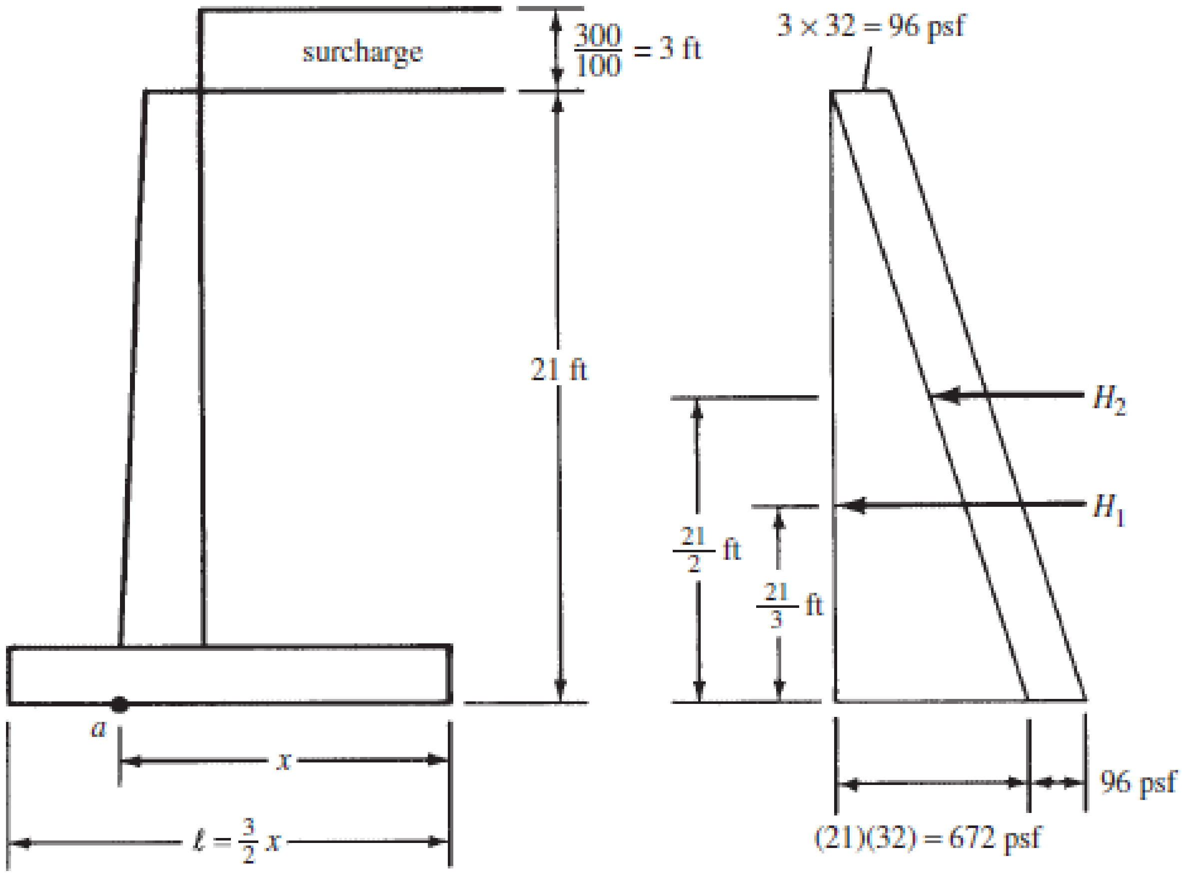

FIGURE 13.16 Forces acting on retaining wall for Example 13.2.

Design Procedure for Cantilever Retaining Walls

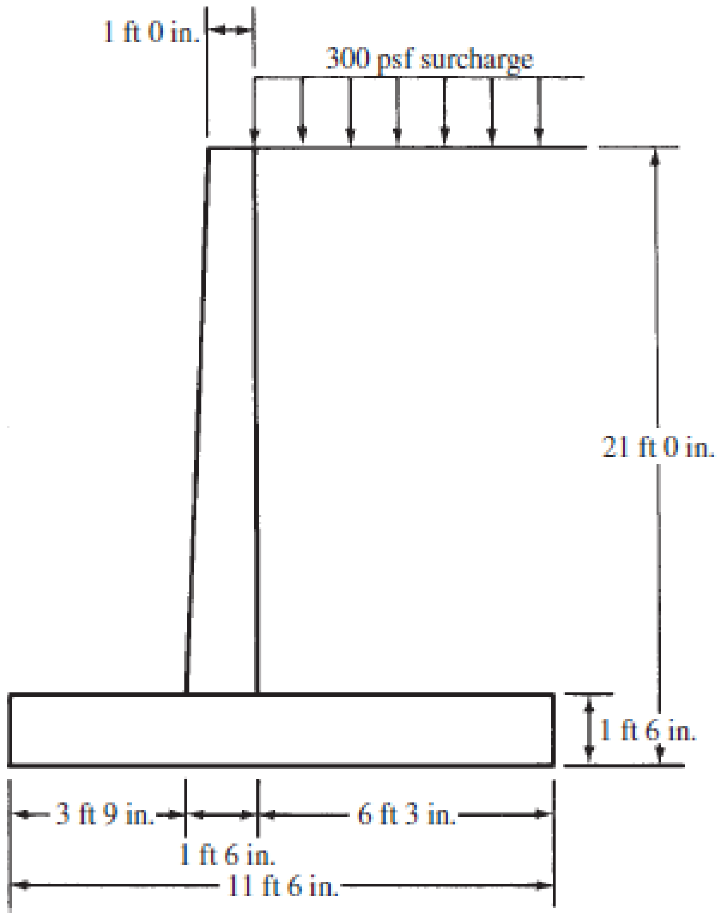

FIGURE 13.22 Dimensions of retaining wall for Example 13.3.

Design Procedure for Cantilever Retaining Walls

Design Procedure for Cantilever Retaining Walls

This section is provides in some detail the procedure used for designing a cantilever retaining wall. At the end, the complete design of such a wall is presented. Once the approximate size of the wall has been established, the stem, toe, and heel can be designed in detail. Each of these parts will be designed individually as a cantilever sticking out of a central mass.

Stem

The values of shear and moment at the base of the stem resulting from lateral earth pressures are computed and used to determine the stem thickness and necessary reinforcing. Because the lateral pressures are considered to be live load forces, a load factor of 1.6 is used.

Design Procedure for Cantilever Retaining Walls

Stem

It will be noted that the bending moment requires the use of vertical reinforcing bars on the soil side of the stem. In addition, temperature and shrinkage reinforcing must be provided. In Section 14.3 of the ACI Code, a minimum value of horizontal reinforcing equal to 0.0025 of the area of the wall, bt, is required as well as a minimum amount of vertical reinforcing (0.0015). These values may be reduced to 0.0020 and 0.0012 if the reinforcing is ⅝ in. or less in diameter and if it consists of bars or welded wire fabric (not larger than $W31$ or $D31$), with f_y equal to or greater than 60,000 psi.

Design Procedure for Cantilever Retaining Walls

Stem

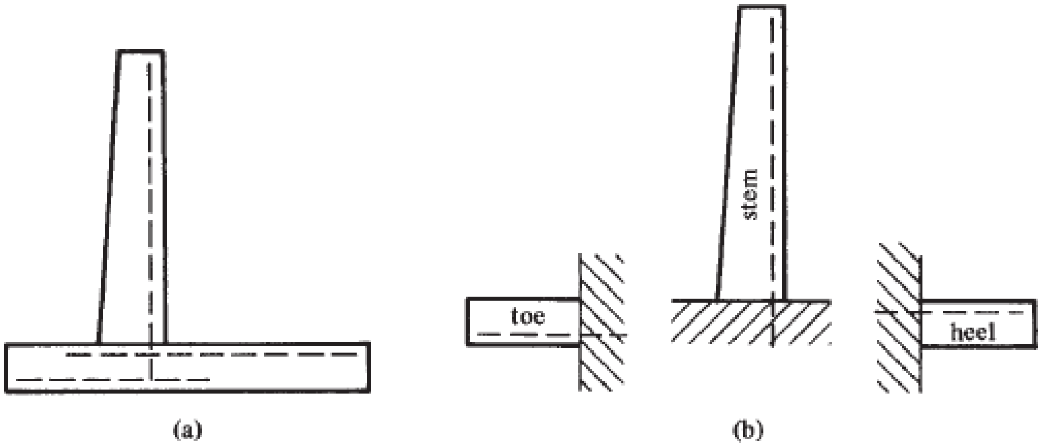

FIGURE 13.17 Cantilever beam model used to design retaining wall stem, heel, and toe.

The major changes in temperature occur on the front or exposed face of the stem. For this reason, most of the horizontal reinforcing (perhaps two-thirds) should be placed on that face with just enough vertical steel used to support the horizontal bars. The concrete for a retaining wall should be placed in fairly short lengths—not greater than 20-ft or 30-ft sections—to reduce shrinkage stresses.

Design Procedure for Cantilever Retaining Walls

Factor of Safety Against Sliding

Consideration of sliding for retaining walls is a most important topic because a very large percentage of retaining wall failures occur because of sliding. To calculate the factor of safety against sliding, the estimated sliding resistance (equal to the coefficient of friction for concrete on soil times the resultant vertical force, μR_v) is divided by the total horizontal force. The passive pressure against the wall is neglected, and the un-factored loads are used.

Typical design values of μ, the coefficient of friction between the footing concrete and the supporting soil, are as follows: 0.45 to 0.55 for coarse-grained soils, with the lower value applying if some silt is present, and 0.6 if the footing is supported on sound rock with a rough surface. Values of 0.3 to 0.35 are used if the supporting material is silt.

Design Procedure for Cantilever Retaining Walls

Factor of Safety Against Sliding

It is usually felt that the factor of safety against sliding should be at least equal to 1.5. When retaining walls are initially designed, the calculated factor of safety against sliding is very often considerably less than this value. To correct the situation, the most common practice is to widen the footing on the heel side. Another practice is to use a lug or key, as shown in Figure 13.18, with the front face cast directly against undisturbed soil. (Many designers feel that the construction of keys disturbs the soil so much that they are not worthwhile.) Keys are thought to be particularly necessary for moist clayey soils. The purpose of a key is to cause the development of passive pressure in front of and below the base of the footing, as shown by P_p in the figure.

Design Procedure for Cantilever Retaining Walls

Factor of Safety Against Sliding

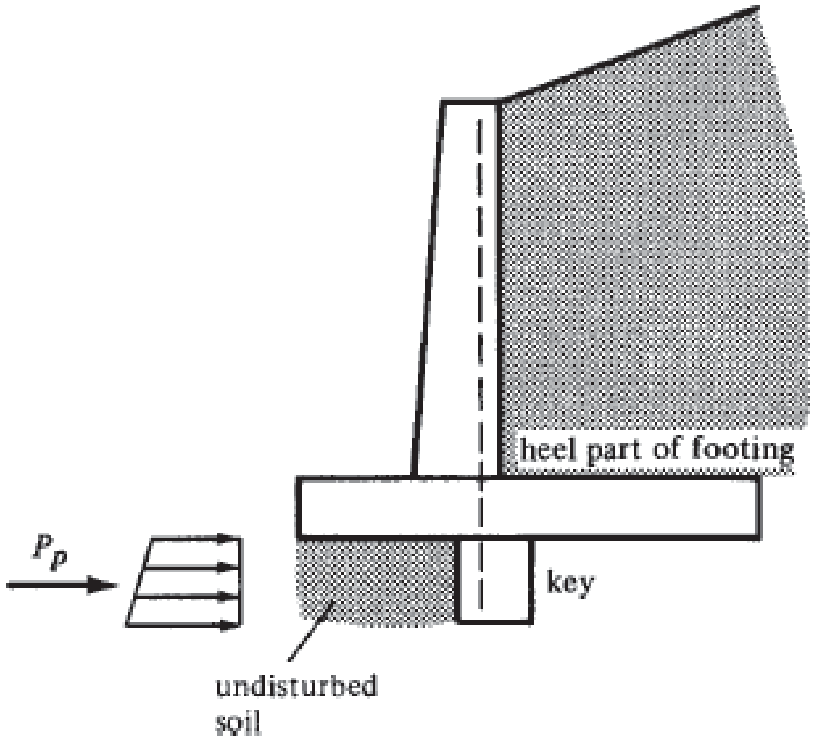

FIGURE 13.18 Passive pressure in a lug.

Design Procedure for Cantilever Retaining Walls

Factor of Safety Against Sliding

Many designers select the sizes of keys by rules of thumb. One common practice is to give them a depth between two-thirds and the full depth of the footing. They are usually made approximately square in cross section and have no reinforcing provided other than perhaps the dowels mentioned in the next paragraph.

Keys are often located below the stem so that some dowels or extended vertical reinforcing may be extended into them. If this procedure is used, the front face of the key needs to be at least 5 in. or 6 in. in front of the back face of the stem to allow room for the dowels. From a soil mechanics view, keys may be a little more effective if they are placed a little farther toward the heel.

Design Procedure for Cantilever Retaining Walls

Factor of Safety Against Sliding

If the key can be extended down into a very firm soil or even rock, the result will be a greatly increased sliding resistance—that resistance being equal to the force necessary to shear the key off from the footing.

Design Procedure for Cantilever Retaining Walls

Heel Design

Lateral earth pressure tends to cause the retaining wall to rotate about its toe. This action tends to pick up the heel into the backfill. The backfill pushes down on the heel cantilever, causing tension in its top. The major force applied to the heel of a retaining wall is the downward weight of the backfill behind the wall. Although it is true that there is some upward soil pressure, many designers choose to neglect it because it is relatively small. The downward loads tend to push the heel of the footing down, and the necessary upward reaction to hold it attached to the stem is provided by the vertical tensile steel in the stem, which is extended down into the footing.

Design Procedure for Cantilever Retaining Walls

Heel Design

Because the reaction in the direction of the shear does not introduce compression into the heel part of the footing in the region of the stem, it is not permissible to determine V_u at a distance d from the face of the stem, as provided in Section 11.1.3.1 of the ACI Code. The value of V_u is determined instead at the face of the stem because of the downward loads. This shear is often of such magnitude as to control the thickness, but the moment at the face of the stem should be checked also. Because the load here consists of soil and concrete, a load factor of 1.2 is used for making the calculations.

It will be noted that the bars in the heel will be in the top of the footing. As a result, the required development length of these "top bars" may be rather large.

Design Procedure for Cantilever Retaining Walls

Heel Design

The percentage of flexural steel required for the heel frequently is less than the ρ_{min} of $200/f_y$ and $3\sqrt{f'_c}/f_y$. Despite the fact that the ACI Code (10.5.4) exempts slabs of uniform from these ρ_{min} values, it is recommended that these be used because the retaining wall is a major beam like structure.

Design Procedure for Cantilever Retaining Walls

Toe Design

The toe is assumed to be a beam cantilevered from the front face of the stem. The loads it must support include the weight of the cantilever slab and the upward soil pressure beneath. Usually any earth fill on top of the toe is neglected (as though it has been eroded). Obviously, such a fill would increase the upward soil pressure beneath the footing, but because it acts downward and cancels out the upward pressure, it produces no appreciable changes in the shears and moments in the toe.

A study of Figure 13.19 shows that the upward soil pressure is the major force applied to the toe. Because this pressure is primarily caused by the lateral force *H*, a load factor of 1.6 is used for the calculations.

Design Procedure for Cantilever Retaining Walls

Toe Design

The maximum moment for design is taken at the face of the stem, whereas the maximum shear for design is assumed to occur at a distance *d* from the face of the stem because the reaction in the direction of the shear does introduce compression into the toe of the footing. The average designer makes the thickness of the toe the same as the thickness of the heel, although such a practice is not essential.

Design Procedure for Cantilever Retaining Walls

Toe Design

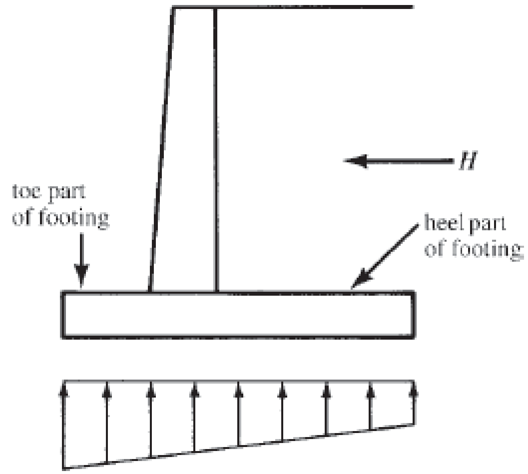

FIGURE 13.19 Assumed soil stress distribution at the base.

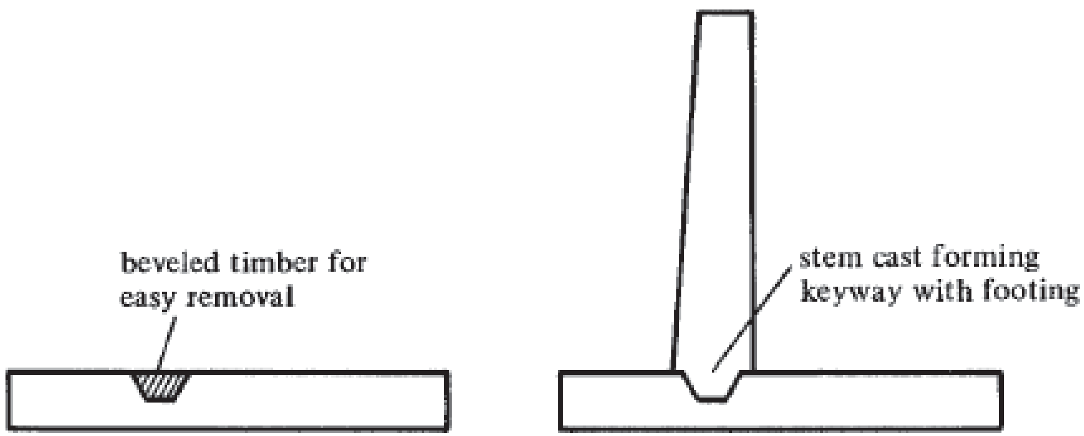

FIGURE 13.20 Keyway for improved shear capacity.

Design Procedure for Cantilever Retaining Walls

Toe Design

It is a common practice in retaining wall construction to provide a shear keyway between the base of the stem and the footing. This practice, though definitely not detrimental, is of questionable value. The keyway is normally formed by pushing a beveled 2 in. × 4 in. or 2 in. × 6 in. into the top of the footing, as shown in Figure 13.20. After the concrete hardens, the wood member is removed, and when the stem is cast in place above, a keyway is formed. It is becoming more and more common simply to use a roughened surface on the top of the footing where the stem will be placed. This practice seems to be just as satisfactory as the use of a keyway.

Design Procedure for Cantilever Retaining Walls

Toe Design

In next example, #8 bars 6 in. on center are selected for the vertical steel at the base of the stem. These bars need to be embedded into the footing for development purposes, or dowels equal to the stem steel need to be used for the transfer. This latter practice is quite common because it is rather difficult to hold the stem steel in position while the base concrete is placed.

The required development length of the #8 bars down into the footing or for #8 dowels is 33 in. when f_y = 60,000 psi and f'_c = 3000 psi. This length cannot be obtained vertically in the 1-ft-6-in. footing used unless the bars or dowels are either bent as shown in Figure 13.21(a) or extended through the footing and into the base key as shown in Figure 13.21(b).

Design Procedure for Cantilever Retaining Walls

Toe Design

Actually, the required development length can be reduced if more but smaller dowels are used. For #6 dowels, l*d* is 20 in.

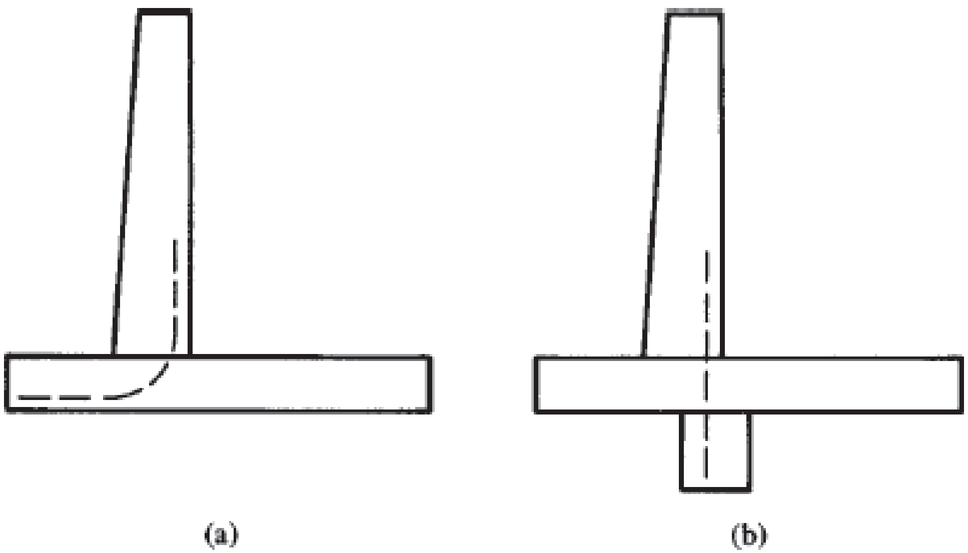

FIGURE 13.21 Bar development options.

Design Procedure for Cantilever Retaining Walls

Toe Design

If instead of dowels the vertical stem bars are embedded into the footing, they should not extend up into the wall more than 8 ft or 10 ft before they are spliced because they are difficult to handle in construction and may easily be bent out of place or even broken. Actually, after examining Figure 13.21(a), you can see that such an arrangement of stem steel can sometimes be very advantageous economically.

The bending moment in the stem decreases rapidly above the base; as a result, the amount of reinforcing can be similarly reduced. It is to be remembered that these bars can be cut off only in accordance with the ACI Code development length requirements.

Design Procedure for Cantilever Retaining Walls

Example 13.3

Complete the design of the cantilever retaining wall whose dimensions were estimated in Example 13.2, if $f'c$ = 3000 psi, fy = 60,000 psi, qa = 4000 psf, and the coefficient of sliding friction equals 0.50 for concrete on soil. Use ρ approximately equal to 0.18$f'c/fy$ to maintain reasonable deflection control.

Solution

The safety factors against overturning and sliding and the soil pressures under the heel and toe are computed using the actual un-factored loads.

Design Procedure for Cantilever Retaining Walls

Example 13.3

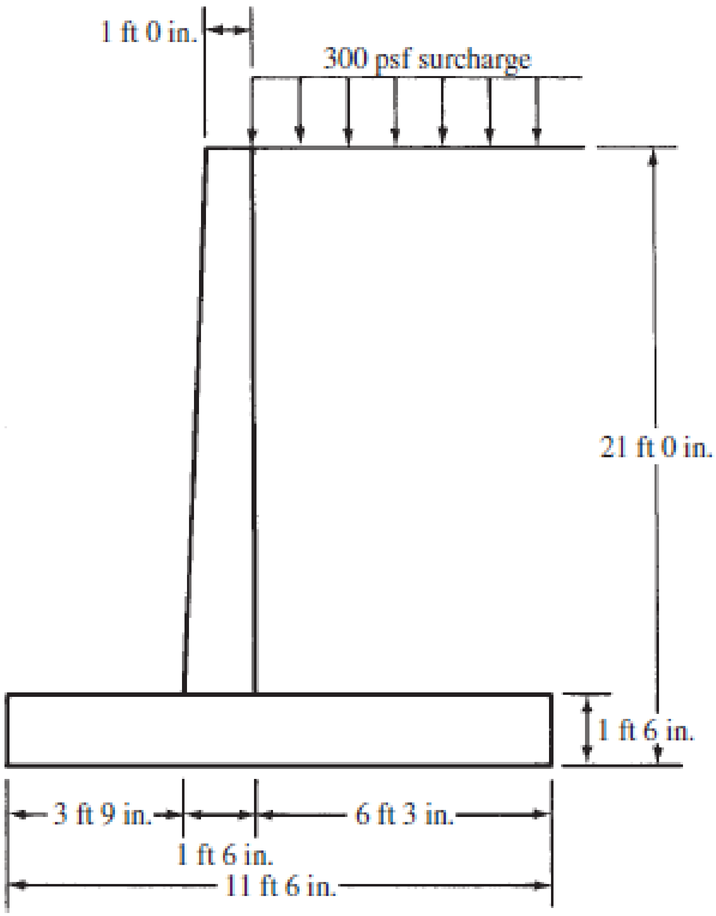

FIGURE 13.22 Dimensions of retaining wall for Example 13.3.

Design Procedure for Cantilever Retaining Walls

Example 13.3

Forces

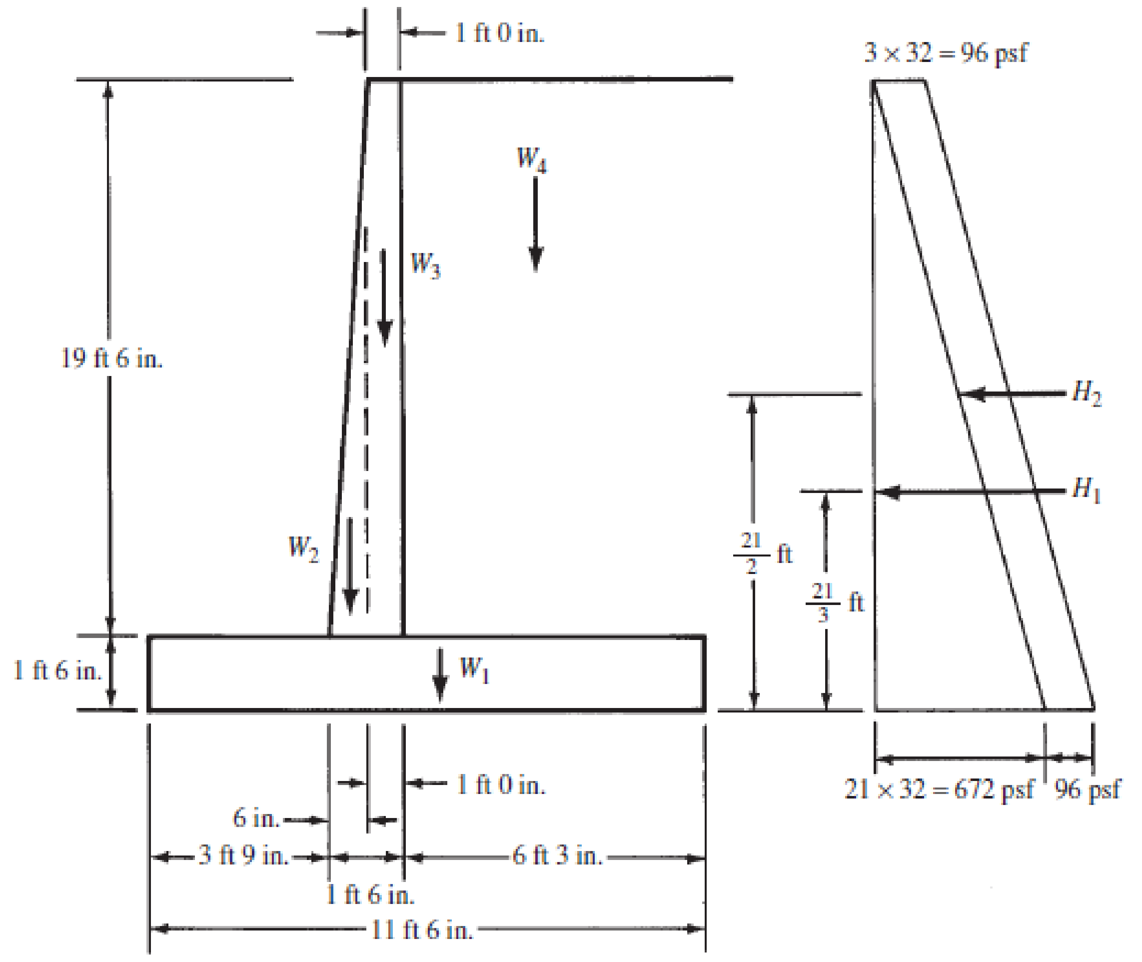

FIGURE 13.23 Forces acting on retaining wall for Example 13.3.

Design Procedure for Cantilever Retaining Walls

Example 13.3

Overturning

Safety Factor against Overturning (with Reference to Figure 13.23)

Overturning Moment		
Force	**Moment Arm**	**Moment**
$H_1 = (\frac{1}{2})(21\text{ ft})(672\text{ psf}) = 7056\text{ lb}$	$\times\ 7.00\text{ ft}$	$= 49{,}392\text{ ft-lb}$
$H_2 = (21\text{ ft})(96\text{ psf}) = 2016\text{ lb}$	$\times\ 10.50\text{ ft}$	$= \underline{21{,}168\text{ ft-lb}}$
Total		70,560 ft-lb

Righting Moment		
Force	**Moment Arm**	**Moment**
$W_1 = (1.5\text{ ft})(11.5\text{ ft})(150\text{ pcf}) = 2{,}588\text{ lb}$	$\times\ 5.75\text{ ft}$	$= 14{,}881\text{ ft-lb}$
$W_2 = (\frac{1}{2})(19.5\text{ ft})(\frac{6}{12}\text{ ft})(150\text{ pcf}) = 731\text{ lb}$	$\times\ 4.08\text{ ft}$	$= 2{,}982\text{ ft-lb}$
$W_3 = (19.5\text{ ft})(\frac{12}{12}\text{ ft})(150\text{ pcf}) = 2{,}925\text{ lb}$	$\times\ 4.75\text{ ft}$	$= 13{,}894\text{ ft-lb}$
$W_4 = (22.5\text{ ft})(6.25\text{ ft})(100\text{ pcf}) = \underline{14{,}062\text{ lb}}$	$\times\ 8.37\text{ ft}$	$= \underline{117{,}699\text{ ft-lb}}$*
$R_v = 20{,}306\text{ lb}$		$M = 149{,}456\text{ ft-lb}$

* Includes surcharge.

Design Procedure for Cantilever Retaining Walls

Factor of Safety Against Sliding

Here the passive pressure against the wall is neglected. Normally it is felt that the factor of safety should be at least 1.5.

$$\text{Force causing sliding} = H_1 + H_2 = 9072 \text{ lb}$$

$$\text{Resisting force} = \mu R_v = (0.50)(20{,}306 \text{ lb}) = 10{,}153 \text{ lb}$$

$$\text{Safety factor} = \frac{10{,}153 \text{ lb}}{9072 \text{ lb}} = 1.12 < 1.50 \qquad \underline{\underline{\text{No good}}}$$

Design Procedure for Cantilever Retaining Walls

Footing Soil Pressures

$R_v = 20{,}306$ lb and is located a distance $\bar{x}$ from the toe of the footing

$$\bar{x} = \frac{149{,}456 \text{ ft-lb} - 70{,}560 \text{ ft-lb}}{20{,}306 \text{ lb}} = \frac{78{,}896 \text{ ft-lb}}{20{,}306 \text{ lb}} = 3.89 \text{ ft}$$

Just inside middle third

$$\text{Soil pressure} = -\frac{R_v}{A} \pm \frac{Mc}{I}$$

$$A = (1 \text{ ft})(11.5 \text{ ft}) = 11.5 \text{ ft}^2$$

$$I = \left(\frac{1}{12}\right)(1 \text{ ft})(11.5 \text{ ft})^3 = 126.74 \text{ ft}^4$$

$$f_{\text{toe}} = -\frac{20{,}306 \text{ lb}}{11.5 \text{ ft}^2} - \frac{(20{,}306 \text{ lb})(5.75 \text{ ft} - 3.89 \text{ ft})(5.75 \text{ ft})}{126.74 \text{ ft}^4}$$

$$= -1766 \text{ psf} - 1714 \text{ psf} = -3480 \text{ psf}$$

$$f_{\text{heel}} = -1766 \text{ psf} + 1714 \text{ psf} = -52 \text{ psf}$$

Design Procedure for Cantilever Retaining Walls

Design of Stem for Moment

$$M_u = (H_1)(6.50\text{ ft}) + (H_2)(9.75\text{ ft}) = (9734\text{ lb})(6.50\text{ ft}) + (2995\text{ lb})(9.75\text{ ft})$$

$$M_u = 92{,}472\text{ ft-lb}$$

Use

$$\rho = \text{approximately } \frac{0.18 f'_c}{f_y} = \frac{(0.18)(3000\text{ psi})}{60{,}000\text{ psi}} = 0.009$$

$$\frac{M_u}{\phi b d^2} = 482.6\text{ psi} \text{ (from Appendix A, Table A.12)}$$

$$bd^2 = \frac{(12\text{ in/ft})(92{,}472\text{ ft-lb})}{(0.9)(482.6\text{ psi})} = 2555\text{ in.}^3$$

$$d = \sqrt{\frac{2555\text{ in.}^3}{12\text{ in.}}} = 14.59\text{ in.}$$

$$h = 14.59\text{ in.} + 2\text{ in.} + \frac{1\text{ in.}}{2} = 17.09\text{ in.} \quad \underline{\underline{\text{Say } 18\text{ in. } (d = 15.50\text{ in.})}}$$

Design Procedure for Cantilever Retaining Walls

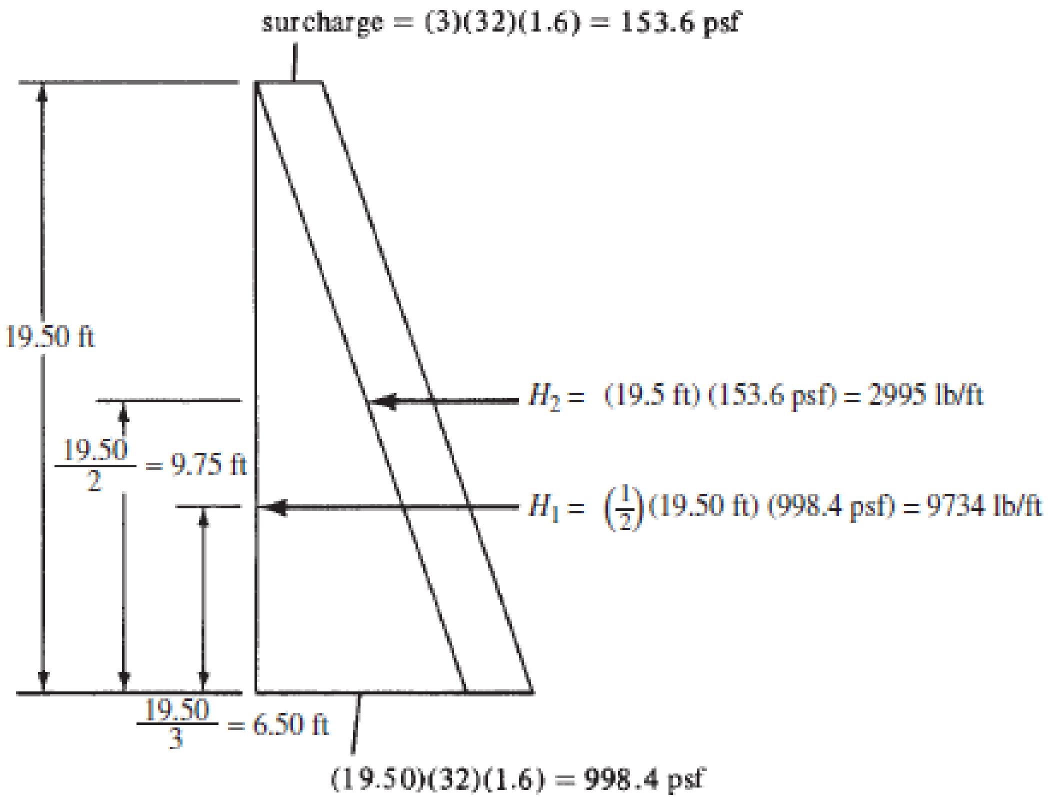

FIGURE 13.24 Lateral forces from backfill and surcharge.

Design Procedure for Cantilever Retaining Walls

$$\frac{M_u}{\phi b d^2} = \frac{(12 \text{ in/ft})(92{,}472 \text{ ft-lb})}{(0.90)(12 \text{ in.})(15.5 \text{ in.})^2} = 427.7 \text{ psi}$$

$$\rho = 0.00786 \text{ (from Appendix A, Table A.12)}$$

$$A_s = (0.00786)(12 \text{ in.})(15.5 \text{ in.}) = 1.46 \text{ in.}^2 \qquad \underline{\underline{\text{Use \#8 @ 6 in. } (1.57 \text{ in.}^2)}}$$

$$\text{Minimum vertical } \rho \text{ by ACI Section 14.3} = 0.0015 < \frac{1.57 \text{ in.}^2}{(12 \text{ in.})(15.5 \text{ in.})} = 0.0084 \qquad \underline{\underline{\text{OK}}}$$

$$\text{Minimum horizontal } A_s = (0.0025)(12 \text{ in.})(\text{average stem } t)$$

$$= (0.0025)(12 \text{ in.})\left(\frac{12 \text{ in.} + 18 \text{ in.}}{2}\right) = 0.450 \text{ in.}^2$$

(say one-third inside face and two-thirds outside face)

$$\underline{\underline{\text{Use \#4 @ } 7\tfrac{1}{2} \text{ in. outside face and \#4 @ 15 in. inside face}}}$$

Design Procedure for Cantilever Retaining Walls

Checking Shear Stress in Stem

Actually, *Vu* at a distance *d* from the top of the footing can be used, but for simplicity:

$$V_u = H_1 + H_2 = 9734 \text{ lb} + 2995 \text{ lb} = 12{,}729 \text{ lb}$$

$$\phi V_c = \phi 2\lambda\sqrt{f'_c}bd = (0.75)(2)(1.0)(\sqrt{3000}\text{ psi})(12\text{ in.})(15.5\text{ in.})$$

$$= 15{,}281 \text{ lb} > 12{,}729 \text{ lb} \qquad \underline{\underline{\text{OK}}}$$

Design of Heel

The upward soil pressure is conservatively neglected, and a load factor of 1.2 is used for calculating the shear and moment because soil and concrete make up the load.

$$V_u = (22.5\text{ ft})(6.25\text{ ft})(100\text{ pcf})(1.2) + (1.5\text{ ft})(6.25\text{ ft})(150\text{ pcf})(1.2) = 18{,}563 \text{ lb/ft}$$

$$\phi V_c = (0.75)(2)(1.0)(\sqrt{3000}\text{ psi})(12\text{ in.})(14.5\text{ in.}) = 14{,}295 \text{ lb} < 18{,}563 \text{ lb} \qquad \underline{\underline{\text{No good}}}$$

Design Procedure for Cantilever Retaining Walls

Example 13.3

Design of Heel

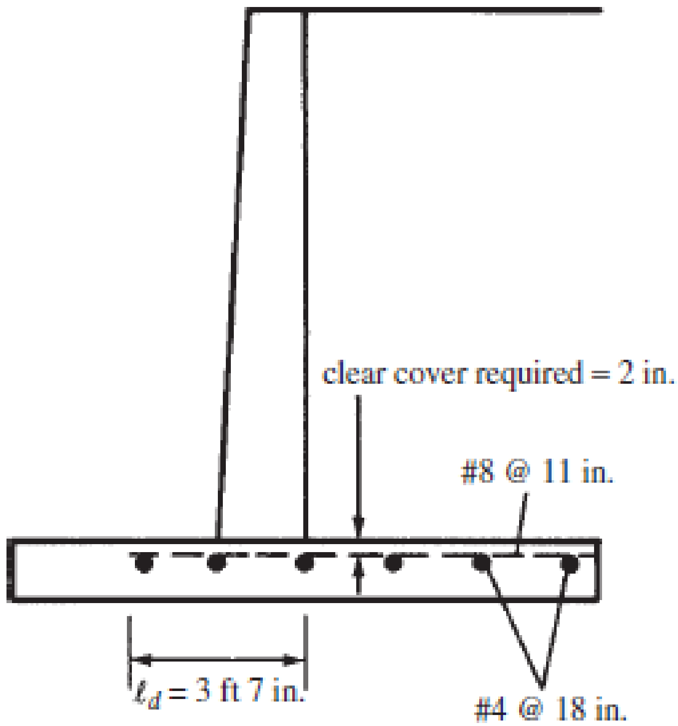

FIGURE 13.25 Heel reinforcing.

Design Procedure for Cantilever Retaining Walls

Try 24-in. Depth (d =20.5 in.)

Neglecting slight change in V_u with different depth

$$\phi V_c = (0.75)(2)(1.0)(\sqrt{3000}\text{ psi})(12\text{ in.})(20.5\text{ in.})$$

$$= 20{,}211\text{ lb} > 18{,}563\text{ lb} \qquad \underline{\underline{\text{OK}}}$$

$$M_u \text{ at face of stem} = (18{,}563\text{ lb})\left(\frac{6.25\text{ ft}}{2}\right) = 58{,}009\text{ ft-lb}$$

$$\frac{M_u}{\phi b d^2} = \frac{(12\text{ in/ft})(58{,}009\text{ ft-lb})}{(0.9)(12\text{ in.})(20.5\text{ in.})^2} = 153\text{ psi}$$

$$\rho = \rho_{\min}$$

Using $\rho = 0.00333$,

$$A_x = (0.00333)(12\text{ in.})(20.5\text{ in.}) = 0.82\text{ in}^2/\text{ft} \qquad \underline{\underline{\text{Use \#8 @ 11 in.}}}$$

ℓ_d required calculated with ACI Equation 12-1 for #8 top bars with $c = 2.50$ in. and $K_{tr} = 0$ is 43 in. $<$ 72 in. available. $\underline{\text{OK}}$

Design Procedure for Cantilever Retaining Walls

Try 24-in. Depth (d =20.5 in.)

Heel reinforcing is shown in Figure 13.25.

Note: Temperature and shrinkage steel is normally considered unnecessary in the heel and toe.

Design of Toe

For service loads, the soil pressures previously determined are multiplied by a load factor of 1.6 because they are primarily caused by the lateral forces, as shown in Figure 13.26.

$$V_u = 10{,}440 \text{ lb} + 7086 \text{ lb} = 17{,}526 \text{ lb}$$

(The shear can be calculated a distance *d* from the face of the stem because the reaction in the direction of the shear does introduce compression into the toe of the slab, but this advantage is neglected because 17,526 lb is already less than the 19,125 lb shear in the heel, which was satisfactory.)

Design Procedure for Cantilever Retaining Walls

Example 13.3

Design of Toe

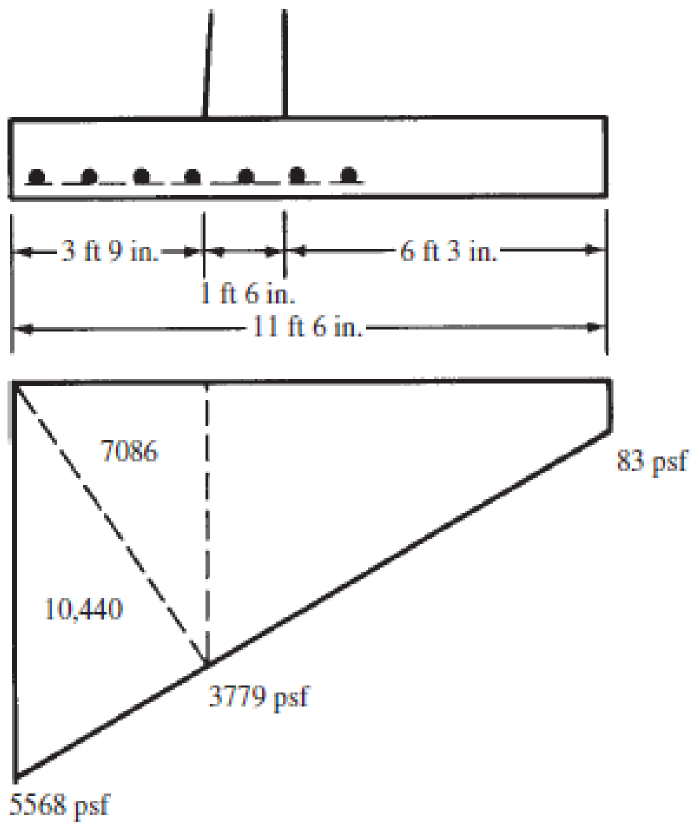

FIGURE 13.26 Soil reactions.

Design Procedure for Cantilever Retaining Walls

Example 13.3

Design of Toe

$$M_u \text{ at face of stem} = (7086 \text{ lb})\left(\frac{3.75 \text{ ft}}{3}\right) + (10{,}440 \text{ lb})\left(\frac{2}{3} \times 3.75 \text{ ft}\right) = 34{,}958 \text{ ft-lb}$$

$$\frac{M_u}{\phi b d^2} = \frac{(12 \text{ in/ft})(34{,}958 \text{ ft-lb})}{(0.9)(12 \text{ in.})(20.5 \text{ in.})^2} = 92 \text{ psi}$$

$$\rho = \text{less than } \rho_{\min}$$

Therefore, use

$$\frac{200}{60{,}000 \text{ psi}} = 0.00333$$

$$A_s = (0.00333)(12 \text{ in.})(20.5 \text{ in.}) = 0.82 \text{ in}^2/\text{ft}$$

Use #8 @ 11 in.

ℓ_d required calculated with ACI Equation 12-1 for #8 bottom bars with $c = 2.50$ in. and $K_{tr} = 0$ equals 33 in. $<$ 42 in. available. OK

Design Procedure for Cantilever Retaining Walls

Design of Toe

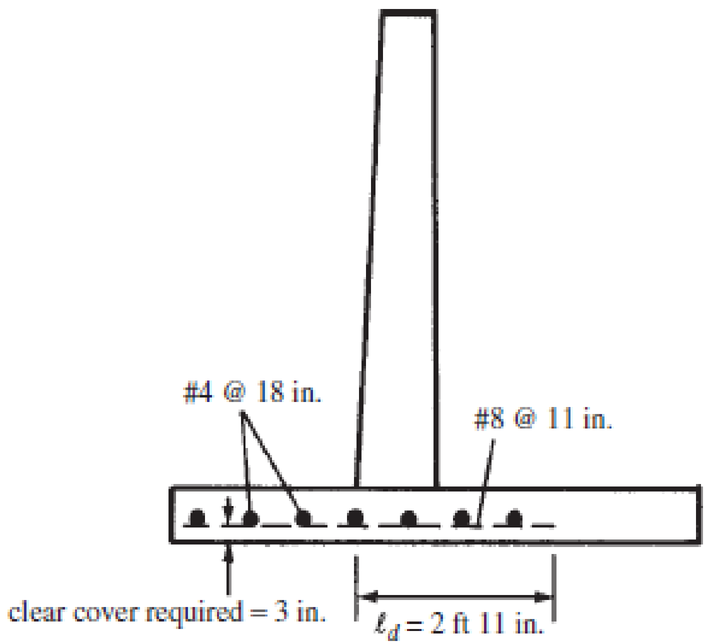

FIGURE 13.27 Toe reinforcing.

Design Procedure for Cantilever Retaining Walls

TABLE 13.1 Stem Design for Example 13.3

Distance from Top of Stem (ft)	M_u (ft-lb)	Effective Stem d (in.)	ρ	$A_{s\ required}$ (in^2/ft)	Bars Needed
5	2,987	11.04	Use $\rho_{min} = 0.00333$	0.44	#8 @ 18 in.
10	16,213	12.58	Use $\rho_{min} = 0.00333$	0.50	#8 @ 18 in.
15	46,080	14.12	0.00452	0.77	#8 @ 12 in.
19.5	92,472	15.50	0.00786	1.46	#8 @ 6 in.

Selection of Dowels and Lengths of Vertical Stem Reinforcing

The detailed selection of vertical bar lengths in the stem is omitted here to save space, and only a few general comments are presented. Table 13.1 shows the reduced bending moments up in the stem and the corresponding reductions in reinforcing required.

Design Procedure for Cantilever Retaining Walls

Selection of Dowels and Lengths of Vertical Stem Reinforcing

After considering the possible arrangements of the steel in Figure 13.21 and the required areas of steel at different elevations in Table 13.1, the authors decided to use dowels for load transfer at the stem base.

Use #8 dowels at 6 in. extending 33 in. down into footing and key.

If these dowels are spliced to the vertical stem reinforcing with no more than one half the bars being spliced within the required lap length, the splices will fall into the class B category (ACI Code 12.15), and their lap length should at least equal $1.3\ell_d = (1.3)(33) = 43$ in. Therefore, two dowel lengths are used—half 3 ft 7 in. up into the stem and the other half 7 ft 2 in.—and the #7 bars are lapped over them, half running to the top of the wall and the other half to mid-depth.

Design Procedure for Cantilever Retaining Walls

Selection of Dowels and Lengths of Vertical Stem Reinforcing

Actually, a much more refined design can be made that involves more cutting of bars. For such a design, a diagram comparing the theoretical steel area required at various elevations in the stem and the actual steel furnished is very useful. It is to be remembered (ACI Code 12.10.3) that the bars cut off must run at least a distance *d* or 12 diameters beyond their theoretical cutoff points and must also meet the necessary development length requirements.