Concrete construction: foundation design
Foundation

- The engineered interface between the earth and the structure it supports that transmits the loads to the soil or rock.
Structural vs. Foundation Design

• structural design
  – choice of materials
  – choice of framing system
  – uniform materials and quality assurance
  – design largely independent of geology, climate, etc.
Structural vs. Foundation Design

- foundation design
  - cannot specify site materials
  - site is usually predetermined
  - framing/structure predetermined
  - site geology influences foundation choice
  - no site the same
  - no design the same
Soil Properties & Mechanics

- unit weight of soil
- allowable soil pressure
- factored net soil pressure
- shear resistance
- backfill pressure
- cohesion & friction of soil
- effect of water
- settlement
- rock fracture behavior
Soil Properties & Mechanics

- compressibility
  - settlements

- strength
  - stability
    - shallow foundations
    - deep foundations
    - slopes and walls
  - ultimate bearing capacity, $q_u$
  - allowable bearing capacity, $q_a = \frac{q_u}{S.F.}$

finehomebuilding.com
Soil Properties & Mechanics

- strength, $q_a$

![Table 1804.3: Presumptive Loadbearing Values of Foundation Materials](image)

**Table 1804.3**

<table>
<thead>
<tr>
<th>Class of Material</th>
<th>Loadbearing pressure (pounds per square foot) $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Crystalline bedrock</td>
<td>12,000</td>
</tr>
<tr>
<td>2. Sedimentary rock</td>
<td>6,000</td>
</tr>
<tr>
<td>3. Sandy Gravel</td>
<td>5,000</td>
</tr>
<tr>
<td>4. Sand, silty sand, clayey sand, silty gravel and clayey gravel</td>
<td>3,000</td>
</tr>
<tr>
<td>5. Clay, sandy clay, silty clay &amp; clayey silt</td>
<td>2,000</td>
</tr>
</tbody>
</table>

*Note a.* 1 psf = 47.9 Pa.

**Figure 2.5**
Presumptive surface bearing values of various soils, as given in the BOCA National Building Code/1996. *(Reproduced by permission)*
Bearing Failure

- shear

slip zone

punched wedge
Lateral Earth Pressure

- **passive vs. active**

![Diagram showing active and passive lateral earth pressure](image)

- **active**
  - (trying to move wall)

- **passive**
  - (resists movement)
Foundation Materials

- concrete, plain or reinforced
  - shear
  - bearing capacity
  - bending
  - embedment length, development length

- other materials (piles)
  - steel
  - wood
  - composite
Basic Foundation Requirements

• safe against instability or collapse
• no excessive/damaging settlements
• consider environment
  – frost action
  – shrinkage/swelling
  – adjacent structure, property lines
  – ground water
  – underground defects
  – earthquake
• economics
Generalized Design Steps

- calculate loads
- characterize soil
- determine footing location and depth
- evaluate soil bearing capacity
- determine footing size (unfactored loads)
- calculate contact pressure and check stability
- estimate settlements
- design footing structure* (factored loads)
Types of Foundations

- spread footings
- wall footings
- eccentric footings
- combined footings
- unsymmetrical footings
- strap footings
Types of Foundations

- mat foundations
- retaining walls
- basement walls
- pile foundations
- drilled piers
Shallow Footings

- **spread footing**
  - a square or rectangular footing supporting a single column
  - reduces stress from load to size the ground can withstand
Actual vs. Design Soil Pressure

- stress distribution is a function of
  - footing rigidity
  - soil behavior

- linear stress distribution assumed
Proportioning Footings

• net allowable soil pressure, $q_{net}$
  
  $q_{net} = q_{allowable} - h_f (\gamma_c - \gamma_s )$
  
  – considers all extra weight (overburden) from replacing soil with concrete
  
  – can be more overburden

• design requirement with total unfactored load:
  
  $\frac{P}{A} \leq q_{net}$
Concrete Spread Footings

- plain or reinforced
- ACI specifications
- $P_u = \text{combination of factored } D, L, W$
- ultimate strength
  - $V_u \leq \phi V_c : \phi = 0.75 \text{ for shear}$
    - plain concrete has shear strength
  - $M_u \leq \phi M_n : \phi = 0.9 \text{ for flexure}$
Concrete Spread Footings

- failure modes

**Figure 9.2** "Shear" failure in a spread footing loaded in a laboratory (Talbot, 1913). Observe how this failure actually is a combination of tension and shear.

**Figure 9.3** Flexural failure in a spread footing loaded in a laboratory (Talbot, 1913).
Concrete Spread Footings

• shear failure

one way shear

two way shear
Over and Under-reinforcement

- **reinforcement ratio for bending**
  \[ \rho = \frac{A_s}{bd} \]
  - use as a design estimate to find \( A_s, b, d \)
  - \( \max \rho \) from \( \varepsilon_{\text{steel}} \geq 0.004 \)
  - minimum for slabs & footings of uniform thickness
    \[ \frac{A_s}{bh} = 0.002 \text{ grade 40/50 bars} \]
    \[ = 0.0018 \text{ grade 60 bars} \]
Reinforcement Length

- need length, \( l_d \)
  - bond
  - development of yield strength

![Diagram of reinforcement development](image-url)
Column Connection

• bearing of column on footing
  - $P_u \leq \phi P_n = \phi (0.85 f'_c A_1)$
    \( \phi = 0.65 \) for bearing
  - confined: increase $x \sqrt{\frac{A_2}{A_1}} \leq 2$

• dowel reinforcement
  - if $P_u > P_b$, need compression reinforcement
  - min of 4 bars and $0.005A_g$
Wall Footings

- continuous strip for load bearing walls
- plain or reinforced
- behavior
  - wide beam shear
  - bending of projection
- dimensions usually dictated by codes for residential walls
- light loads
Eccentrically Loaded Footings

- footings subject to moments

- soil pressure resultant force may not coincide with the centroid of the footing
Differential Soil Pressure

– to avoid large rotations, limit the differential soil pressure across footing

– for rigid footing, simplification of soil pressure is a linear distribution based on constant ratio of pressure to settlement
Kern Limit

- boundary of e for no tensile stress
- triangular stress block with \( p_{\text{max}} \)

\[
\text{volume} = \frac{wpx}{2} = N
\]

\[
P_{\text{max}} = \frac{2N}{wx}
\]
Guidelines

– want resultant of load from pressure inside the middle third of base (kern)
  • ensures stability with respect to overturning

\[ SF = \frac{M_{\text{resist}}}{M_{\text{overturning}}} = \frac{R \cdot x}{M} \geq 1.5 \]

– pressure under toe (maximum) \( \leq q_a \)
– shortcut using uniform soil pressure for design moments gives similar steel areas
Combined Footings

- supports two columns
- used when space is tight and spread footings would overlap or when at property line
- soil pressure might not be uniform
- proportion so pressure will uniform for sustained loads
- behaves like beam lengthwise
Combined Footing Types

– rectangular
– trapezoid

– strap or cantilever
  • prevents overturning of exterior column

– raft/mat
  • more than two columns over an extended area
Proportioning

– uniform settling is desired
– area is proportioned with sustained column loads
– want the resultant to coincide with centroid of footing area for uniformly distributed pressure assuming a rigid footing

\[ q_{\text{max}} \leq q_a \]
Retaining Walls

- **purpose**
  - retain soil or other material

- **basic parts**
  - wall & base
  - additional parts
    - counterfort
    - buttress
    - key
Retaining Walls

- **considerations**
  - overturning
  - settlement
  - allowable bearing pressure
  - sliding
  - (adequate drainage)

![Diagram showing three failure mechanisms in retaining walls: overturning, sliding, and undermining.](image)
Retaining Walls

- procedure
  - proportion and check stability with working loads for bearing, overturning and sliding
  - design structure with factored loads

\[ SF = \frac{M_{\text{resist}}}{M_{\text{overturning}}} \geq 1.5 - 2 \]

\[ SF = \frac{F_{\text{horizontal-resist}}}{F_{\text{sliding}}} \geq 1.25 - 2 \]
Retaining Wall Proportioning

- **estimate size**
  - footing size, $B \approx \frac{2}{5} - \frac{2}{3}$ wall height ($H$)
  - footing thickness $\approx \frac{1}{12} - \frac{1}{8}$ footing size ($B$)
  - base of stem $\approx \frac{1}{10} - \frac{1}{12}$ wall height ($H+h_f$)
  - top of stem $\geq 12”$
Retaining Walls Forces

- design like cantilever beam
  - \( V_u \) & \( M_u \) for reinforced concrete
  - \( V_u \leq \phi V_c : \phi = 0.75 \) for shear
  - \( M_u \leq \phi M_n : \phi = 0.9 \) for flexure
Retaining Wall Types

• “gravity” wall
  – usually unreinforced
  – economical & simple

• cantilever retaining wall
  – common
Retaining Wall Types

- **counterfort wall**
- **buttress wall**
- **bridge abutment**
- **basement frame wall** *(large basement areas)*

very tall walls (> 20 - 25 ft)
Deep Foundations

• usage
  – when spread footings, mats won’t work
  – when they are required to transfer the structural loads to good bearing material
  – to resist uplift or overturning
  – to compact soil
  – to control settlements of spread or mat foundations
Deep Foundation Types

- **piles** - usually driven, 6”-8” $\phi$, 5’ +
- **piers**
- **caissons**
- **drilled shafts**
- **bored piles**
- **pressure injected piles**

Deep Foundation Types

- drilled, excavated, concreted (with or without steel)
- 2.5’ - 10’/12’ $\phi$
Deep Foundation Types

Deep foundation types include:
- Grade: 200–900 mm
- Cross section of plain pipe pile
- Shell thickness: 8–12
- 300–900 dia.
- Cross section of pipe pile with steel core
- End closure may be omitted
- Socket required for vertical high loads only
- Rock
- Cased or uncased concrete
- Timber
- Steel pipe, concrete filled
- Concrete filled steel shell
- HP section
- Taper may be omitted
- 300–600 mm
- 300–600 diam.
- Note: reinforcing may be prestressed
- 300–1400 diam.
- Typical cross sections
- 200–450 diameter
- Cross section: Corrugated shell
- Thickness: 10 ga to 24 ga
- Sides straight or tapered
- Grade
- Butt diameter: 300–500 mm
- Pile may be treated with wood preservative
- Cross section
- Tip diameter: 150–250
- Welded Rail
- Welded Sheet pile
- 300–450 mm diameter
- Typical cross section
- Rails or sheet pile sections can be used as shown below:
- Sides straight or tapered
- 250–900 dia.
- Shell thickness: 3–8
- Typical cross section (fluted shell)
- Minimum tip diameter: 200
- 350–500 diameter
- Typical cross section
- Pedestal may be omitted
Deep Foundations

• classification
  – by material
  – by shape
  – by function (structural, compaction...)

• pile placement methods
  – driving with pile hammer (noise & vibration)
  – driving with vibration (quieter)
  – jacking
  – drilling hole & filling with pile or concrete
Piles Classified By Material

• **timber**
  - use for temporary construction
  - to densify loose sands
  - embankments
  - fenders, dolphins (marine)

• **concrete**
  - precast: ordinary reinforcement or prestressed
  - designed for axial capacity and bending with handling
Piles Classified By Material

• steel
  – rolled HP shapes or pipes
  – pipes may be filled with concrete
  – HP displaces little soil and may either break small boulders or displace them to the side
Piles Classified By Function

– end bearing pile (point bearing)

- soft or loose layer
- “socketed”

\[ P_a = A_p \cdot f_a \]

for use in soft or loose materials over a dense base

\[ R_p \]

– friction piles (floating)

- common in both clay & sand

\[ R_s = f(\text{adhesion}) \]

\[ R_p \approx 0 \]

- tapered:
  - sand & silt

\[ P \]

\[ T \]

\[ N \]
Piles Classified By Function

– combination friction and end bearing

– uplift/tension piles
  structures that float, towers

– batter piles
  angled, cost more, resist large horizontal loads

1:12 to 1:3 or 1:4
Piles Classified By Function

– fender piles, dolphins, pile clusters

large # of piles in a small area

– compaction piles
  • used to densify loose sands

– drilled piers
  • eliminate need for pile caps
  • designed for bearing capacity (not slender)
Pile Caps and Grade Beams

– like multiple column footing
– more shear areas to consider