Elements of Architectural Structures: Form, Behavior, and Design
ARCH 614
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lecture
twenty six

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, $q_a$

Bearing Failure

- shear

Table 1804.3

<table>
<thead>
<tr>
<th>Class of material</th>
<th>Loadbearing pressure (pounds per square foot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Graystone bedrock</td>
<td>12,000</td>
</tr>
<tr>
<td>2. Sedimentary rock</td>
<td>5,000</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 silty, silty clayey &amp; silty clayey</td>
<td>2,000</td>
</tr>
</tbody>
</table>

Figure 2.5

Presumptive bearing values of various soils, as given in the BOCA National Building Code, 1996. (Reproduced by permission)
Lateral Earth Pressure

- passive vs. active

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

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

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
- \( P_u = \) combination of factored \( D, L, W \)
- ultimate strength
  - \( V_u \leq \phi V_c: \phi = 0.75 \) for shear
  - \( M_u \leq \phi M_n: \phi = 0.9 \) for flexure

Concrete Spread Footings

- failure modes
  - shear failure
  - bending
  - 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
    \[ \frac{A_s}{bh} = 0.002 \text{ grade } 40/50 \text{ bars} \]
    \[ = 0.0018 \text{ grade } 60 \text{ bars} \]

Column Connection

- bearing of column on footing
  \[ P_u < \phi P_n = \phi (0.85 f' c A_k) \]
  \( \phi = 0.65 \) for bearing
  - confined: increase \( x \)
  \[ \sqrt{\frac{A_2}{A_1}} \leq 2 \]
- dowel reinforcement
  - if \( P_u > P_{br} \) 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

Reinforcement Length

- need length, \( \ell_d \)
  - bond
  - development of yield strength
**Eccentrically Loaded Footings**

- footings subject to moments

\[ P \]

by statics:

\[ M = Pe \]

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

\[ \text{volume} = \frac{wp x}{2} = N \]

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

**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

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

\[ R = P_1 + P_2 \]

**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 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

- 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 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
  - very tall walls (> 20 - 25 ft)
- buttress wall
- bridge abutment
- basement frame wall (large basement areas)

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

- 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)**
  
  ![Diagram](image)
  
  \[ P_a = A_p \cdot f_a \]
  
  for use in soft or loose materials over a dense base

- **friction piles (floating)**
  
  ![Diagram](image)
  
  \[ R_s = f(\text{adhesion}) \]
  \[ R_p \approx 0 \]
  
  common in both clay & sand

- **socketed**
  
  soft or loose layer

Piles Classified By Function

- **combination friction and end bearing**

- **uplift/tension piles**
  
  ![Diagram](image)
  
  structures that float, towers

- **batter piles**
  
  ![Diagram](image)
  
  angled, cost more, resist large horizontal loads

  \[ P \]
  \[ R_s \]
  \[ R_p \]

  1:12 to 1:3 or 1:4

Piles Classified By Function

- **fender piles, dolphins, pile clusters**

  ![Diagram](image)

  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**

  ![Diagram](image)