“$V_{S30}$ - A Basis for Characterization of Seismic Site Response for Site-specific, Regional, and Global Mapping of Seismic Hazard

Roger D. Borcherdt

1st Annual Meeting of the Strategic Chinese-Korean-Japanese Cooperative Program: Seismic Hazard Assessment for the Next Generation Map

November 25-30, 2011
Harbin Institute of Technology
Harbin, China

borcherdt@usgs.gov
Outline

• Definition \( V_{S30} \)

• \( V_{S30} \) as a Basis for Characterization of Site-Specific Site Response
  • Theoretical Dependence of Amplification on \( V_{S30} \)
  • Empirical Dependence of Amplification on \( V_{S30} \)
  • \( V_{S30} \) correlations with \( V_{S30} \) at other depths

• \( V_{S30} \) as a Basis for Mapping Site Response
  Correlations of \( V_{S30} \) with:
  • Physical Properties -- Site Class definitions
  • Geologic Age
  • Topographic Slope

• Applications of \( V_{S30} \)
  • Site-Specific Response Characterization – Site Classes, Site Coefficients, Building Codes
  • Regional Site Response Mapping – GMPEs, ShakeMaps, PSHA, GEM
$V_{S30}$ Definition

$V_{s30} \equiv 30 \text{ m/Travel time to 30 m}$

(from Borcherdt, 1994)
Theoretical Response of a Viscoelastic Soil Layer versus Vs Ratio and Normalized Frequency

Amplitude Response versus Frequency
Homogeneous Linear S Wave, Vertical Incidence

Solution:

\[
\frac{D_0}{D_1} = F[(\text{inc. wave field par.}, \text{material par.})]
\]

\[
\frac{D_0}{D_1} = F[(\theta, 2, f, \frac{v_{Hs_1}}{v_{Hs_2}}, \frac{Q_{Hs_1}}{Q_{Hs_2}}, \frac{\rho_1}{\rho_2})]
\]

where \(f_0\) = fundamental frequency.
Empirical Spectral Amplification Values versus $V_{S30}$

Loma Prieta Earthquake; $I_a < 0.1g$

**Short-Period Band (0.1 - 0.5 s)**

- $F = (997 \text{ m/s} / v)^{0.56}$
- 95% Confidence Limits for Ordinate
- ± 2 Standard Error of Estimate

**Intermediate-Period Band (0.5 - 1.5 s)**

- $F = (1004 \text{ m/s} / v)^{0.69}$
- 95% Confidence Limits for Ordinate
- ± 2 Standard Error of Estimate

**Long-Period Band (1.5 - 5.0 s)**

- $F = (1077 \text{ m/s} / v)^{0.67}$
- 95% Confidence Limits for Ordinate
- ± Standard Error of Estimate

**Mid-Period Band (0.4 - 2.0 s)**

- $F = (1067 \text{ m/s} / v)^{0.64}$
- 95% Confidence Limits for Ordinate
- ± Standard Error of Estimate

Mean Shear-Wave Velocity to 30 m (100 ft) $(v, \text{ m/s})$

*(Borcherdt, 1994)*

Mean Shear-Wave Velocity to 30 m (100 ft) $(v, \text{ m/s})$
Empirical Spectral Amplification Values versus $V_{S30}$
Northridge Earthquake; $I_a < 0.2g$, $I_a > 0.2g$
Empirical Dependence of Amplification on $V_{S30}$
(Site Coefficients for Seismic Design)

**Short- and Mid-Period Amplification Factors are:**

$$F_a = (V\text{ref} / V_{S30})^{m_a}$$
and

$$F_v = (V\text{ref} / V_{S30})^{m_v}$$

where,

1) $V_{S30}$ is inferred or measured mean shear-wave velocity to 30 m at site,
2) $V\text{ref}$ is $V_{S30}$ for reference ground condition,
3) $m_a$ and $m_v$ depend on input ground motion level.
$F_a$ versus Input Amplitude & $V_{S30}$

$I_a = 0.1, 0.2, 0.3, 0.4 \text{ g (linear scales)}$

$F_a = \left( \frac{v_{SC-Ib}}{v} \right)^{m_a} = \left( \frac{1050 \text{ m/s}}{v} \right)^{m_a}$

- $I=0.1\text{g}$: $m_a = 0.35$
- $I=0.2\text{g}$: $m_a = 0.25$
- $I=0.3\text{g}$: $m_a = 0.10$
- $I=0.4\text{g}$: $m_a = -0.05$

$Fa (0.1\text{g})$ for Site Class Intervals

Soft soils

SC-IV

SC-III

SC-II

SC-Ib

Firm to Hard rocks

Soft rocks

Gravelly soils and
Sandy soils

Stiff clays and

Mean Shear-Wave Velocity to 30 m (100 ft) ($v$, m/s)

(Borcherdt, 1994)
$F_v$ versus Input Amplitude & $V_{S30}$

$I_v = 0.1, 0.2, 0.3, 0.4$ g (linear scales)

$F_v = \left( \frac{v_{SC-Ib}}{v} \right)^{m_v} = \left( \frac{1050 \, m/s}{v} \right)^{m_v}$

- $I=0.1g; \ m_v = 0.65$
- $I=0.2g; \ m_v = 0.60$
- $I=0.3g; \ m_v = 0.53$
- $I=0.4g; \ m_v = 0.45$

$F_v(0.1g)$ for Site Class Intervals

- $F_v$ for Site Classes

Borcherdt, 1994
NEHRP & NGA Short-Period Amplification versus $V_{S30}$

Aa=0.1g; Avg. 0.1-0.5s; Vs30 norm 1050 m/s
NEHRP & NGA Mid-Period Amplification versus $V_{S30}$

$Av = 0.1g$; Avg. 0.4-2.0 s; $Vs30$ norm 1050 m/s

(NGA values from Stewart and Seyhan, 2011)
$V_{S\ 30}$ Correlation with $V_{S\ Z}$ at other Depths

$V_{S\ 30}$ as a function of $V_{S\ Z}$ at another depth:

$$\log[V_{S\ 30}] = c_0 + c_1 \log[V_{S\ Z}] = G(V_{S\ Z})$$

(Cadet, et al., 2009; Boore, et al., 2011)

Hence, amplification as a function of $V_{S\ 30}$:

$$F_a = (V_{S\ 30\ \text{ref}} / V_{S\ 30})^{m_a} = F_a (V_{S\ 30\ \text{ref}}, V_{S\ 30})$$

Implies amplification as a function of $V_{S\ Z}$ at other depths:

$$F_a = H_a (V_{S\ Z\ \text{ref}}, V_{S\ Z})$$
$V_{s\ 30}$ as a Basis for Mapping Site Response

Correlations of $V_{s\ 30}$ with:

- Physical Properties -- Site Class definitions
- Geologic Age
- Topographic Slope
$V_{S30}$ for USGS Boreholes in CA
$V_{S30}$ versus Physical Property Classification for USGS Boreholes in CA
Suggests Seismically Distinct Units
$V_{S_{30}}$ Statistics for Physical Property Classification
(Texture, Fracture Spacing, & Age -- USGS Boreholes in CA)

Statistics for Texture, Fracture Spacing, Age Classification of USGS Boreholes in CA

Shear Wave Velocity (m/s) vs Site Class

Physical Property Classes

- Qhbm
- Qyf
- Qym
- Qof
- Qym/Qoc
- Qom
- Qyc
- Ts & Tv
- KJs (close fs)
- KJs (wide fs)
Vs30 Statistics for Physical Property NEHRP Site Classes
(Texture, Fracture Spacing, & Age -- USGS Boreholes in CA)

Boreholes in CA (NEHRP Boundaries)

Shear Wave Velocity (m/s)

Site Class

af/Qhbm         Qyf, Qym, Qof       Qym/Qoc, Qom, Qyc, Ts, Tv, KJs c f s       gr, Kjs w f s

0               200               400               600               800

from Borcherdt, 1994
Geologic Site Condition Map
($V_{s30}$ correlations with Geologic Age)

Wills et al., 2000
CGS Geologic Classification versus $V_{S30}$

CGS Classification for USGS Boreholes in CA

Borehole
$V_{S30}$ Correlations with Topographic Slope

(from Wald and Allen, 2007)
$V_{s30}$ Map
(Derived from Topographic Slope)
$V_{s30}$ Maps
(Derived from Geologic Age and Topographic Slope)

(Wald and Allen, 2007)
Applications of $V_{S30}$

- **Site-Specific Response Characterization**
  - Site Classes & Site Coefficients for Site-specific Design Spectra, Building Codes
  - Ground Motion Prediction Equations (GMPE) developed as a continuous function of Vs30

- **Regional Site Response Map in**
  - ShakeMaps
  - PSHA Maps
  - Global Earthquake Model (GEM)
Definition of Site-Dependent Response Spectra (log-log scale)

(NEHRP, UBC, IBC, ASCE 7 Provisions)
Site-Dependent Response Spectra (linear-linear scale) (NEHRP, UBC, IBC, ASCE 7 Provisions)

\[ S_a = I_a F_a = S_{DS} = \frac{2}{3} S_{MS} = \left( \frac{2}{3} \frac{S_S}{T} \right) F_a \]

\[ S_a = \frac{I_v}{T} F_v = S_{D1} = \frac{2}{3} S_{M1} = \left( \frac{2}{3} \frac{S_1}{T} \right) F_v \]

\[ S_a \left( T : T \geq T_L \right) = S_{D1} \left( \frac{T_L}{T^2} \right) \]
$F_a$ versus Input Amplitude & $V_{S30}$

$I_a = 0.1, 0.2, 0.3, 0.4$ g (linear scales)

$F_a = (v_{SC-Ib} / v)^{m_a} = (1050 \text{ m/s} / v)^{m_a}$

Borcherdt, 1994
$F_v$ versus Input Amplitude & $V_{S30}$

$I_v = 0.1, 0.2, 0.3, 0.4$ g (linear scales)

$F_v = \left( \frac{v_{SC-Ib}}{v} \right)^{m_v} = \left( \frac{1050 \text{ m/s}}{v} \right)^{m_v}$

- $I=0.1g$: $m_v = 0.65$
- $I=0.2g$: $m_v = 0.60$
- $I=0.3g$: $m_v = 0.53$
- $I=0.4g$: $m_v = 0.45$

Fv(0.1g) for Site Class Intervals

Fv for Site Classes

Soft soils

Stiff clays and Sandy soils

Gravelly soils and Soft rocks

Firm to Hard rocks

Mean Shear-Wave Velocity to 30 m (100 ft) ($v$, m/s)

(Borcherdt, 1994)
Short-Period Site Coefficient $F_a$
(NEHRP, UBC, IBC, AASHTO, ASCE 7 Provisions)

<table>
<thead>
<tr>
<th>Site Class</th>
<th>$A_a \leq 0.1$</th>
<th>$A_a = 0.20$</th>
<th>$A_a = 0.30$</th>
<th>$A_a = 0.40$</th>
<th>$A_a \geq 0.50$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_s &lt; 0.25$</td>
<td>$S_s = 0.50$</td>
<td>$S_s = 0.75$</td>
<td>$S_s = 1.00$</td>
<td>$S_s \geq 1.25$</td>
</tr>
<tr>
<td>A</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>B</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>C</td>
<td>1.2</td>
<td>1.2</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>D</td>
<td>1.6</td>
<td>1.4</td>
<td>1.2</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>E</td>
<td>2.5</td>
<td>1.7</td>
<td>1.2</td>
<td>0.9</td>
<td>*</td>
</tr>
<tr>
<td>F</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

* Site-specific geotechnical investigation and dynamic site response analysis shall be performed.
Mid-Perio Site Coefficient $F_v$
(NEHRP, UBC, IBC, AASHTO Provisions)

<table>
<thead>
<tr>
<th>Site Class</th>
<th>$A_v \leq 0.1$</th>
<th>$A_v = 0.20$</th>
<th>$A_v = 0.30$</th>
<th>$A_v = 0.40$</th>
<th>$A_v \geq 0.50$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_l &lt; 0.1$</td>
<td>$S_l = 0.20$</td>
<td>$S_l = 0.30$</td>
<td>$S_l = 0.40$</td>
<td>$S_l \geq 0.50$</td>
</tr>
<tr>
<td>A</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>B</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>C</td>
<td>1.7</td>
<td>1.6</td>
<td>1.5</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>D</td>
<td>2.4</td>
<td>2.0</td>
<td>1.8</td>
<td>1.6</td>
<td>1.5</td>
</tr>
<tr>
<td>E</td>
<td>3.5</td>
<td>3.2</td>
<td>2.8</td>
<td>2.4</td>
<td>*</td>
</tr>
<tr>
<td>F</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

* Site-specific geotechnical investigation and dynamic site response analysis shall be performed.
Anelastic Soil Layer
Damping Ratio 5%
Vertical Incidence

Response versus Period, Shear Velocity, and Code Site Class

$RQ_2 = 0.02$
$RQ_1 = 2$
$DR = 0.1$

Anelastic Soil Layer
Damping Ratio 5%
Vertical Incidence
Code Site Coefficients and Theoretical Response 15 % Damping or $I_a \sim 0.4 \, g$

Anelastic Soil Layer
Damping Ratio 15 %
$I_a \sim 0.4 \, g$
Vertical Incidence

Homogeneous Linear S Wave

Soil

Rock

$D_0/D_1$

$T/T_0$

$RQ_2 = 0.02 \quad RQ_1 = 2 \quad DR = 0.3$

Fa B
Fa C
Fa D
Fa E
Fv B
Fv C
Fv D
Fv E
NGA Ground Motion Prediction Equations

\[ \text{GMPE} = f(V_{S30}) \]

\[ \ln Y = f_{mag} + f_{dis} + f_{style of faulting} + f_{site} + f_{sed} + \epsilon \]

Where, site condition term = \( f_{site} \left( V_{S30} \right) \)

\[
\begin{align*}
  &c_{10} \ln \left( \frac{V_{S30}}{k_1} \right) + k_2 \left[ \ln \left( A_{1100} + c \left( \frac{V_{S30}}{k_1} \right)^n \right) \right] = \ln \left( A_{1100} + c \right); V_{S30} < k_1 \\
  &f_{site} = \begin{cases} 
  (c_{10} + k_2 n) \ln \left( \frac{V_{S30}}{k_1} \right) & ; k_1 \leq V_{S30} < 1100 \\
  (c_{10} + k_2 n) \ln \left( \frac{1100}{k_1} \right) & ; V_{S30} \geq 1100
\end{cases}
\end{align*}
\]

(from Campbell and Bozorgnia, 2004)
$V_{S30}$ for Regional Site Response Mapping

ShakeMaps
$V_{S30}$ Map (Topographic Slope)  
(San Francisco Bay Region)
Spectral Acceleration ShakeMaps
Loma Prieta Earthquake
(San Francisco Bay Region)

http://earthquake.usgs.gov/hazards/apps/
Instrumental Intensity ShakeMap
Loma Prieta Earthquake
(San Francisco Bay Region)

http://earthquake.usgs.gov/hazards/apps/
$V_{S30}$ Map (Topographic Slope)
(Haiti Region)
Spectral Acceleration ShakeMaps
Tohoku Japan Earthquake M 9.0
(Honshu Japan Region)

Spectral Acceleration 0.3 Sec

Spectral Acceleration 1.0 Sec

http://earthquake.usgs.gov/hazards/apps/
Instrumental Intensity ShakeMap
Haiti Earthquake M 7.0

http://earthquake.usgs.gov/hazards/apps/
\( V_{S30} \) for Seismic Hazard and Risk Mapping

- PSHA Maps
- GEM Global Seismic Hazard Mapping Project
$V_{S\,30}$ Map (Topographic Slope) (Western US)
PSHA Map for Rock
(NGA GMPE 2008 SA @2 s, 2% PE 50 yr, \( V_{S30} = 760 \text{ m/s} \))
PSHA Map Including Site Conditions ($V_{S30}$)
(SA @1 s, 2% PE 50 yr)

(Kalkan and Grazier, 2010)
Global GMPE for GEM
(Site condition characterization based on $V_{S30}$)

Bozorgnia and others, 2011
Conclusions

• Theoretical models and empirical measurements show $V_{S30}$ shows a strong correlation with amplification, $F_a$ and $F_v$, at specific sites.

• Correlations of $V_{SZ}$ with $V_{S30}$ imply $V_{SZ}$ at other depths can be used to predict $V_{S30}$ and amplification, $F_a$ and $F_v$.

• Correlations of $V_{S30}$ with Physical Properties, Geologic Age, and Topographic Slope imply $V_{S30}$ can be mapped on regional and global scales.

• Hence, $V_{S30}$ serves as a useful basis for characterization of site response for specific sites and for regional mapping purposes for the appropriate applications.

• Important applications of $V_{S30}$ include:
  – Unambiguous definitions of site classes and site coefficients for routine design in building codes
  – Characterization of site response for GMPEs for use in Site Specific, Regional, and Global Mapping of Seismic Hazard for appropriate interpretations: ShakeMaps, PSHA Maps, GEM Model

borcherdt@usgs.gov