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, \( q_a = \frac{q_u}{S.F.} \)
Soil Properties & Mechanics

- strength, $q_a$

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

- 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

Figure 5.1 Spread footing shapes and dimensions.
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
  - \( V_u \leq \phi V_c : \phi = 0.75 \) for shear
    - plain concrete has shear strength
  - \( M_u \leq \phi M_n : \phi = 0.9 \) 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.

shear

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

bending
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
    \[ \frac{A_s}{bh} = 0.002 \text{ grade } 40/50 \text{ bars} \]
    \[ = 0.0018 \text{ grade } 60 \text{ bars} \]
Reinforcement Length

• need length, $\ell_d$
  – bond
  – development of yield strength
Column Connection

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

- **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

By statics:

- 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 $p_{\text{max}}$

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

\[
\begin{align*}
\text{Max} \, P & = \frac{2N}{wx} \\
\end{align*}
\]
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) ≤ \(q_a\)
- 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 of retaining walls with mechanisms: Overturning, Sliding, Undermining.](image)
Retaining Walls

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

\[
\begin{align*}
SF &= \frac{M_{\text{resist}}}{M_{\text{overturning}}} \geq 1.5 - 2 \\
SF &= \frac{F_{\text{horizontal-resist}}}{F_{\text{sliding}}} \geq 1.25 - 2
\end{align*}
\]
Retaining Wall Proportioning

• estimate size
  – footing size, $B \approx 2/5 - 2/3$ wall height ($H$)
  – footing thickness $\approx 1/12 - 1/8$ footing size ($B$)
  – base of stem $\approx 1/10 - 1/12$ 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

![Figure 24.12](image-url)

*Figure 24.12* Typical loading diagrams for stem design: (a) with no surcharge loads; (b) with uniform surcharge load; (c) with point surcharge load.
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” φ, 5’ +
- **piers**
- **caissons**
- **drilled shafts**
- **bored piles**
- **pressure injected piles**

Deep Foundation Types (cont.)

- **drilled, excavated, concreted** (with or without steel)
- **2.5’ - 10’/12’ φ**
Deep Foundation Types

- 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

- Typical combinations
  - Cased or uncased concrete
  - Timber
  - Steel pipe concrete filled
  - Concrete filled steel shell

- 300–600 mm
  - Note: reinforcing may be prestressed
  - 300–1400 diam.

- Grade
  - 200–450 diameter
  - Cross section
  - Corrugated shell thickness 10 ga to 24 ga

- Pile may be treated with wood preservative
- Tip diameter 150–250
- Rail
- Welded
- Sheet pile

- Typical cross section
  - Rails or sheet pile sections can be used as shown below:
- Welded tapered

- Typical cross section
  - Fluted shell
  - 250–900 dia.
  - Shell thickness 3–8

- Typical cross section
  - Minimum tip diameter 200

- 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)**

  \[ P_a = A_p \cdot f_a \]

  for use in soft or loose materials over a dense base

  - soft or loose layer
  - “socketed”

  \[ R_p \]

- **friction piles (floating)**

  common in both clay & sand

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

  \[ R_p \approx 0 \]

  tapered: sand & silt

  \[ P \]

  \[ N \]

  \[ T \]
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
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