SITE EFFECTS IN STRONG-IMPEDANCE ENVIRONMENTS AND THE IMPORTANCE OF $f_0$: LESSONS LEARNED IN BOSTON, MASSACHUSETTS

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Site Effects in Strong-Impedance Environments and the Importance of $f_0$: Lessons Learned in Boston, Massachusetts

Laurie G. Baise, James Kaklamanos, and John E. Ebel

• Background and motivation
• Site response analyses
• Microtremor studies and $f_0$
• Conclusions
Boston, Massachusetts

- Shallow sedimentary basin with a sharp impedance contrast at bedrock depth of 10-80 m
- Large areas near the Charles and Mystic Rivers have been extensively filled, resulting in loose layers of artificial fill overlying organic material and marine sediments (e.g. Boston Blue Clay)
- Large amounts of geotechnical data
  - > 3500 borings with soil information
  - 30 shear-wave velocity profiles (27 SASW and 3 sCPT)
  - 570 microtremor measurements of ambient noise and fundamental site period
**$V_S$ profiles**

- **SASW:** 27 $V_S$ measurements in various geologic units
- Generic profiles for (a) glacio-fluvial, (b) fill, and (c) bedrock sites

2011 M 5.8 Mineral, Virginia Earthquake

- NEU – Northeastern University Seismic Array (surface + downhole)
- JP – Jamaica Pond Veteran’s Hospital (surface)

08/23/2011 M 5.8 Virginia earthquake
Epicentral distance = 760 km
NEU PGA = 0.004g
2011 M 5.8 Mineral, Virginia Earthquake

- NEU – Northeastern University Seismic Array (surface + downhole)
- JP – Jamaica Pond Veteran’s Hospital (surface)

Amplification ratio of 10-15 near 1.4 Hz (0.7 s)

2 km apart
Design ground motions for Boston

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Parametric study

• Effect of soil thickness, H
  • Soil thickness (H) varies from 10-80 m

• Effect of soil/rock impedance contrast
  • Soil $V_s$ varies from 100-500 m/s (fill sites)
  • Bedrock $V_s$ set to two values:
    • $V_{sb} = 2000$ m/s (based on SASW measurements)
    • $V_{sb} = 3000$ m/s (Hashash et al., 2014)

• Effect of quality factor, Q
  • Linear site response quality factor set to two values: $Q = 15$ and $Q = 30$

• Effect of site response model
  • Linear (L)
  • Equivalent-Linear (EQL)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of soil column (H)</td>
<td>10 – 80 m</td>
</tr>
<tr>
<td>Shear-wave velocity of the soil ($V_s$)</td>
<td>100 – 500 m/s</td>
</tr>
<tr>
<td>Shear-wave velocity of the bedrock ($V_{sb}$)</td>
<td>1750 – 2250 m/s</td>
</tr>
<tr>
<td>Density of soil ($\rho_s$)</td>
<td>1.4 – 1.9 g/cm³</td>
</tr>
<tr>
<td>Density of bedrock ($\rho_b$)</td>
<td>2.75 g/cm³</td>
</tr>
<tr>
<td>Quality factor (Q)</td>
<td>10 – 30</td>
</tr>
</tbody>
</table>
### Generic $V_S$ profile for Boston (fill sites)

#### Properties of generic $V_S$ profile

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Layer type</th>
<th>Unit weight (kN/m$^3$)</th>
<th>Modulus-reduction and damping curve for EQL analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–3</td>
<td>Fill</td>
<td>20</td>
<td>Seed and Idriss (1970): Sand</td>
</tr>
<tr>
<td>3–6</td>
<td>Organics</td>
<td>17</td>
<td>Vucetic and Dobry (1991): Clay, $P_I = 30$</td>
</tr>
<tr>
<td>6–15</td>
<td>Sand and gravel</td>
<td>19</td>
<td>Seed and Idriss (1970): Sand</td>
</tr>
<tr>
<td>15–$H^*$</td>
<td>Clay</td>
<td>18.5</td>
<td>Vucetic and Dobry (1991): Clay, $P_I = 30$</td>
</tr>
<tr>
<td>–</td>
<td>Bedrock</td>
<td>27</td>
<td>Linear</td>
</tr>
</tbody>
</table>

*For profiles with $H \leq 15$ m, the bottom soil layer is sand and gravel.*

Depth to bedrock ($H$) varies from 10-80 m
Presentation of results

- $F_a$: Mean short period amplification ratio (0.1-0.5 s)
- $F_v$: Mean intermediate period amplification ratio (0.5-1.5 s)
Amplification functions

All panels: $V_{SB} = 2000$ m/s
Amplification function
Mean short-period (0.1-0.5 s) and intermediate-period (0.5-1.5 s) amplification
Site coefficients:
$F_a$ (0.1-0.5 s)
$F_v$ (0.5-1.5 s)
Linkage to NEHRP site coefficients

- Mean amplifications and fundamental period as a function of bedrock depth
- Comparison to NEHRP site coefficients
- Validation with observed amplifications from Mineral earthquake
Linkage to NEHRP site coefficients

Panels (a) and (b):
- Linear, $V_{sb} = 2000$ m/s, $Q = 15$
- Linear, $V_{sb} = 3000$ m/s, $Q = 15$
- Linear, $V_{sb} = 2000$ m/s, $Q = 30$
- Linear, $V_{sb} = 3000$ m/s, $Q = 30$
- Equivalent Linear, $V_{sb} = 2000$ m/s
- Equivalent Linear, $V_{sb} = 3000$ m/s
- Site Coefficients, $F_a$ and $F_v$
- NEU00/NEU51 Observed Amplification
- NEU00/JP Observed Amplification
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H/V estimates of fundamental site period

- Microtremor study: 570 ambient noise measurements (H/V analysis) to determine fundamental site period (FSP)
- Comparison to 27 SASW $V_s$ profiles from Thompson et al. (2014)

$fo = \frac{1}{FSP}$

Fundamental site period (FSP) versus $V_{S30}$
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Conclusions

In strong impedance contrast environments like Boston:

- Amplification can be significant – on the order of 10 times for linear ground motions – and can be accurately estimated using 1D site response calculations (controlled by depth to bedrock and impedance contrast)

- NEHRP site coefficients $F_a$ and $F_v$ may severely underpredict soil amplifications, perhaps warranting revisions in strong impedance contrast environments
  - $F_a$: underpredictions for shallow and deep soil columns
  - $F_v$: underpredictions for deep soil columns, and overpredictions for shallow soil columns

- Fundamental site period can be accurately predicted by ambient noise H/V measurements

- Fundamental site period and $V_{S30}$ are strongly related, and the relationship for Boston is consistent with that observed in Ottawa and Montreal (other high impedance environments)
Acknowledgments

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References

