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Soil-Structure Interaction

Foundation Force-Deformation
- Foundation Flexibility
- Soil-Foundation Interface Yielding

Foundation Damping
- Radiation Damping
- Soil Hysteretic Damping

Kinematic Interaction
- Base Slab Averaging
- Embedment
What We Should Do

- Structure
  - Foundation elements
  - Foundation-soil interface elements
- Soil elements
- Transmitting boundary
- Bedrock
- $\ddot{u}_g(t,x,y,z)$
What We Actually Do
Geotechnical Engineer

Spatially-INCOHERENT ground motions from the rock motion through the soil column

nonlinear-inelastic soil spring-dashpots at each soil lens

Spatially-INCOHERENT ground motions from the rock motion through the soil column
What We Actually Do
USGS Maps
What We Actually Do

Structural Engineer
ASCE 7-16/ 2015 NEHRP Provisions

Based on ATC-83 Report (NIST NIST GCR 12-917-21)

Direct inclusion of soil flexibility

Merger ASCE 41-13 Provisions with ASCE 7-10

Updated foundation damping equations

Update & clarify limitations on use
Foundation Flexibility

(ii) Flexible Foundation (Distributed Springs)
Foundation Flexibility - Example

Reinforced concrete shear wall building
4 Story + 1 Basement
Site class D soil
Oakland, California
Foundation Flexibility - Example

Fixed Base Modal Period
T = 0.39 sec

Flexible Base Modal Period
T = 0.49 sec

25% increase in period due to foundation flexibility
Foundation Flexibility - Example

[Spectral Acceleration, Sa (g)]

Period, T (sec)

Sa_MCER_(MaxDir)

Sa_DE_(MaxDir)
Foundation Flexibility - Example

![Graph showing psa (g) vs. Period (sec)]
Foundation Yielding

Currently no requirement for foundation to be stronger than superstructure

Foundations and soil actions designed with same forces

Soil actions typically ASD
Foundation Yielding

Currently no requirement for foundation to be stronger than superstructure

Foundations and soil actions designed with same forces

Soil actions typically ASD
ASCE 7-16 => LRFD Soil Design

Introduced provisions to allow LRFD for soil actions

Phi factors based on material (clay vs. sand) and level of testing
Foundation Yielding – Example

Code Design:
40’x18’ footing
14-#7 Long & #7@12” Trans

Soil stronger than wall:
40’x24’ footing
16-#8 Long & #8@12” Trans

Footing stronger than soil or wall
40’x18’ footing
14-#8 Long & #8@12” Trans
Foundation Damping

Waves from structure moving interfere with ground motion waves

Soil Hysteretic damping affects shaking building feels
Foundation Damping

Radiation damping & soil hysteretic damping addressed

Modification of the design base-shear or response spectrum

Explicit damping elements required for nonlinear analysis
Foundation Damping

$S_a(g) \propto \text{Base Shear}$

$\tilde{T}, \beta_0 = \text{Flexible-base period, damping ratio}$

$T, \beta_i = \text{Fixed-base period, damping ratio}$

- Increased base shear
- Decreased base shear

$T \text{ (linear scale)}$

$T \text{ (log scale)}$

$F \rightarrow m$

$h \rightarrow k$

$z \rightarrow x$

$u_r \rightarrow k_x$

$\theta \rightarrow k_z$

$\Delta \rightarrow k_{yy}$
Foundation Damping & the R-Factor

“you get two for the dirt” – Henry Degenkolb

How much SSI is in the R-factor?

ASCE 7-10 limited to a 30% reduction

\[
\tilde{V} = V - \Delta V \\
\Delta V = \left[ C_s - \tilde{C}_s \left( \frac{0.05}{\beta} \right)^{0.4} \right] \bar{W} \leq 0.3V
\]
\[ \Delta V = \left( C_s - \frac{C_s}{B_{SSI}} \right) W \]

\[ \beta_o = \beta_f + \frac{\beta}{(\tilde{T}/T)_{eff}^2} \]

\[ \alpha = \begin{cases} 
0.7 & \text{for } R \leq 3 \\
0.5 + R/15 & \text{for } 3 < R < 6 \\
0.9 & \text{for } R \geq 6 
\end{cases} \]

\[ \beta_f = \left[ \frac{(\tilde{T}/T)^2 - 1}{(\tilde{T}/T)^2} \right] \beta_s + \beta_r \]
# Soil Damping

<table>
<thead>
<tr>
<th>Site Class</th>
<th>Effective Peak Acceleration, $S_{DS}/2.5^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_{DS}/2.5$ = 0</td>
</tr>
<tr>
<td>A</td>
<td>0.01</td>
</tr>
<tr>
<td>B</td>
<td>0.01</td>
</tr>
<tr>
<td>C</td>
<td>0.01</td>
</tr>
<tr>
<td>D</td>
<td>0.01</td>
</tr>
<tr>
<td>E</td>
<td>0.01</td>
</tr>
<tr>
<td>F</td>
<td>*</td>
</tr>
</tbody>
</table>
Radiation Damping

\[
\beta_r = [1/(T/T_y)^2]\beta_y + [1/(T/T_{xx})^2]\beta_{xx}
\]

(Eq. 19.3-5)

\[
T_y = 2\pi M K_y
\]

(Eq. 19.3-6)

\[
T_{xx} = 2\pi M K_{xx}
\]

(Eq. 19.3-7)

\[
K_y = \frac{GB}{2-v} \left[ 6.8 \left( \frac{L}{B} \right)^{0.65} + 0.8 \left( \frac{L}{B} \right) + 1.6 \right]
\]

(Eq. 19.3-8)

\[
K_{xx} = \frac{GB^3}{1-v} \left[ 3.2 \left( \frac{L}{B} \right) + 0.8 \right]
\]

(Eq. 19.3-9)

\[
\beta_y = \frac{4(L/B)}{(K_y/GB)} \left[ a_0 \right] \left[ \frac{a_0}{2} \right]
\]

(Eq. 19.3-10)

\[
a_0 = \frac{2\pi B}{Tv_y}
\]

(Eq. 19.3-11)

\[
\beta_{xx} = \left[ \frac{(4\psi/3)(L/B)a_0^2}{(K_{xx}/GB^3)[2.2 - \frac{0.4}{(L/B)^3} + a_0^2]} \right] \left[ \frac{a_0}{2\alpha_{xx}} \right]
\]

(Eq. 19.3-12)

\[
\psi = \frac{2(1-v)}{\sqrt{1-2v}} \leq 2.5
\]

(Eq. 19.3-13)

\[
\alpha_{xx} = 1.0 - \left[ \frac{0.55 + 0.01\sqrt{(L/B) - 1}a_0^2}{2.4 - \frac{0.4}{(L/B)^3} + a_0^2} \right]
\]

(Eq. 19.3-14)
Foundation Damping Example

Structural Damping, $\beta = 5\%$
Radiation Damping, $\beta_f = 11\%$
Soil Damping, $\beta_f = 7\%$

Foundation Damping

$$\beta_f = \left[ \frac{(0.49/0.39)^2 - 1}{(0.49/0.39)^2} \right] \times 0.07 + 0.11 = 0.14$$

Total Damping

$$\beta_0 = 0.11 + \frac{0.05}{1.7^2} = 0.16$$

$$B_{SSI} = \frac{4}{[5.6 - \ln(100\beta_0)]} = \frac{4}{[5.6 - \ln(100 \times 0.16)]} = 1.4$$
Foundation Damping Example

Damping Base Shear Reduction

\[ \Delta V = \left( C_s - \frac{\tilde{C}_s}{B_{SSI}} \right) \bar{W} = \left( 0.20 - \frac{0.20}{1.4} \right) \times 14,500 = 800 \text{ kips} \]

Base Shear

\[ \tilde{V} = V - \Delta V = 3,300 - 800 = 2,500 \text{ kips} = 0.15W \]

R-factor limit

\[ \alpha = 0.5 + R/15 = 0.5 + 5/15 = 0.83 \]

Revised base shear based on limit

\[ \tilde{V} \geq \alpha V = 0.83 \times 3,300 = 2,700 \text{ kips} = 0.17W \]
## Foundation Damping Example

<table>
<thead>
<tr>
<th>Property</th>
<th>Fixed Base – No SSI</th>
<th>Flexible Base – SSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Thickness</td>
<td>14 inches</td>
<td>12 inches</td>
</tr>
<tr>
<td>Horizontal Reinf.</td>
<td>#5 @ 12” o.c.</td>
<td>#4 @ 12” o.c.</td>
</tr>
<tr>
<td>Vertical Reinf.</td>
<td>#5 @ 12” o.c.</td>
<td>#4 @ 12” o.c.</td>
</tr>
<tr>
<td>Boundary Region</td>
<td>14 - #7</td>
<td>None</td>
</tr>
<tr>
<td>Footing Dimensions</td>
<td>40-ft x 14-ft</td>
<td>40-ft x 14-ft</td>
</tr>
<tr>
<td>Footing Long. Reinf.</td>
<td>14 - #7 T&amp;B</td>
<td>12 - #7 T&amp;B</td>
</tr>
<tr>
<td>Footing Trans Reinf.</td>
<td>#7 @ 12” T&amp;B</td>
<td>#7 @ 14” T&amp;B</td>
</tr>
</tbody>
</table>
Kinematic Interaction

> Spatial variability of input ground motion along the foundation

  **Embedment Effects** – Deamplification of ground motion with depth (Vertical)
  **Base-Slab Averaging** – Wave incoherence across foundation (Horizontal)

> Affects high-frequency input
> Multi-support excitation in modeling
Base Slab Averaging

Low frequency components...

2003 Off-Miyagi Eqk
FF, s-wave window

\[ u_{FIM}(\omega) \approx u_g(\omega) \]
Base Slab Averaging

High frequency components...

2003 Off-Miyagi Eqk FF, p-wave window

$u_{FIM}(\omega) < u_g(\omega)$
Embedment Effect

Low frequency

Long wavelength
\[ \lambda = \frac{V_s}{f} \]

\[ u_{FIM} \approx u_g \]

\[ \theta_{FIM} \approx 0 \]
Embedment Effect

High frequency

Short wavelength

\[ \lambda = \frac{V_s}{f} \]

\[ u_{FIM} < u_g \]

\[ \theta_{FIM} > 0 \]
Kinematic Interaction

![Graph showing Kinematic Interaction](graph.png)
Ground Motions – Free Field

Scaled Target Spectrum
- Chi-Chi, Taiwan :: TCU078 :: SRSS
- Chi-Chi, Taiwan :: TCU120 :: SRSS
- Denali, Alaska :: TAPS Pump Station #10 :: SRSS
- Imperial Valley-02 :: El Centro Array #9 :: SRSS
- Kobe, Japan :: Nishi-Akashi :: SRSS
- Kocaeli, Turkey :: Izmit :: SRSS
- Kocaeli, Turkey :: Yarimca :: SRSS
- Landers :: Joshua Tree :: SRSS
- Northridge-01 :: LA - Sepulveda VA Hospital :: SRSS
- Northridge-01 :: Newhall - Fire Sta :: SRSS
- Scaled Modified SRSS Average
Ground Motions – At-Depth Amp-Scaled
Concerns / Issues

- Base slab averaging reduction is unlimited at short periods
- Base slab averaging equation predicts negative values at large base dimensions
- Embedment & base slab averaging can reduce PGA to 0.3 second values to 0.22*Free Field
- Kinematic effects greatest at short periods, but no requirement to include foundation flexibility
Scatter on Observed Data
Look at Existing Data – Wadsworth Hospital

Los Angeles, Wadsworth V.A. -- Northridge 1994

Ratio between basement and free-field record (average)

ASCE 41-06 BSA + Embedment Effects
Issues addressed

• Require soil flexibility modeled
• Provide overall kinematic limit of 50%
• Temper reductions for kinematic effects
• Limit base area for BSA
• Update equations for BSA
Soil-Foundation-Structure Interaction

Base Slab Averaging & Embedment Equations Updated

\[ RRS_{bsa} = 0.25 + 0.75 \times \left\{ \frac{1}{b_0^2} \left[ 1 - \exp(-2b_0^2) \right] B_{bsa} \right\}^{1/2} \]

\[ B_{bsa} = \exp(2b_0^2) \left[ 1 - \frac{1}{\sqrt{\pi}b_0} \left( 1 - \frac{1}{16b_0^2} \right) \right] \quad b_0 \leq 1 \]

\[ B_{bsa} = \exp(2b_0^2) \left[ 1 - \frac{1}{\sqrt{\pi}b_0} \left( 1 - \frac{1}{16b_0^2} \right) \right] \quad b_0 > 1 \]

Base area limited based on testing limits, 260 feet.

\[ RRS_e = 0.25 + 0.75 \times \cos \left( \frac{2\pi e}{Tn\nu_s} \right) \geq 0.50 \]

0.75 factor reduces the reduction

Max reduction can only be 50%
ASCE 7-16 Kinematic Interaction

**Only can be used with nonlinear response history**

Limited to 20% reduction from site specific

Limited to 30% reduction from USGS spectra

2015 NEHRP allowed to 40% with peer review
  - 40% eliminated in ASCE 7-16

Must model soil flexibility
Kinematic Interaction - Example

![Graph showing Sa (g) vs. Periods (s) with different lines representing Sa_MCE, Sa_MCE (SSI 7-16), and Sa_MCE (2015 NEHRP).]
Kinematic Interaction - Example

Displacement

Story elevation, ft

displacement, in

- Sa_MCER
- Sa_MCE (SSI 7-16)
- Sa_MCE (2015 NEHRP)
Kinematic Interaction - Example

Story Drift Ratio

- Sa_MCE
- Sa_MCE (SSI 7-16)
- Sa_MCE (2015 NEHRP)