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, $q_a = \frac{q_u}{S.F.}$

$S.F. = \frac{q_u}{q_a}$
Soil Properties & Mechanics

- strength, $q_a$

### Table 1804.3
PRESUMPTIVE LOADBEARING VALUES OF FOUNDATION MATERIALS

<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
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**
  - $V_u \leq \phi V_c : \phi = 0.75$ 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
    \[ \frac{A_s}{bh} = 0.002 \text{ grade 40/50 bars} \]
    \[ = 0.0018 \text{ grade 60 bars} \]
Reinforcement Length

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

- **bearing of column on footing**
  - \( P_u \leq \phi P_n = \phi (0.85 f'_c A_1) \)
  - \( \phi = 0.65 \) 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 - #5 bars (or 15 metric)
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

\[ M = P_e \]

- 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 \( p_{\text{max}} \)

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

\[
\frac{p_{\text{max}}}{wx} = 2N
\]
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 of Retaining Walls]

**Figure 2.50**
Three failure mechanisms in retaining walls.
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, $B \approx 2/5 - 2/3$ 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*  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" $\phi$, 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 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)

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

\[ R_P \approx 0 \]

common in both clay & sand

tapered: sand & silt
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