FOUNDATION DESIGN

Proportioning elements for:
- Transfer of seismic forces
- Strength and stiffness
- Shallow and deep foundations
- Elastic and plastic analysis
Load Path and Transfer to Soil

Soil Pressure

Force on a pile

EQ on unloaded pile

Pile supporting structure

Inertial force

Unmoving soil

EQ Motion

deflected shape

soil pressure

deflected shape

soil pressure

deflected shape

soil pressure
Load Path and Transfer to Soil
Soil-to-foundation Force Transfer

Passive earth pressure

Friction

EQ motion
Load Path and Transfer to Soil

Soil-to-foundation Force Transfer

Deep

Motion

Soil pressure

EQ Motion

Bending moment
Load Path and Transfer to Soil

*Vertical Pressures - Shallow*

Overturning moment

EQ motion
Load Path and Transfer to Soil

*Vertical Pressures - Deep*

- Overturning moment
- EQ Motion
Reinforced Concrete Footings: Basic Design Criteria (concentrically loaded)

Outside face of concrete column or line midway between face of steel column and edge of steel base plate (typical)

(a) Critical section for flexure

extent of footing (typical)

(b) Critical section for one-way shear

(c) Critical section for two-way shear

d/2 (all sides)
Footing Subject to Compression and Moment: Uplift Nonlinear

- (a) Loading
- (b) Elastic, no uplift
- (c) Elastic, at uplift
- (d) Elastic, after uplift
- (e) Some plastification
- (f) Plastic limit
Example
7-story Building:
Shallow foundations designed for perimeter frame and core bracing.
Shallow Footing Examples

Soil parameters:
- Medium dense sand
- (SPT) N = 20
- Density = 120 pcf
- Friction angle = 33°

Gravity load allowables
- 4000 psf, B < 20 ft
- 2000 psf, B > 40 ft

Bearing capacity (EQ)
- $2000B$ concentric sq.
- $3000B$ eccentric
- $\phi = 0.6$
Footings proportioned for gravity loads alone

Corner: 6'x6'x1'-2" thick
Perimeter: 8'x8'x1'-6" thick
Interior: 11'x11'x2'-2" thick
Design of Footings for Perimeter Moment Frame

A B C D E F G H

1 2 3 4 5 6

7 at 25'-0"

5 at 25'-0"

N
7-Story Frame, Deformed
Combining Loads

- Maximum downward load:
  \[ 1.2D + 0.5L + E \]
- Minimum downward load:
  \[ 0.9D + E \]
- Definition of seismic load effect \( E \):
  \[
  E = \rho_1 Q_{E1} + 0.3 \rho_2 Q_{E2} + \pm 0.2 S_{DS}D \\
  \rho_x = 1.08 \quad \rho_y = 1.11 \quad \text{and} \quad S_{DS} = 1.0
  \]
## Reactions

<table>
<thead>
<tr>
<th>Grid</th>
<th>Dead</th>
<th>Live</th>
<th>$E_x$</th>
<th>$E_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-5</td>
<td>P</td>
<td>203.8 k</td>
<td>43.8 k</td>
<td>-3.8 k</td>
</tr>
<tr>
<td></td>
<td>$M_{xx}$</td>
<td>53.6 k-ft</td>
<td>243.1 k-ft</td>
<td>-1011.5 k-ft</td>
</tr>
<tr>
<td></td>
<td>$M_{yy}$</td>
<td>103.5 k</td>
<td>22.3 k</td>
<td>-51.8 k</td>
</tr>
<tr>
<td></td>
<td></td>
<td>47.7 k-ft</td>
<td>-246.9 k-ft</td>
<td>-891.0 k-ft</td>
</tr>
</tbody>
</table>

FEMA 451, Design Examples
Foundation Design 14-15
Reduction of Overturning Moment

- **NEHRP Recommended Provisions** allow base overturning moment to be reduced by 25% at the soil-foundation interface.
- For a moment frame, the column vertical loads are the resultants of base overturning moment, whereas column moments are resultants of story shear.
- Thus, use 75% of seismic vertical reactions.
Additive Load w/ Largest Eccentricity

• At A5:  \( P = 1.4(203.8) + 0.5(43.8) + 0.75(0.32(-3.8) + 1.11(21.3)) = 324 \text{ k} \)
  \[ M_{xx} = 0.32(53.6) + 1.11(-1011.5) = -1106 \text{ k-ft} \]

• At A6:  \( P = 1.4(103.5) + 0.5(22.3) + 0.75(0.32(-51.8) + 1.11(-281)) = -90.3 \text{ k} \)
  \[ M_{xx} = 0.32(47.7) + 1.11(-891) = -974 \text{ k-ft} \]

• Sum \( M_{xx} = 12.5(-90.3-324) -1106 -974 = -7258 \)
Counteracting Load with Largest $e$

- At A-5: $P = 0.7(203.8) + 0.75(0.32(-3.8) + 1.11(21.3)) = 159.5$ k
  
  $M_{xx} = 0.32(53.6) + 1.11(-1011.5) = -1106$ k-ft

- At A-6: $P = 0.7(103.5) + 0.75(0.32(-51.8) + 1.11(-281)) = -173.9$ k
  
  $M_{xx} = 0.32(47.7) + 1.11(-891) = -974$ k-ft

- Sum $M_{xx} = 6240$ k-ft
Elastic Response

- Objective is to set $L$ and $W$ to satisfy equilibrium and avoid overloading soil.
- Successive trials usually necessary.
Additive Combination

Given $P = 234\ k$, $M = 7258\ k$-ft
Try 5 foot around, thus $L = 35\ ft$, $B = 10\ ft$
• Minimum $W = \frac{M}{(L/2)} - P = 181\ k = 517\ \text{psf}$
Try 2 foot soil cover & 3 foot thick footing
• $W = 245\ k$; for additive combo use $1.2W$
• $Q_{\text{max}} = \frac{(P + 1.2W)}{3(L/2 - e)B/2} = 9.4\ \text{ksf}$
• $\phi Q_n = 0.6(3)B_{\text{min}} = 10.1\ \text{ksf}$, OK by Elastic
Plastic Response

- Same objective as for elastic response.
- Smaller footings can be shown OK thus:
Counteracting Case

Given $P = -14.4$ k; $M = 6240$

Check prior trial; $W = 245$ k (use $0.9W$)
- $e = \frac{6240}{(220.5 - 14.4)} = 30.3 > \frac{35}{2}$ NG

New trial: $L = 40$ ft, 5 ft thick
- $W = 400$ k; $e = 18.0$ ft; plastic $Q_{max} = 8.6$ ksf
- $\phi Q_n = 0.6(3)4 = 7.2$ ksf, close
- Solution is to add 5 k, then $e = 17.8$ ft and $Q_{max} = \phi Q_n = 7.9$ ksf
Additional Checks

• Moments and shears for reinforcement should be checked for the overturning case.
• Plastic soil stress gives upper bound on moments and shears in concrete.
• Horizontal equilibrium: $H_{max} < \phi \mu (P+W)$ in this case friction exceeds demand; passive could also be used.
Results for all SRS Footings

Corner: 10'x40'x5'-0" w/ top of footing 2'-0" below grade

Middle: 5'x30'x4'-0"

Side: 8'x32'x4'-0"
Design of Footings for Core-braced 7-story Building

25 foot square bays at center of building
Solution for Central Mat

Mat: 45'x95'x7'-0"
with top of mat 3'-6" below grade

Very high uplifts at individual columns; mat is only practical shallow foundation.
Bearing Pressure Solution

Plastic solution is satisfactory; elastic is not; see linked file for more detail.

(a) Plastic solution

(b) Elastic solution pressures (ksf)
Pile/Pier Foundations

Passive resistance (see Figure 4.2-5)

p-y springs (see Figure 4.2-4)

View of cap with column above and piles below.
Pile/Pier Foundations

Pile Stiffness:
- Short (rigid)
- Intermediate
- Long
Cap influence
Group action

Soil Stiffness
- Linear springs – nomographs e.g. NAVFAC DM7.2
- Nonlinear springs – LPILE or similar analysis
Sample $\rho$-$y$ Curves

Soil resistance, $p \text{ (lb/in.)}$

Pile deflection, $y \text{ (in.)}$

- Site Class C, depth = 30 ft
- Site Class C, depth = 10 ft
- Site Class E, depth = 30 ft
- Site Class E, depth = 10 ft
Passive Pressure

![Graph showing Passive Pressure vs. \( \delta/H \)]
Group Effect

- Group effect factor vs. group size (piles per side)
- Group sizes: s = 1.5 D, s = 2 D, s = 3 D, s = 4 D
Pile Shear: Two Soil Stiffnesses

![Graph showing pile shear for two soil stiffnesses, with depth on the y-axis and shear on the x-axis. The graph compares Site Class C and Site Class E.]
Pile Moment vs Depth

- Site Class C
- Site Class E
Pile Reinforcement

- Site Class C
- Larger amounts where moments and shears are high
- Minimum amounts must extend beyond theoretical cutoff points
- “Half” spiral for 3D

4" pile embedment

Section A
- (6) #5
- #4 spiral at 3.75 inch pitch

Section B
- (6) #5
- #4 spiral at 7.5 inch pitch

Section C
- (4) #5
- #4 spiral at 11 inch pitch

4" pile embedment

Section A
- (6) #5
- #4 spiral at 3.75 inch pitch

Section B
- (6) #5
- #4 spiral at 7.5 inch pitch

Section C
- (4) #5
- #4 spiral at 11 inch pitch
Pile Design

- Site Class E
- Substantially more reinforcement
- “Full” spiral for 7D
- Confinement at boundary of soft and firm soils (7D up and 3D down)
Other Topics for Pile Foundations

• Foundation Ties:  \( F = P_G(S_{DS}/10) \)
• Pile Caps: high shears, rules of thumb; look for 3D strut and tie methods in future
• Liquefaction: another topic
• Kinematic interaction of soil layers
Tie Between Pile Caps

- Designed for axial force (+/-)
- Pile cap axial load times $S_{DS}/10$
- Often times use grade beams or thickened slabs one grade

- 2" clear at sides
- 3" clear at top and bottom
- (2) #6 top bars
- #4 ties at 7" o.c.
- (3) #6 bottom bars