ENCE 4610 Foundation Analysis and Design
Lecture 8
Concrete Cast-in-Place Retaining Walls

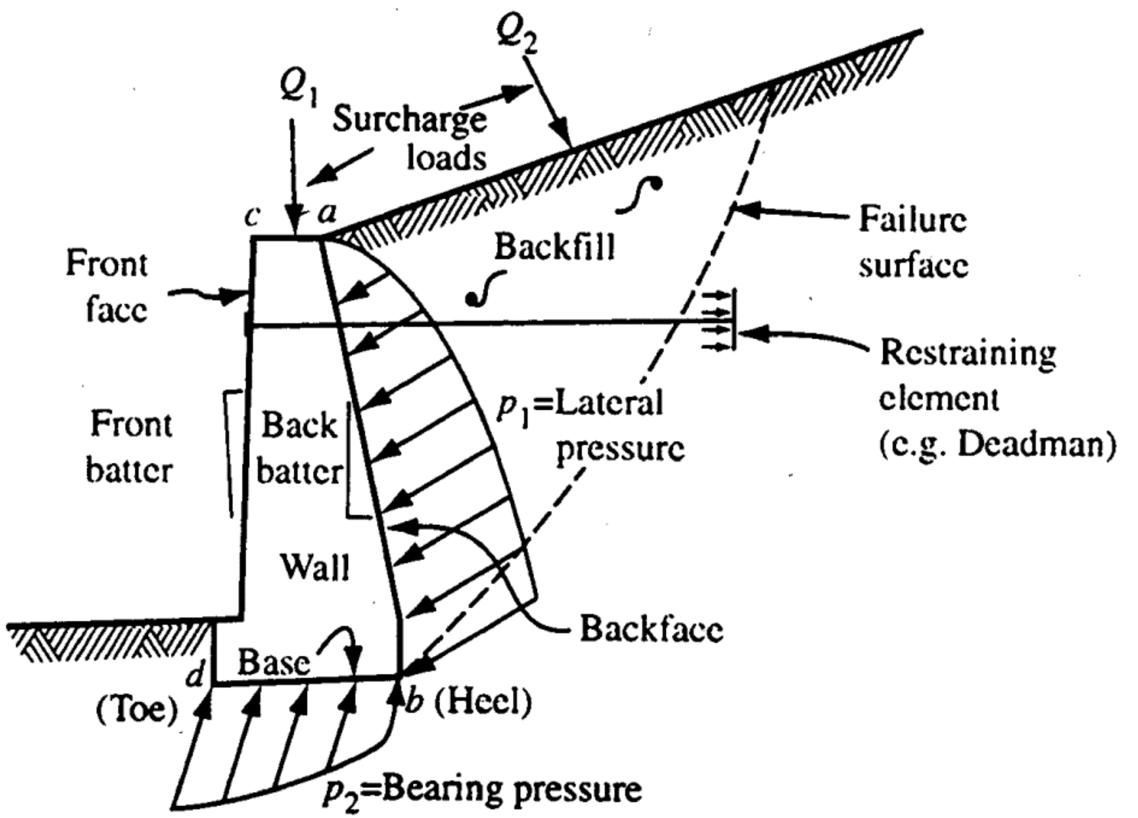


Figure 10-1. Schematic of a retaining wall and common terminology.

External vs. Internal Stability

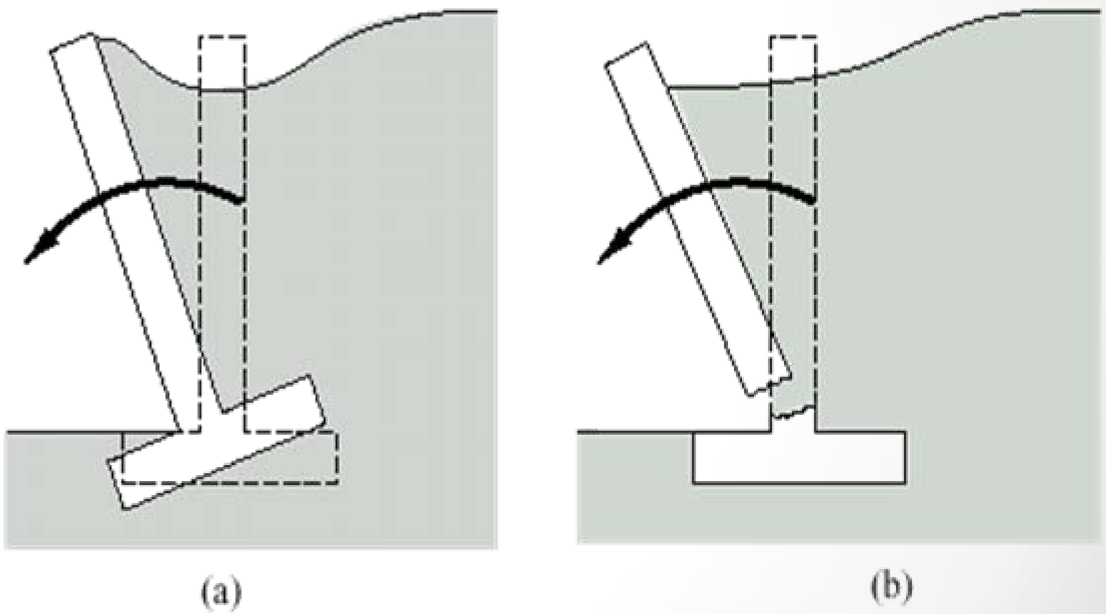


Figure 24.1 (a) A wall that lacks sufficient external stability moves away from its desired location because the soil fails; (b) A wall with inadequate internal stability (structural integrity) is unable to carry the necessary internal stresses and experiences a structural failure.

External Stability Problems

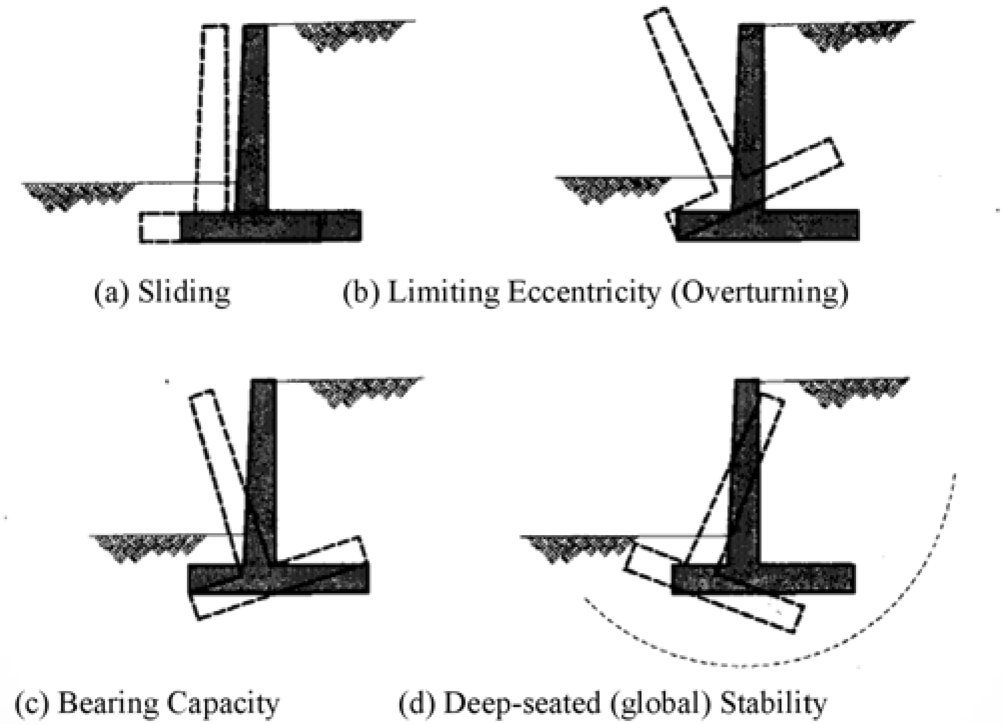
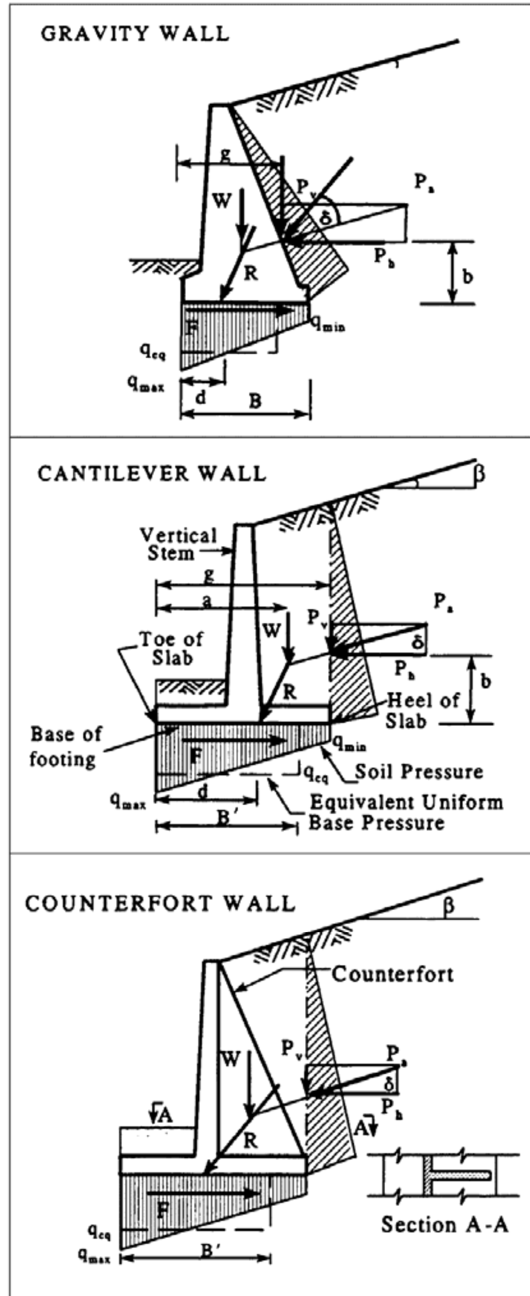


Figure 10-15. Potential failure mechanisms for rigid gravity and semi-gravity walls.

Design Parameters for Rigid Walls

- Contact Pressure on Foundation: Use Shallow Foundation Bearing Capacity Methods
- Overall Stability: use slope stability methods



DEFINITIONS

B = width of the base of the footing

$\tan \delta_b$ = friction factor between soil and base (see Table 10-1 for guidance)

W = weight at the base of wall. Includes weight of wall for gravity walls. Includes weight of the soil above footing for cantilever and counterfort walls

c = cohesion of the foundation soil

c_a = adhesion between concrete and soil

δ = angle of wall friction

P_p = passive resistance

LOCATION OF RESULTANT, R

Based on moments about toe (assuming P_p=0)

$$d = \frac{Wa + P_V g - P_h b}{W + P_V}$$

CRITERIA FOR ECCENTRICITY, e

$$e = d - \frac{B}{2}\ ;\ e \le B/6 \text{ for soils; } e \le B/4 \text{ for rocks}$$

FACTOR OF SAFETY AGAINST SLIDING

$$FS_S = \frac{(W + P_V)\tan \delta_b + c_a B}{P_h} \ge 1.5\,(\text{min})$$

APPLIED STRESS AT BASE (q_{max}, q_{min}, q_{eq})

$$q_{max} = \frac{(W + P_V)}{B}\left(1 + \frac{6e}{B}\right)$$

$$q_{min} = \frac{(W + P_V)}{B}\left(1 - \frac{6e}{B}\right)$$

Equivalent uniform (Meyerhof) applied stress, q_{eq}, is given as follows:

$$q_{eq} = \frac{(W + P_V)}{B'} \text{ where } B' = B - 2e$$

Use uniform stress, q_{eq}, for soils and settlement analysis; use trapezoidal distribution with q_{max} and q_{min} for rocks and structural analysis

DEEP-SEATED (GLOBAL) STABILITY

Evaluate global stability using guidance in Chapter 6 (Slope Stability)

Figure 10-17. Design criteria for cast-in-place (CIP) Concrete retaining walls (after NAVFAC, 1986b).

Typical Dimensions for Cast-in-Place Concrete Retaining Walls

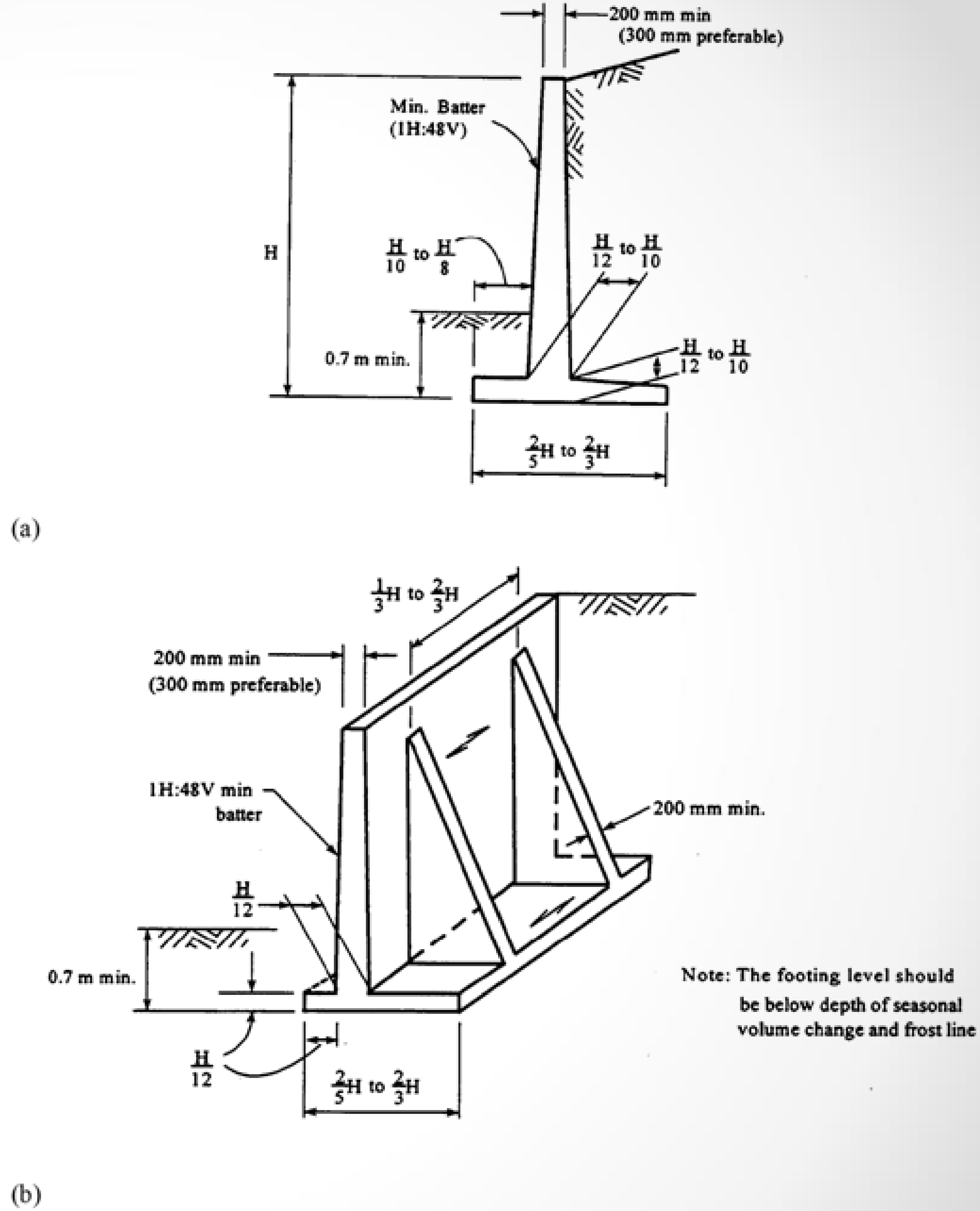


Figure 10-16. Typical dimensions (a) Cantilever wall, (b) Counterfort wall (Teng, 1962).
[1 m = 3.28 ft; 25.4 mm= 1in]

Design Procedure for Cast-in-Place Walls

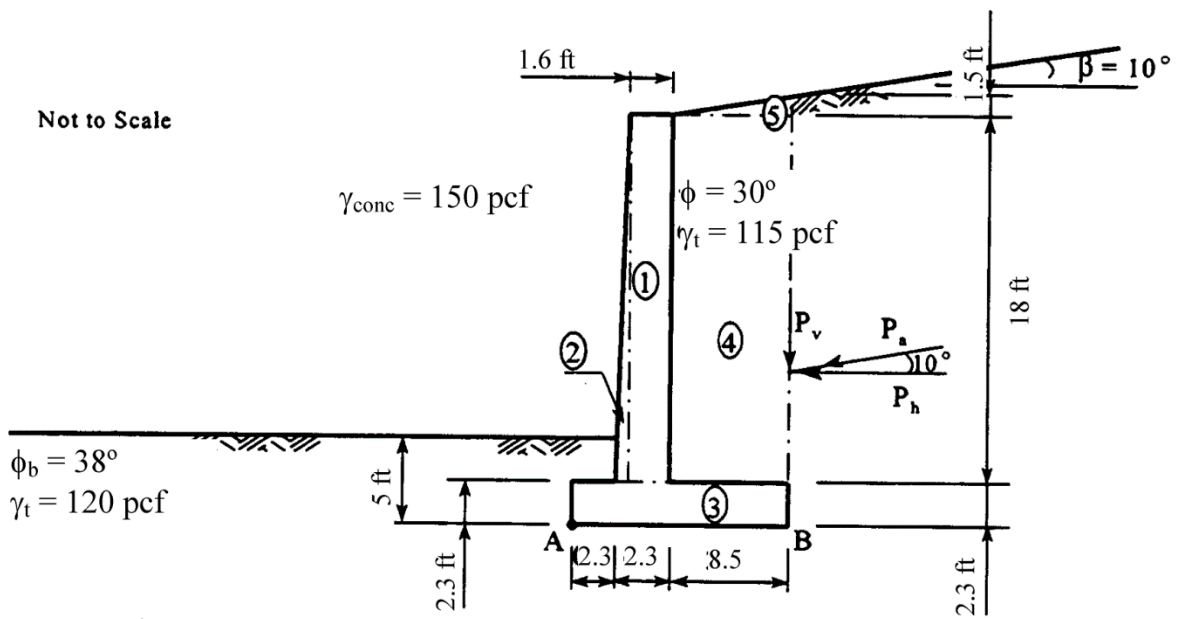
Table 10-2

Design steps for gravity and semi-gravity walls

Step 1.	Establish project requirements including all geometry, external loading conditions such as (temporary, permanent, and seismic, performance criteria, and construction constraints.
Step 2.	Evaluate site subsurface conditions and relevant properties of in situ soil and rock and wall backfill.
Step 3.	Evaluate soil and rock parameters for design and establish factors of safety.
Step 4.	Select initial base dimension of wall for evaluation of external stability.
Step 5.	Select lateral earth pressure distribution. Add appropriate water, surcharge, and seismic pressures and develop total lateral pressure diagram for design.
Step 6.	Evaluate bearing capacity.
Step 7.	Evaluate limiting eccentricity (overturning) and sliding.
Step 8.	Check overall stability and revise wall design if necessary.
Step 9.	Estimate maximum lateral wall movement, tilt, and wall settlement. Revise design if necessary.
Step 10.	Design wall drainage systems.

Cantilever Wall Design Example

Analyze the CIP cantilever wall shown below for factors of safety against sliding, overturning and bearing capacity failure. The backfill and foundation soils consist of clean, fine to medium sand, and the groundwater table is well below the base of the wall.



Geometry and parameters for example problem.

Cantilever Wall Design Example

Solution

Step 1: Determine the total height of soil exerting pressure.

H = thickness of base slab + height of stem + (width of heel slab) tan (backslope angle)

H = 2.3 ft + 18 ft + 8.5 ft (tan 10°)

= 21.8 ft

Step 2: Compute the coefficient of active earth pressure by using the equation of K_a in Figure 10-5 for a vertical backface (θ=0).

$$K_a = \frac{\cos^2 \phi}{\cos\delta\left[1+\sqrt{\frac{\sin(\phi+\delta)\sin(\phi-\beta)}{\cos\delta\cos(-\beta)}}\right]^2}$$

where:

ϕ = internal friction angle of soil = 30°

β= angle of backfill slope = 10°

δ= angle of wall friction = β = 10°

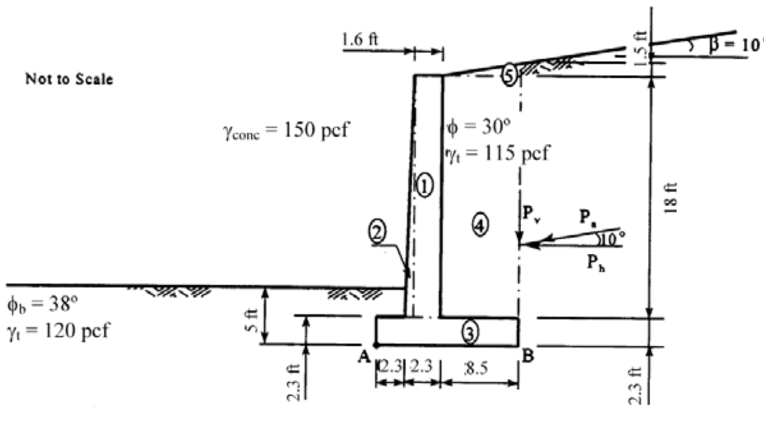
For the example problem:

$$K_a = \frac{\cos^2 30°}{\cos 10°\left[1+\sqrt{\frac{\sin(30°+10°)\sin(30°-10°)}{\cos 10°\cos(-10°)}}\right]^2}$$

$$K_a = 0.35$$

Coulomb Theory

Analyze the CIP cantilever wall shown below for factors of safety against sliding, overturning and bearing capacity failure. The backfill and foundation soils consist of clean, fine to medium sand, and the groundwater table is well below the base of the wall.

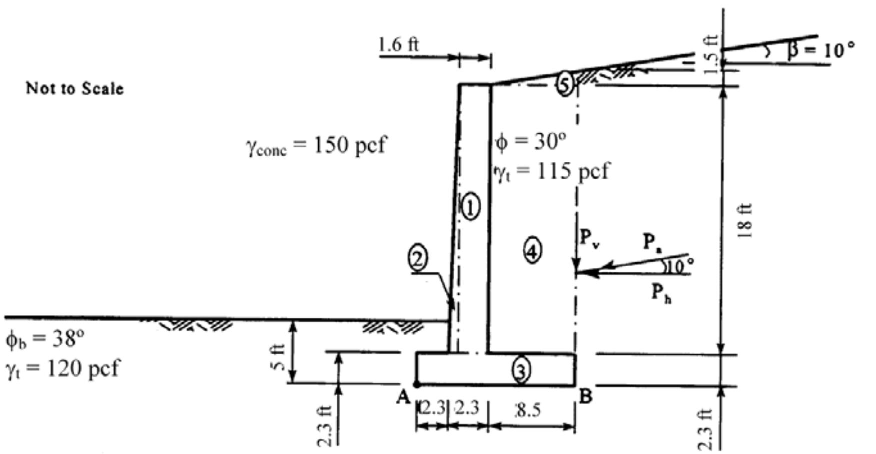


Geometry and parameters for example problem.

AASHTO approach for lateral earth pressure theories: Coulomb active, Log-spiral passive

Cantilever Example

Analyze the CIP cantilever wall shown below for factors of safety against sliding, overturning and bearing capacity failure. The backfill and foundation soils consist of clean, fine to medium sand, and the groundwater table is well below the base of the wall.



Geometry and parameters for example problem.

Step 3. Compute the magnitude of the resultant of active pressure, P_a, per foot of wall into the plane of the paper.

$$P_a = \frac{1}{2} K_a \gamma H^2$$

$$= \frac{1}{2}(0.35)(115\,\text{pcf})(21.8\,\text{ft})^2 = 9{,}564.2\,\text{lb/ft}$$

Step 4. Resolve P_a into horizontal and vertical components:

$$P_h = P_a \cos\beta = (9{,}564.2\ \text{lb/ft})\cos 10^\circ = 9{,}418.9\ \text{lb/ft}$$

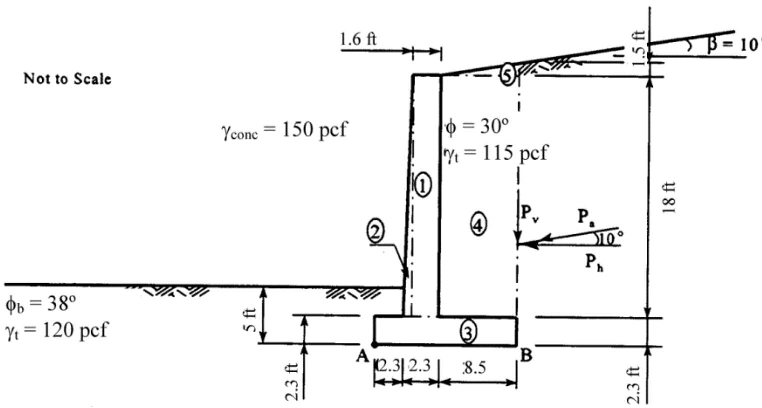
$$P_v = P_a \sin\beta = (9{,}564.2\ \text{lb/ft})\sin 10^\circ = 1{,}660.8\ \text{lb/ft}$$

Moment arm of P_h about point A = (2.3 ft + 18 ft + 1.5 ft)/3 = 21.8/3 = 7.27 ft = b

Moment arm of P_v about point A = 2.3 ft + 2.3 ft + 8.5 ft = 13.1 ft = g

Cantilever Example

Analyze the CIP cantilever wall shown below for factors of safety against sliding, overturning and bearing capacity failure. The backfill and foundation soils consist of clean, fine to medium sand, and the groundwater table is well below the base of the wall.



Geometry and parameters for example problem.

Step 5: Determine weights and sum moments about the toe of the wall (point A).

The weights of various areas and the moments due to the weights shown in the geometry of the example problem are set out in the following table. The unit weight of concrete is assumed to be 150 pcf and the weight of the soil above the footing toe is neglected.

Area	Weight, lb/ft	Moment arm about A, ft	Moment about A, lb.ft/ft
1	(1.6 ft) (18 ft) (150 pcf) = 4,320	2.3 ft+0.7 ft+(1.6/2) ft = 3.80	(4,320 lb) (3.80 ft) = 16,416.0
2	(0.5) (0.7 ft) (18 ft) (150 pcf) = 945	2.3 ft+ (2/3) (0.7) ft = 2.77	(945 lb) (2.77 ft) = 2,617.7
3	(13.1 ft) (2.3 ft) (150 pcf) = 4,519.5	13.1/2 ft = 6.55	(4,519.5 lb) (6.55 ft) = 29,602.7
4	(8.5 ft) (18 ft) (115 pcf) = 17,595	2.3 ft+ 2.3 ft+(8.5/2) ft = 8.85	(17,595 lb) (8.85 ft) = 155,715.8
5	(0.5) (8.5 ft) (1.5 ft) (115 pcf) = 733.1	2.3 ft+2.3 ft+(2/3)(8.5) ft = 10.27	(733.1lb) (10.27 ft) = 7,528.9
Total	**W = 28,112.6**		**M_w = 211,881.1**

Cantilever Example

Step 6: Check factor of safety against sliding; neglect passive resistance of embedment depth soil (Refer to Figure 10-20)

$$FS_s = \frac{(W + P_V)\tan\delta_b}{P_h}$$

where:

W = weight of concrete and soil on the base of the wall footing AB

δ_b = friction angle between concrete base and foundation soil

Use $\delta_b = (3/4)\,\phi_b = (3/4)\,(38°) = 28.5°$, for friction angle between concrete and clean, fine to medium sand (see NAVFAC, 1986b). This value of δ_b is within the range of values listed in Table 10-1 for clean fine to medium sand.

$$FS_s = \frac{(28{,}112.6\,\text{lb/ft} + 1{,}660.8\,\text{lb/ft})\tan 28.5°}{9{,}418.9\,\text{lb/ft}} = \frac{16{,}165.6\,\text{lb/ft}}{9{,}418.9\,\text{lb/ft}} = 1.72 \qquad \textbf{O.K.}$$

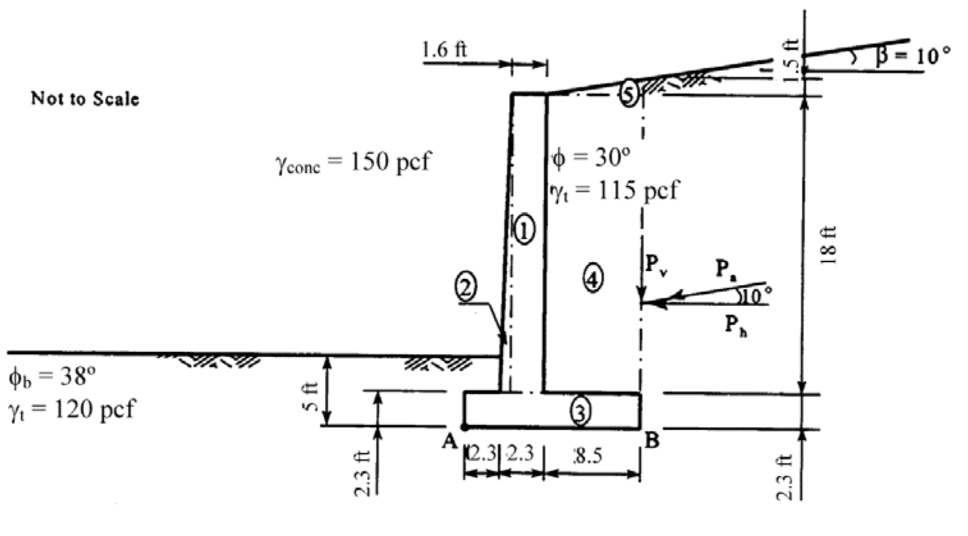
Check factor of safety for overturning

$$FS_{overturning} = \frac{M_{resisting}}{M_{driving}} = \frac{\sum M_R}{\sum M_O}$$

$$FS_{overturning} = \frac{211{,}881\ {}^{ft-lbs}/{}_{ft} + (1{,}661\ {}^{lb}/{}_{ft})\,(13.1\ ft.)}{(9{,}419\ {}^{lb}/{}_{ft})\,(7.27\ ft.)}$$

$$FS_{overturning} = 3.4$$

Analyze the CIP cantilever wall shown below for factors of safety against sliding, overturning and bearing capacity failure. The backfill and foundation soils consist of clean, fine to medium sand, and the groundwater table is well below the base of the wall.



Geometry and parameters for example problem.

Step 7: Check the limiting eccentricity and factor of safety against bearing failure.

(1) Compute the location of resultant at distance d from point A.

$$d = \frac{\sum M_R - \sum M_0}{\sum V}$$

$$d = \frac{M_W - P_h b + P_v g}{W + P_V}$$

$$d = \frac{21{,}1881.1\,\text{lb.ft/ft} + (1{,}660.8\,\text{lb/ft})(13.1\,\text{ft}) - (9{,}418.9\,\text{lb/ft})(7.27\text{ft})}{28{,}112.6\,\text{lb/ft} + 1{,}660.8\,\text{lb/ft}}$$

where: $W + P_V = \Sigma V$

$$d = \frac{16{,}5162.2\ \text{lb.ft/ft}}{29{,}773.4\,\text{lb/ft}} = 5.55\ \text{ft}$$

(2) Compute the eccentricity of the load about the center of base.

$$e = \frac{B}{2} - d = \frac{13.1\text{ft}}{2} - 5.55\text{ft} = 1.0\,\text{ft}$$

$$e = 1.0\text{ft} < \frac{B}{6} = \frac{13.1\text{ft}}{6} = 2.18\ \text{ft}\quad \text{O.K.}$$

(3) Compute the maximum and minimum pressures under the wall footing.

$$q_{max,min} = \frac{\sum V}{B}\left(1 \pm \frac{6e}{B}\right)$$

$$= \frac{29{,}773.4\,\text{lb/ft}}{13.1\,\text{ft}}\left(1 \pm \frac{6(1.0\,\text{ft})}{13.1\,\text{ft}}\right)$$

$$= 2{,}272.7\,\text{psf}\ (1.46 \text{ or } 0.54)$$

i.e., $q_{max} = 3{,}318.1\,\text{psf}$

$q_{min} = 1{,}227.3\ \text{psf}$

(4) Estimate ultimate bearing capacity.

Use the procedures presented in Chapter 8 (Shallow Foundations). Assume that for a footing with eccentric and inclined loading the ultimate bearing capacity computed by the geotechnical specialist is:

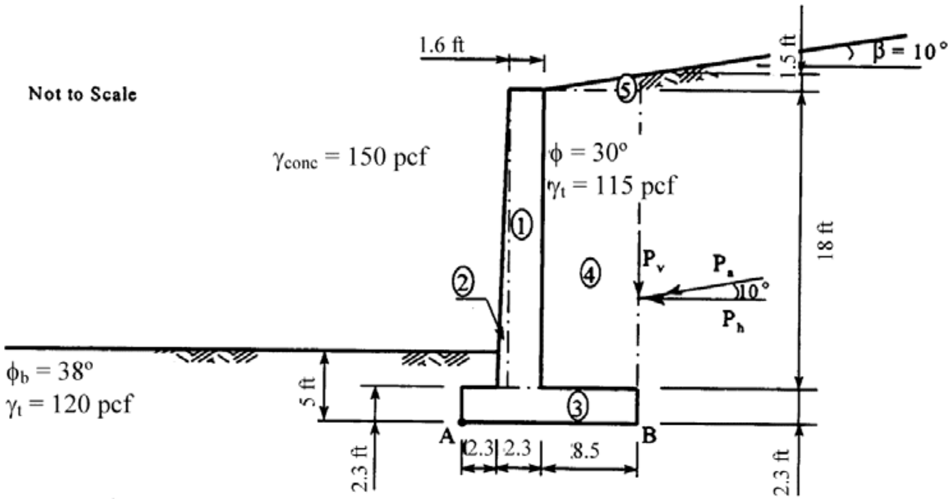
q_{ult} =20,000 psf

(5) Check factor of safety against bearing capacity failure.

$$FS_{bc} = \frac{q_{ult}}{q_{max}} = \frac{20{,}000\,\text{psf}}{3{,}318.1\,\text{psf}} = 6.03 > 3.0\quad \text{O.K.}$$

Cantilever Example

Analyze the CIP cantilever wall shown below for factors of safety against sliding, overturning and bearing capacity failure. The backfill and foundation soils consist of clean, fine to medium sand, and the groundwater table is well below the base of the wall.



Geometry and parameters for example problem.

Cantilever Example

SUMMARY

Factor of safety against sliding	FS_s	= 1.72
Eccentricity	e	= 1.0 ft < B/6
Factor of safety against bearing failure	FS_{bc}	= 6.03

In addition, the factor of safety against global failure and wall settlement including tilting and lateral squeeze should be evaluated to complete the analysis.

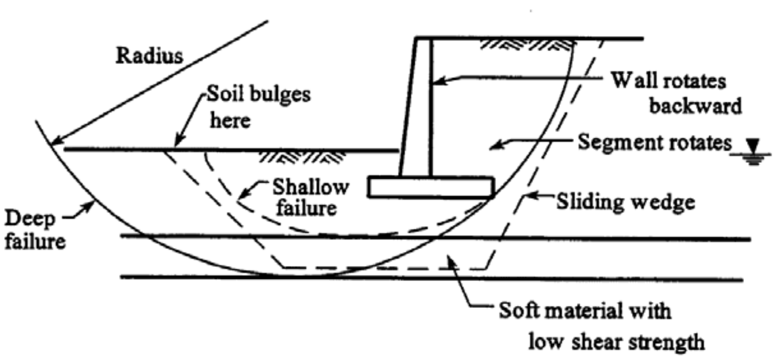


Figure 10-21. Typical modes of global stability (after Bowles, 1996)

- Notes
  - Global stability can be evaluated using the same methods used for slope stability analysis
  - Factors of Safety for cast-in-place concrete cantilever walls:
    - Sliding: FS > 1.5
    - Overturning in soil: FS > 2.0
    - Overturning in rock: FS > 1.5
    - Bearing Capacity: FS > 3.0
  - Eccentricity: within kern

Lateral Squeeze

10.5.4.2 Deep Foundations

CIP walls founded on a deep foundation may be subject to potentially damaging ground and structural displacements at sites underlain by cohesive soils. Such damage may occur if the weight of the backfill material exceeds the bearing capacity of the cohesive subsoils causing plastic displacement of the ground beneath the retaining structure and heave of the ground surface in front of the wall. When the cohesive soil layer is located at or below the base of the wall, the factor of safety against this type of bearing capacity failure can be approximated by the following equation (Peck, *et al.*, 1974):

$$FS = \frac{5c}{(\gamma H + q)} \qquad 10\text{-}15$$

where H is the height of the fill, γ is the unit weight of fill, c is the shear strength of the cohesive soil and q is the uniform surcharge load.

The computed factor of safety should not be less than 2.0 for the embankment loading. Below this value progressive lateral movements of the retaining structure are likely to occur (Peck, *et al.*, 1974). As the factor of safety decreases, the rate of movement will increase until failure occurs at a factor of safety of unity. For CIP walls founded on vertical piles or drilled shafts, this progressive ground movement would be reflected by an outward displacement of the wall. CIP walls founded on battered piles typically experience an outward displacement of the wall base and a backward tilt of the wall face (Figure 10-19).

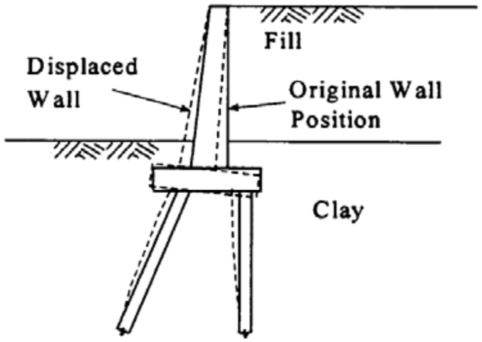
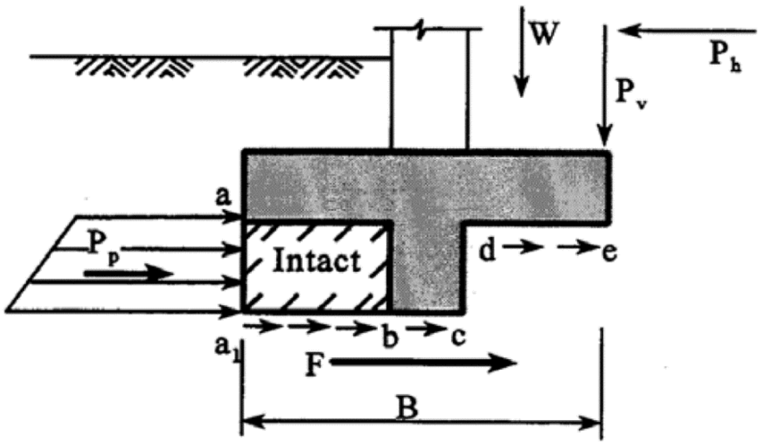


Figure 10-19. Typical Movement of pile-supported cast-in-place (CIP) wall with soft foundation.

Keyed Foundation for Sliding Resistance

If the wall is supported by rock, granular soils or stiff clay, a key may be installed below the foundation to provide additional resistance to sliding. The method for calculating the contribution of the key to sliding resistance is shown in Figure 10-20.



Cohesive Soils:

$$F = (W + P_v)\tan\delta_b + c_a(B - \overline{a_1 b}) + c(\overline{a_1 b}) + P_p$$

Granular Soils:

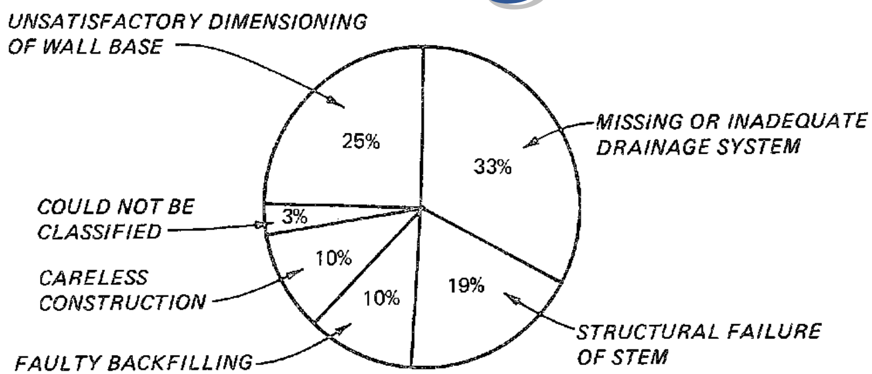
$$F = (W + P_v)\tan\delta_b + P_p$$

Factor of Safety $\quad FS = F/P_h$

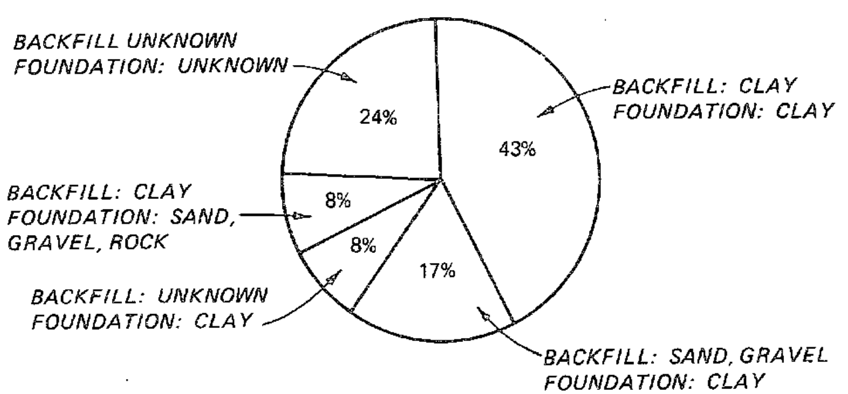
Note: See Figure 10-17 for list of symbol definitions.

Figure 10-20. Resistance against sliding from keyed foundation.

Failure Causes for Retaining Walls



a. Causes of failure of rigid concrete retaining walls (Techeng and Iseux 1972)



b. Foundation and backfill material of unsatisfactory retaining walls (Ireland 1964)

Retaining Wall Drainage

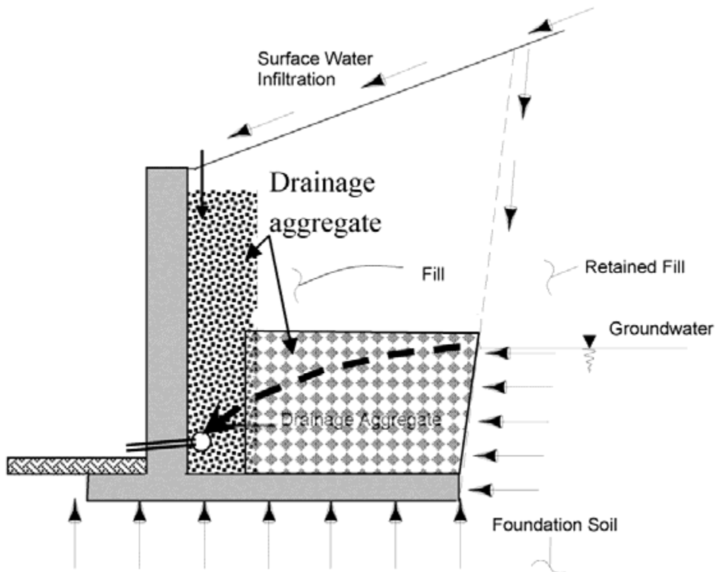


Figure 10-22. Potential sources of subsurface water.

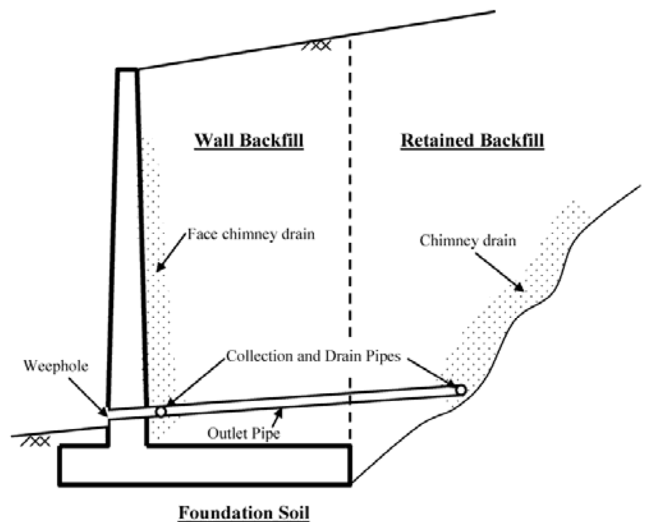


Figure 10-24. Drains behind backfill in cantilever wall in a cut situation.

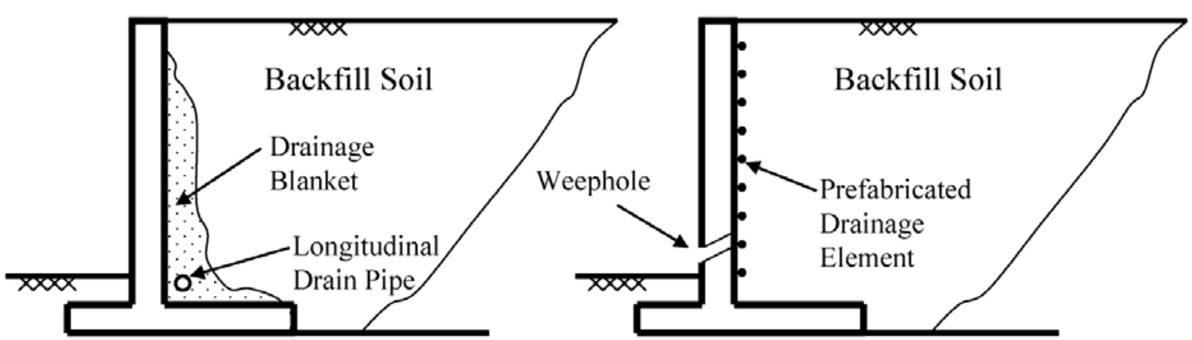


Figure 10-23. Typical retaining wall drainage alternatives.

Presumptive Lateral Earth Pressures

- Based on Terzaghi theory
- Suitable for relatively simple retaining walls in homogeneous soils (low walls, H < 12')
- Classifies soils into three types:
  1. "Clean" coarse grained soils
  2. Coarse grained soils of low permeability; mixed with fine grained soils
  3. Residual soils with granular materials and clay content
- Result of chart are equivalent fluid pressures, which can then be applied to wall stability calculations
- Horizontal and vertical pressures are then computed as follows:

$$P_h = \frac{K_h H^2}{2}$$

$$P_v = \frac{K_v H^2}{2}$$

Terzaghi and Peck "Low Walls," Straight Backfill

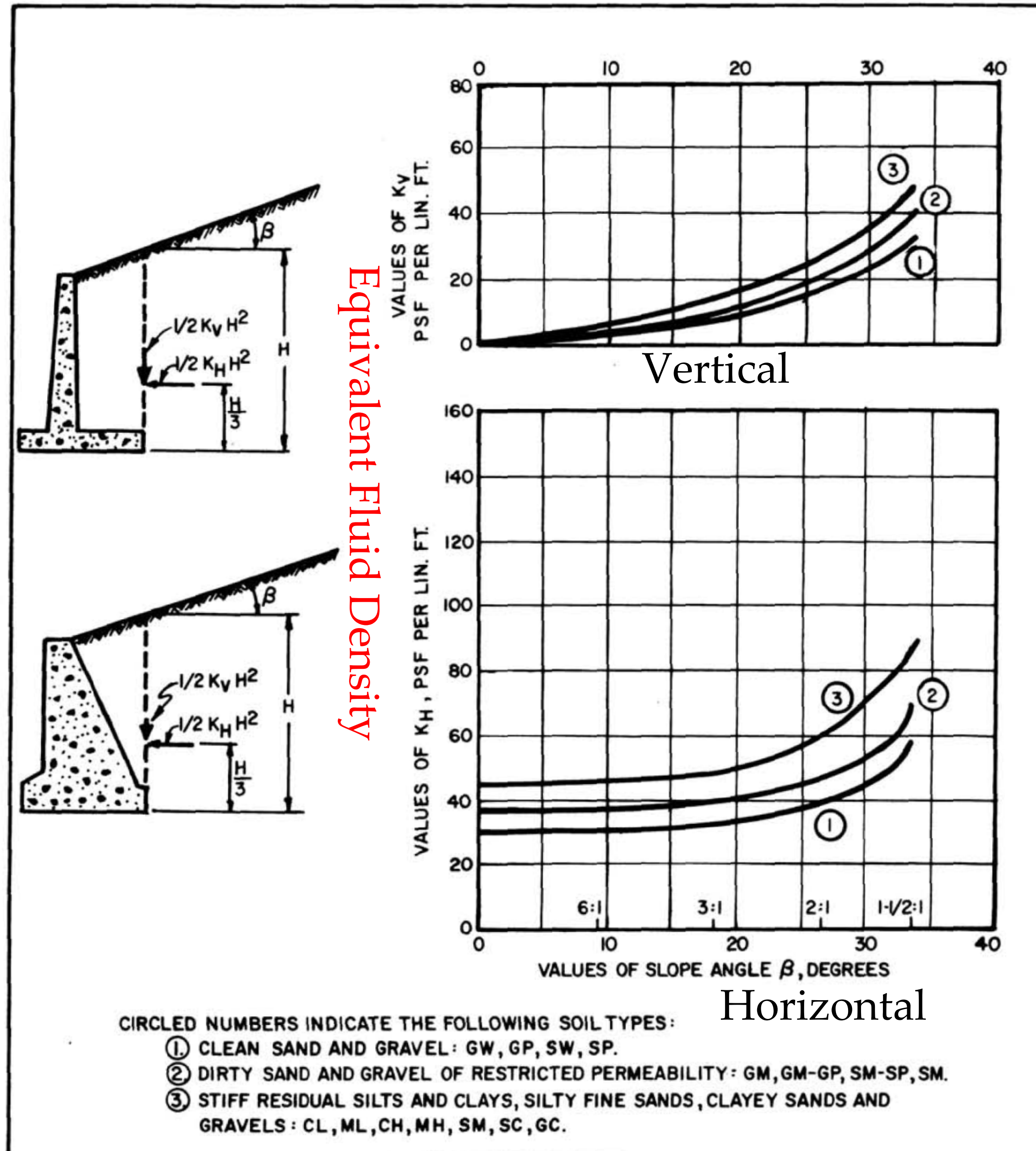


FIGURE 16
Design Loads for Low Retaining Walls (Straight Slope Backfill)

“Low Walls,” Broken Backfill

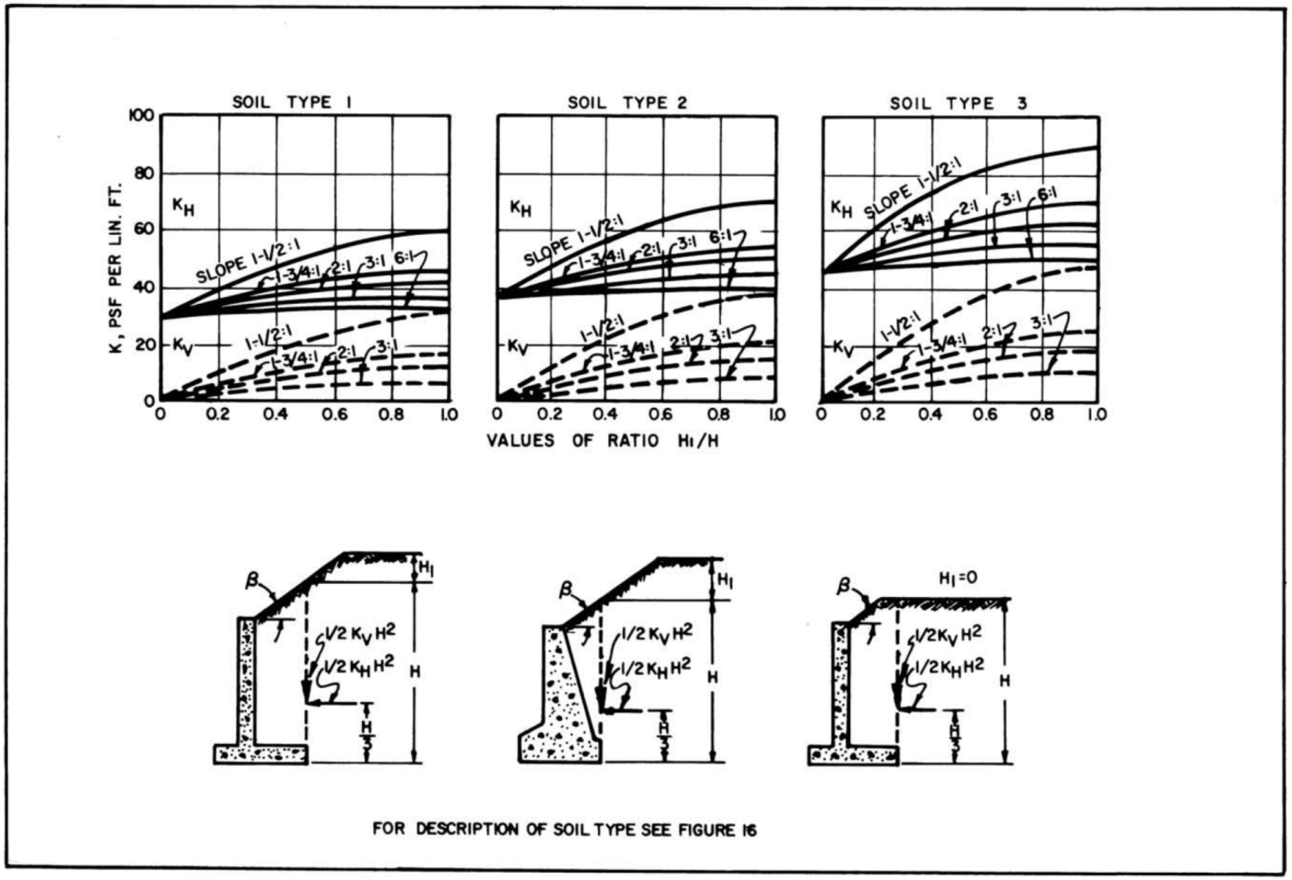


FIGURE 17
Design Loads for Low Retaining Walls (Broken Slope Backfill)

Example with Terzaghi & Peck Charts

- Use Previous Example
  - Soil Type (1) (clean sand)
  - H = 21.8’
  - $\beta = 10^o$
  - P_v = 475 (1660) lb/ft
  - P_h = 7192 (9418) lb/ft
- Once these values are known, wall is analysed in the usual way
-

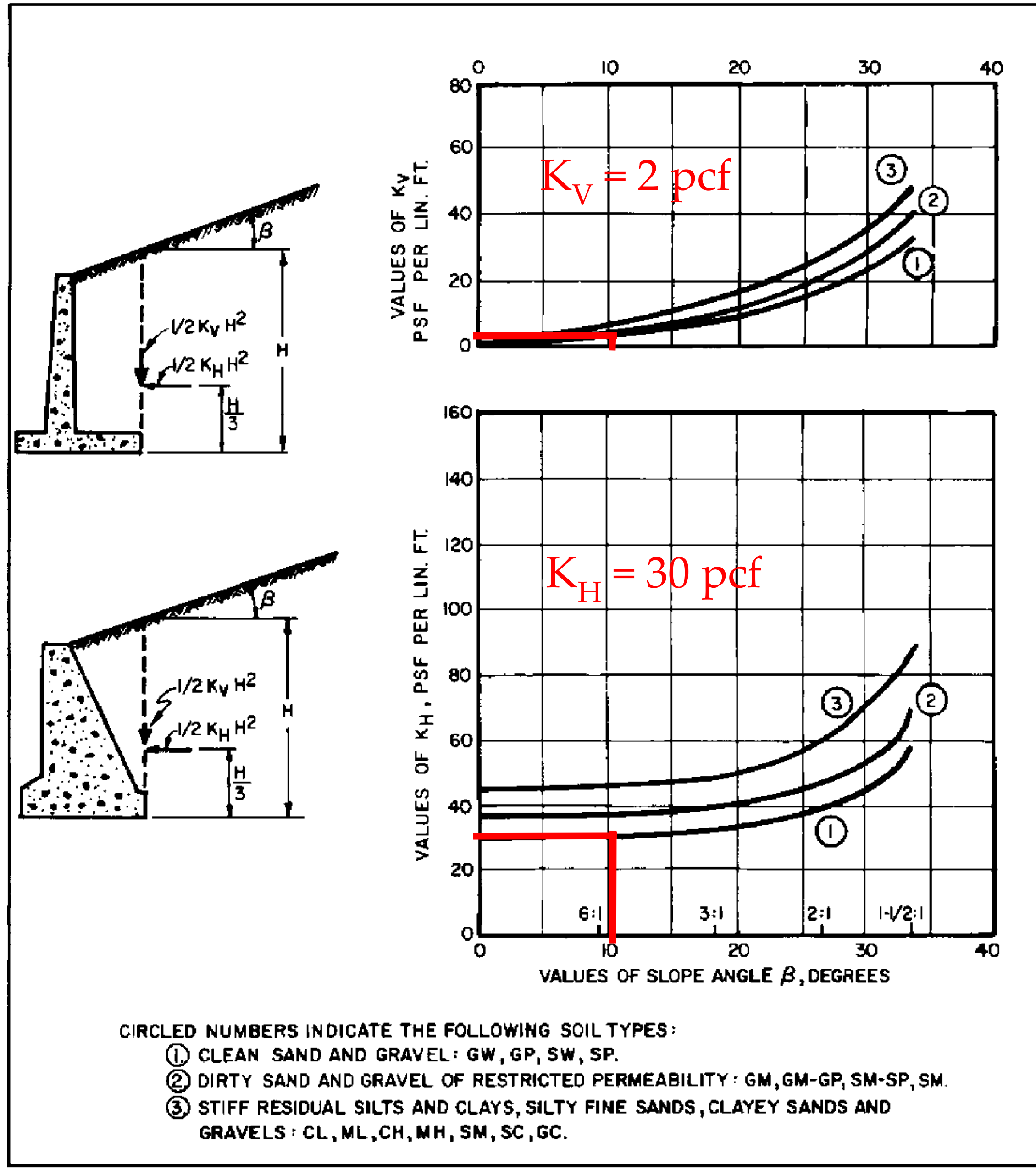


FIGURE 16

Design Loads for Low Retaining Walls (Straight Slope Backfill)

Questions