Architectural Structures: Form, Behavior, and Design
ARCH 331
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lecture
twenty three

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

![Suggested drill pattern for soil borings](image)
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
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

Diagram:
- 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.

**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

![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 - #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

– 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

\[ q_{max} \leq q_a \]
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)
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+hf)
  - 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)

- common in both clay & sand

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

\[ R_p \approx 0 \]

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