A Site Response Map of the Continental U.S.

H. Magistrale & Y. Rong
FM Global, Norwood MA USA

W. Silva
Pacific Engineering & Analysis, El Cerrito CA USA

E. Thompson
Tufts University, Medford MA USA

SUMMARY
We follow the topographic slope methodology, which uses correlations between slope and Vs30, to create a site response map of the continental U.S. We develop new separate regional correlations for the tectonically stable central and eastern U.S. (CEUS) and the tectonically active western U.S. (WUS), and introduce a novel correlation for areas of the WUS that hosted Pleistocene and younger lakes. The correlations are calibrated to the Vs30 observation database of Pacific Engineering and Analysis. The slopes are determined from SRTM digital elevation data. We merge the two tectonic regions by a linear weighting over the Rocky Mountain physiographic province, which we identify as representing a tectonic condition intermediate between the CEUS and WUS.

Keywords: Vs30, site response, topography, North America

1. INTRODUCTION

Earthquake ground motions are a function of site conditions (Wood, 1908; Reid, 1910). Vs30, the measure of the average shear-wave velocity to a depth of 30 m, has become a widely accepted description of site conditions (Borcherdt, 1994a, 1994b; Rinne, 1994; Dobry et al., 1999). Vs30 has been incorporated into U.S. building codes (NEHRP, 1994, 1997; UBC, 1997; BSSC, 2000, 2004) to characterize site amplifications, and recently incorporated into Ground Motion Prediction Equations (GMPEs) (Boore et al., 1997; Atkinson and Boore, 2006; Power et al., 2008).

Vs30 can be readily determined by downhole and surface techniques but these measurements are expensive for regional-scale applications. This motivates the use of proxy correlations for Vs30. There are currently three classes of proxies: (i) surficial geology (Wills and Silva, 1998; Wills and Clahan, 2004, 2006); (ii) generic site categories or classifications, such as Geomatrix, Campbell, or Spudich (Chiou et al., 2008) which are loosely based on geology, anticipated depth to rock, or local setting, for example, wide or narrow valley; and (iii) physiographic characteristics such as topographic slope (Wald and Allen, 2007) and terrain (Yong et al., 2008, 2010, 2012).

Here we use topographic slope as a proxy for Vs30. It is recognized (Wald and Allen, 2007) that certain geologic factors may confound topographic slope-Vs30 correlations. For example, tectonically active regions have a different correlation than tectonically inactive regions (Wald and Allen, 2007). Herein we identify a separate correlation for areas of the WUS that hosted Pleistocene and younger lakes.

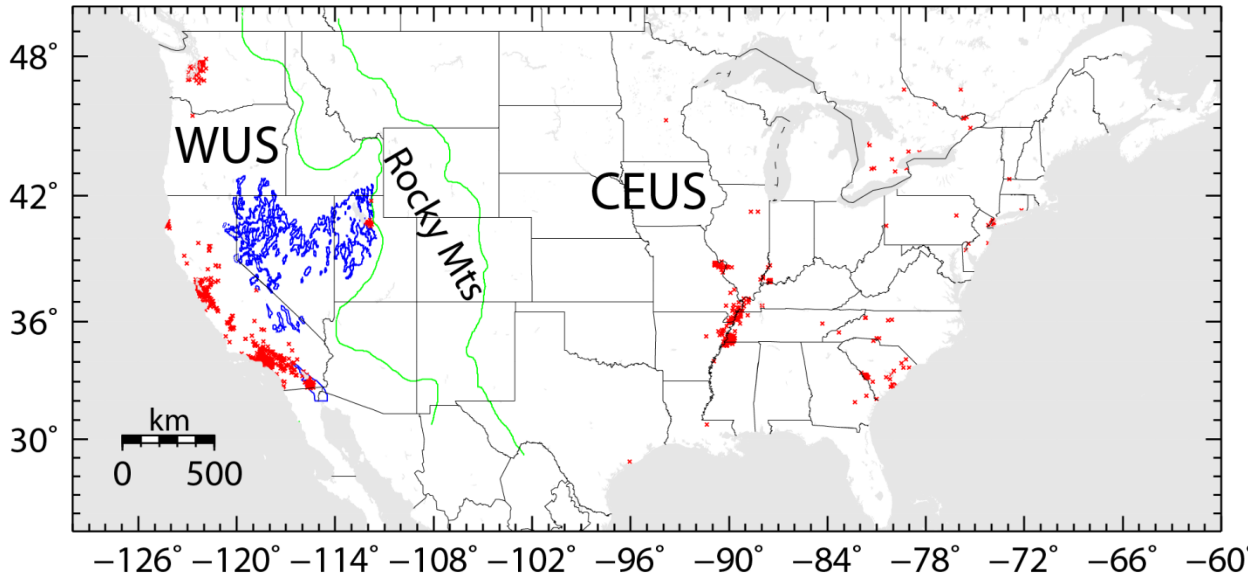

Figure 1. Regions and data distribution in the continental U.S. Green lines divide the U.S. into the WUS (western U.S.), the Rocky Mountains physiographic province (here including the Colorado Plateau and the Rio Grande rift), and the CEUS (central and eastern U.S.). Blue lines outline areas formerly occupied by lakes. Red symbols indicate Vs30 measurement sites in the Pacific Engineering and Analysis database.

2. DATA

The slope in the WUS is computed from 9 arcsecond (~280 m) SRTM data (Jarvis et al., 2008). For the CEUS, slope is computed from 30 arcsecond (~900 m) data (Becker et al., 2009). We use different resolutions because topography changes over a shorter length scale (is steeper) in the WUS. We confirmed that slope is computed in a manner consistent with Wald and Allen (2007; D. Wald, personal communication, 2011).

The Vs30 data come from the profile database of Pacific Engineering and Analysis (PEA; W. Silva, personal communication, 2011). The database consists of measured velocities determined by borehole (suspension, crosshole, downhole, seismic cone) and surface (ReMi, SASW, MASW, reflection, refraction) techniques. Each profile was vetted by examining the accompanying acquisition information or metadata. Currently, the profile database contains about 1450 measured profiles in the continental U.S. and southern Canada (Figure 1). Due to the private nature of many profiles, the database is proprietary. We also use 229 Vs30 values calculated from Vs measurements in the Salt Lake City area collated by the Utah Geological Survey (McDonald and Ashland, 2008).

To augment the small number of NEHRP A and B sites in the database, we add the hard rock category shear-wave velocity assignments of Atkinson and Assatourians (2010) at ~30 CEUS sites identified as having instruments founded in or near rock (C. Cramer, personal communication, 2011). We assume a Vs30 of 1500 m/s to account for shallow soils at those rock sites (Silva et al., 2011).

To obtain Vs30, we computed the time average to 30 m for profiles which extend to at least 30 m. For cases where measurements do not extend to 30 m, the deepest layer velocity is continued to 30 m. Profiles which extend to at least 20 m provide a reliable Vs30 estimate with a bias of about 2% underprediction (Yu and Silva, 2011). Profiles with depths less than 20 m were not used.

3. REGIONAL CORRELATIONS

3.1 CEUS

In developing the CEUS topographic slope and Vs30 correlation, we gave qualitative consideration to capturing the trends in Vs30 in regions that are well understood in terms of Vs30 measurements, surficial geology, and physiography. We did not use a regression analysis (e.g., piecewise linear least squares regression) because of the importance of the qualitative constraints on the model. The CEUS correlation is thoroughly documented in Silva et al. (2011).

Two well-understood regions with plentiful Vs30 measurements are the northern Mississippi Embayment and the Atlantic Coastal Plain regions. The northern Mississippi Embayment provides a demarcation in stiffness between the loess bluffs of the uplands and Holocene river deposits of the lowlands, separated roughly by the Mississippi River (Figure 2A). The Atlantic Coastal Plain region (including Georgia, the Carolinas, and Virginia) consists of a wedge of deep soft soils near the coast decreasing in thickness moving inland to the "fall line" where the hilly region of the Piedmont begins. The Piedmont typically consists of shallow (tens to hundreds feet thick) saprolite soils overlying hard crystalline basement rocks, with a very steep velocity gradient from the soil into the hard rock. Further inland are the Blue Ridge Mountain Province and the Appalachian Mountains (Figure 2B).

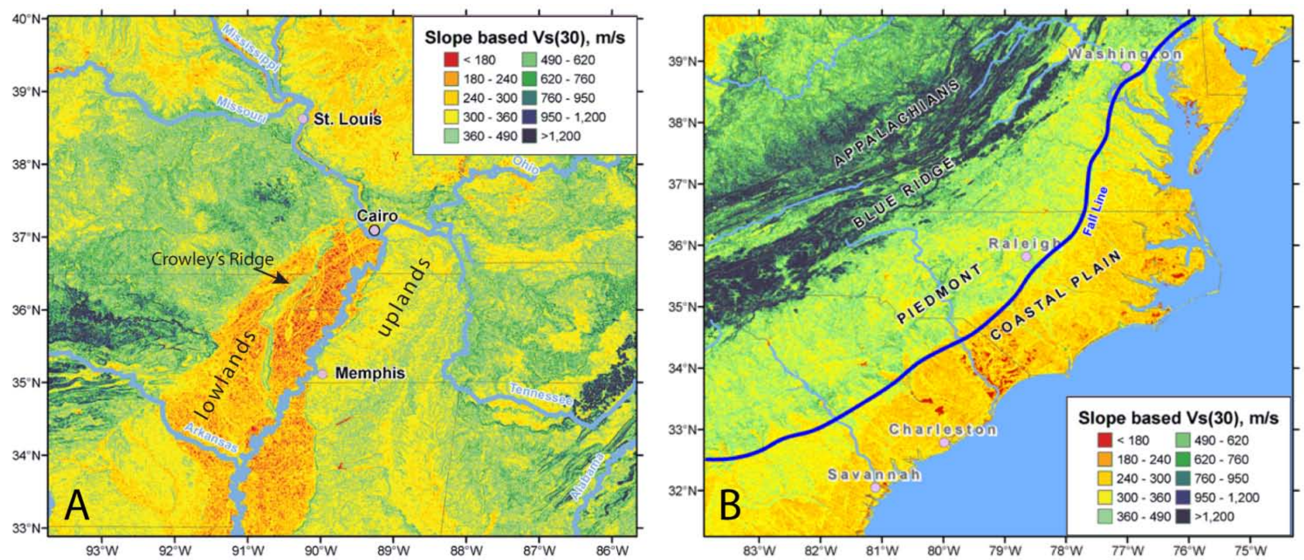

Figure 2. (A) Topographic slope based Vs30 map for the northern Mississippi Embayment region. (B) Topographic slope based Vs30 map for the Atlantic Coastal Plain area.

We tested multiple models with various correlation bins over the slope and Vs30 values. The final model was developed to be consistent with the NEHRP site classes and provide sufficient qualitative Vs30 resolution to (i) distinguish the lowlands, uplands, and Crowley's Ridge of the northern Mississippi Embayment (Figure 2A), and (ii) distinguish the Atlantic coastal sediments, the shallow saprolite soils of the Piedmont region, and the harder rocks of the Blue Ridge and Appalachian Mountains (Figure 2B). In developing the final model (Figure 3), we also considered the bias and standard deviations computed for each bin in topographic slope and Vs30. For the overall model the bias is -0.002 (about a 0.2% overestimate) and the natural logarithm standard deviation ($\ln\sigma$) is 0.331 (Table 1). The key difference between this model and the Wald and Allen (2007) correlation for tectonically stable areas is that we extended their model to NEHRP site classes A and B.

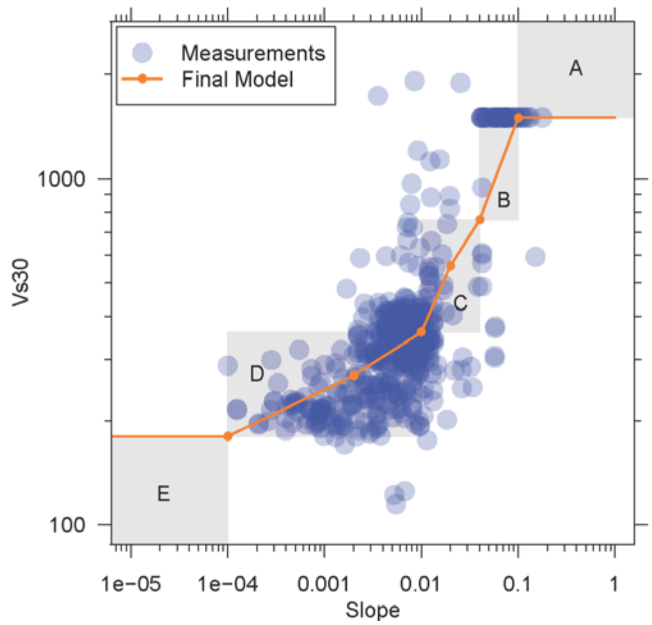

Figure 3. Vs30 estimates (orange line) as a function of topographic slope (m/m) developed for CEUS. The cluster of Vs30 values at 1,500 m/s shows assumed values at shallow soil over rock sites (Section 2).

3.2 WUS

To develop the WUS correlations, we used a stochastic simulation to step through slope and Vs30 bins and calculate the standard deviation and bias. After trial simulations, we separated data from the Utah basins along the Wasatch Front and the Imperial Valley, California, from the WUS data and performed simulations on each separate data set. We selected the best model (Figures 4 and 5) for each set based on three criteria: (i) bias and standard deviation are among the smallest; (ii) the correlations will not change dramatically for neighboring bins; and (iii) the Vs30 bin boundaries can be matched to NEHRP categories. The overall lnσ of the final correlation for non-lake regions is 0.397 and the bias is -0.002 (Table 2).

3.3 Lakes

Relative to WUS, the Utah and Imperial Valley Vs30 values are low for a given slope. Wald and Allen (2007) recognized the low values for Utah. We attribute the low values to the occupation of these areas by Pleistocene and younger lakes. The Utah basins were occupied by the Pleistocene Lake Bonneville (Gilbert, 1890) and the Imperial Valley was occupied by various stands of the Holocene Lake Cahuilla (Blake, 1858). When sediment-laden streams entered these lakes, the flow velocity was reduced so that all coarse sediments were deposited at the lake margin, and only very fine grained (and seismically slow) material was distributed over the lake bed. This model is confirmed by: (i) relatively high Vs30 values (Luke, 2007) in the geologically similar Las Vegas Valley that was not occupied by a lake (Page et al., 2005); (ii) ordinary Vs30 values in Utah and Imperial Valley locations above the high lake stands; and (iii) a consistent pattern of Vs30 values (Scott et al., 2004; Pancha et al., 2007) in the Reno, Nevada, basin across a paleo-lake boundary (Rehels, 1999). The overall lnσ of the final Lakes correlation is 0.238 and the bias is -0.011 (Table 3).

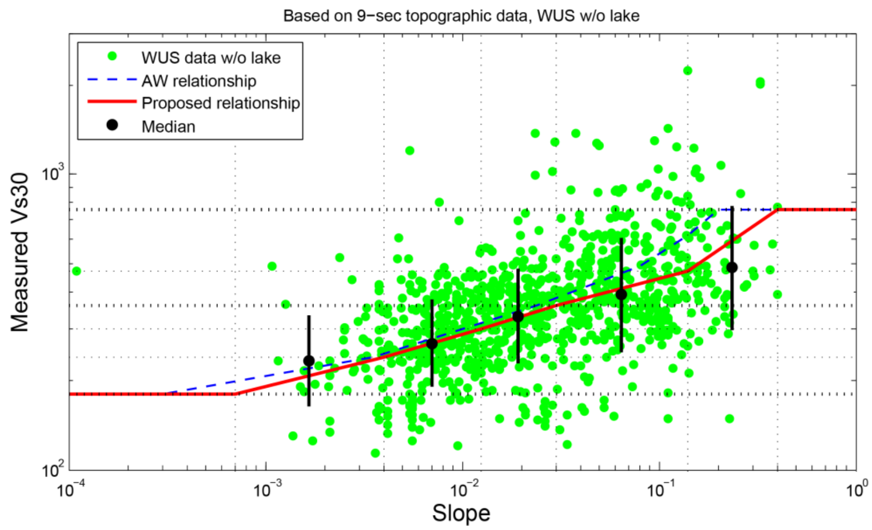

Figure 4. Vs30 estimates (red line) as a function of topographic slope (m/m) developed for WUS. Blue dashed line is relation of Allen and Wald (2009). Black symbols are medians and standard deviations (natural logarithm) for each slope bin.

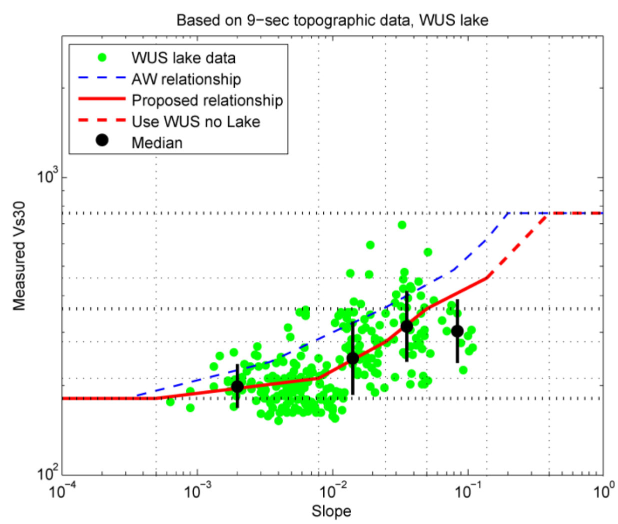

Figure 5. Vs30 estimates (red line) as a function of topographic slope (m/m) developed for lake-occupied areas. Blue dashed line is relation of Allen and Wald (2009). Black symbols are medians and standard deviations (natural logarithm) for each slope bin. For larger slopes, we use the WUS correlation (dashed red line).

3.4 Artificial Fill

We identify reclaimed land in the cities of San Diego, Seattle, San Francisco Bay area, Boston, New York, Baltimore, Los Angeles/Long Beach, Chicago, Portland (Maine), and some cities in New Jersey. The reclaimed land was digitized from maps and satellite images. We did not determine a correlation for the reclaimed land; instead, all reclaimed land is assumed to be site class E (soft soil) because conventional construction practice tends to produce a deposit which is not densely packed and poses additional hazards due to uneven settlement during shaking, and liquefaction if a high water table is present.

4. MAP CONSTRUCTION

The CEUS correlation is appropriate for tectonically stable regions, and the WUS correlation for tectonically active regions. To merge the two correlations, we address two issues: first, we must locate the boundary between the tectonically active WUS and the stable CEUS; and second, we wish to avoid introducing abrupt transitions in site response class where the two regional correlations abut.

The Rocky Mountains formed ~40 to ~80 million years ago due to tractions on the base of the continental lithosphere exerted by low-angle subduction of the Farallon plate during the Laramide orogeny (Humphreys, 2009). Since that time, the Rocky Mountains have been subject to only epeirogenic activity (McMillan et al., 2006). Earthquakes, a measure of tectonic activity, occur in the Rocky Mountains at a rate more similar to the CEUS than the WUS (USGS, 2009). Topography relief of the Rocky Mountains (~1.5 km; McMillan et al., 2006) is similar to the WUS. Thus, the Rocky Mountains represent a tectonic condition intermediate between the CEUS and WUS.

We outline the Rocky Mountain physiographic province (Figure 1). East of that province, we use the CEUS correlation, and west of the province we use the WUS correlation. Within the province we use a combination of the two correlations, weighted by the distances to the province boundaries. The Lakes correlation lies entirely within the WUS. We identified and digitized areas that hosted Pleistocene and younger lakes (Figure 1; Currey et al., 1984; Rehels, 1999; Tchakerian and Lancaster, 2002). In those areas we use the Lakes correlation.

We use the regional correlations to convert topographic slope into Vs30. Next, we assign the Vs30 values into NEHRP site classes A, B, C, D, and E (UBC, 1997). To achieve greater resolution in site conditions, we define intermediate NEHRP classes AB, BC, CD, and DE (Table 4). Amplifications for the intermediate classes can be obtained by interpolation of the amplification factors of the primary classes (UBC, 1997). We plot the resulting site class map on a ~1 km grid in Figure 6.

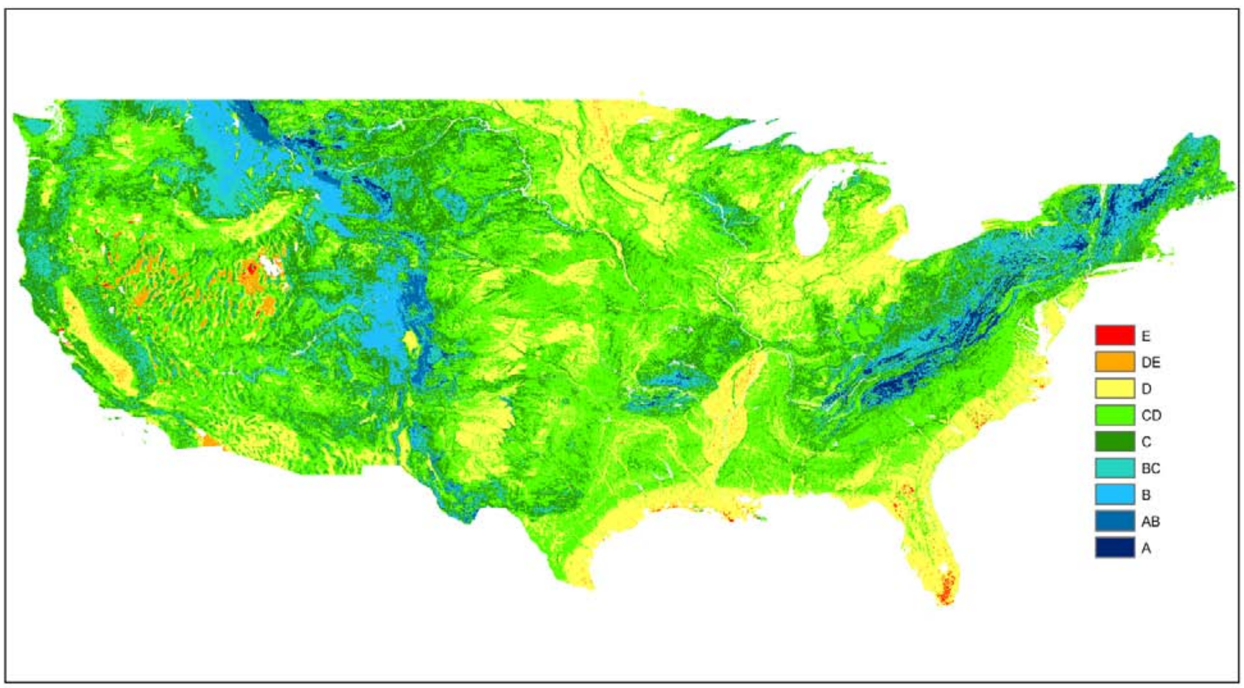

Figure 6. Site class map of the continental U.S. See Table 4 for site class definitions.

CONCLUSIONS

The topographic slope method to define site response is useful in large-scale applications because topographic data of extensive coverage are readily available. We develop new regional slope-Vs30 correlations for the CEUS and WUS. A weakness in the method is that certain geologic circumstances can confound the slope-Vs30 correlations. Here we show it is possible to identify and account for such circumstances. We determine that pluvial basins do not fit the WUS correlation, and account for them with a separate correlation.

Table 1. Topographic slope ranges and NEHRP Vs30 site classes for CEUS.

CEUS	Slope m/m		Vs30 m/s		Bias (ln)	Standard Deviation (ln)	Number in Bin
NEHRP	Min	Max	Min	Max			
E	----	10^{-4}	----	180	0.471	----	1
D	10^{-4}	2×10^{-3}	180	270	-0.067	0.171	82
	2×10^{-3}	10^{-2}	270	360	0.024	0.300	332
C	10^{-2}	2×10^{-2}	360	560	-0.063	0.360	63
	2×10^{-2}	4×10^{-2}	560	760	-0.535	0.656	9
B	4×10^{-2}	10^{-1}	760	1500	0.140	0.491	41
A	10^{-1}	----	1500	----	-0.564	0.327	8
Combined					-0.002	0.331	536
Combined using Wald and Allen (2007)					0.041	0.394	536

Table 2. Topographic slope ranges and NEHRP Vs30 site classes for WUS.

WUS	Slope m/m		Vs30 m/s		Bias (ln)	Standard Deviation (ln)	Number in Bin
NEHRP	Min	Max	Min	Max			
E	----	7×10^{-4}	----	180	0.785	0.796	3
D	7×10^{-4}	4×10^{-3}	180	240	0.065	0.357	53
	4×10^{-3}	1.25×10^{-2}	240	300	-0.008	0.328	253
	1.25×10^{-2}	3×10^{-2}	300	360	0.005	0.370	207
C	3×10^{-2}	1.4×10^{-1}	360	470	-0.013	0.439	324
	1.4×10^{-1}	5×10^{-1}	470	760	-0.0.18	0.488	71
B	5×10^{-1}	----	760	----	----	----	0
Combined					-0.002	0.397	911
Combined using Allen and Wald (2009)					-0.094	0.418	911

Table 3. Topographic slope ranges and NEHRP Vs30 site classes for Lakes.

Lakes	Slope m/m		Vs30 m/s		Bias (ln)	Standard Deviation (ln)	Number in Bin
NEHRP	Min	Max	Min	Max			
E	----	5×10^{-4}	----	180	----	----	0
D	5×10^{-4}	8×10^{-3}	180	210	-0.004	0.171	126
	8×10^{-3}	2.5×10^{-2}	210	280	0.031	0.255	83
	2.5×10^{-2}	5×10^{-2}	280	360	-0.025	0.292	40
C	5×10^{-2}	1.4×10^{-1}	360	460	-0.261	0.370	15
	1.4×10^{-1}	4×10^{-1}	460	760	----	----	0
B	4×10^{-1}	----	760	----	----	----	0
Combined					-0.011	0.235	264
Combined using Allen and Wald (2009)						0.343	264

Table 4. NEHRP site classes and Vs30 ranges used in Figure 6.

<table>
<tr><th rowspan="2">NEHRP</th><th colspan="2">Vs30 m/s</th><th rowspan="2">Figure 6</th><th colspan="2">Vs30 m/s</th></tr>
<tr><th>Min</th><th>Max</th><th>Min</th><th>Max</th></tr>
<tr><td>E</td><td>----</td><td>180</td><td>E</td><td>----</td><td>180</td></tr>
<tr><td rowspan="3">D</td><td rowspan="3">180</td><td rowspan="3">360</td><td>DE</td><td>180</td><td>225</td></tr>
<tr><td>D</td><td>225</td><td>315</td></tr>
<tr><td rowspan="2">CD</td><td rowspan="2">315</td><td rowspan="2">460</td></tr>
<tr><td rowspan="3">C</td><td rowspan="3">360</td><td rowspan="3">760</td></tr>
<tr><td>C</td><td>460</td><td>660</td></tr>
<tr><td rowspan="2">BC</td><td rowspan="2">660</td><td rowspan="2">945</td></tr>
<tr><td rowspan="3">B</td><td rowspan="3">760</td><td rowspan="3">1500</td></tr>
<tr><td>B</td><td>945</td><td>1315</td></tr>
<tr><td>AB</td><td>1315</td><td>1500</td></tr>
<tr><td>A</td><td>1500</td><td>----</td><td>A</td><td>1500</td><td>----</td></tr>
</table>

REFERENCES

Allen, T., and Wald, D. (2009). On the use of high-resolution topographic data as a proxy for seismic site-conditions (V_{S30}). *Bulletin Seismological Society of America* **99:2A**, 935-943.

Atkinson, G., and Assatourians, K. (2010). Attenuation and source characteristics of the June 23, 2010 M 5.0 Val Des Bois, Quebec earthquake. *Seismological Research Letters* **81**, 849-860.

Atkinson, G., and Boore, D. (2006). Earthquake ground-motion prediction equations for eastern North America. *Bulletin Seismological Society America* **96**, 2181–2205. Supplement**.**

Becker, J., Sandwell, D., Smith, W., Braud, J., Binder, B., Depner, J., Fabre, D., Factor, J., Ingalls, S., Kim, S-H., Ladner, R., Marks, K., Nelson, S., Pharaoh, A., Trimmer, R., Von Rosenberg, J., Wallace, G. and Weatherall, P. (2009). Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30_PLUS. *Marine Geodesy* **32:4**, 355-371. (These data are a blend of TOPO11.1, SRTM, and IBCAO).

Blake, W. (1858). Report of a geological reconnaissance in California: made in connection with the expedition to survey routes in California, to connect with the surveys of routes for a railroad from the Mississippi river to the Pacific Ocean, under the command of Lieut. R.S. Williamson, Corps Top. Eng'rs. H. Bailliere, New York, 370 pp.

Boore, D., Joyner, W., and Fumal, T. (1997). Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: a summary of recent work. *Seismological Research Letters* **68**, 128–153.

Borcherdt, R. (1994a). Simplified site classes and empirical amplification factors for site-dependent code provisions. *Proc. of the NCEER/SEAOC/BSSC Workshop on Site Response During Earthquakes and Seismic Code Provisions*, University of Southern Calif., Los Angeles, 1992, edited by G.R. Martin.

Borcherdt, R. (1994b). Estimates of site-dependent response spectra for design (methodology and justification). *Earthquake Spectra*, 10:4, 617-653.

Building Seismic Safety Council (BSSC) (2000). National Earthquake Hazards Reduction Program (NEHRP) Part 1: Recommended provisions for seismic regulations for new buildings and other structures. 2000 Edition (FEMA 368). Prepared by the Building Seismic Safety Council for the Federal Emergency Management Agency, Washington D.C.

Building Seismic Safety Council (BSSC) (2004). NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures. 2003 Edition (FEMA 450), National Institute of Building Sciences, Washington, D.C.

Chiou, B., Darragh, R., Gregor, N., and Silva, W. (2008). NGA project strong-motion database. *Earthquake Spectra* **24**, 23-44.

Currey, D., Atwood, G., and Mabey, D. (1984) Major levels of Great Salt Lake and Lake Bonneville. *Utah Geological and Mineral Survey Map 73*, Salt Lake City, Utah, 1 plate.

Dobry, R., Ramos, R., and Power, M. (1999). Site factors and site categories in seismic codes. MCEER-99-0010.

Gilbert, G. (1890). Lake Bonneville. *Monographs* **1**. U.S. Geological Survey, Washington D.C., 438 pp.

Humphreys, E. (2009). Relation of flat subduction to magmatism and deformation in the western United States, *in* Kay, S., Ramos, V., and Dickinson, W., eds., Backbone of the Americas: shallow subduction, plateau uplift, and ridge and terrane collision. *Geological Society of America Memoir* **204**, 85-98.

Jarvis, A., Reuter, H., Nelson, A., and Guevara, E. (2008). Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database http://www.cgiar-csi.org/component/content/article/73-srtm-90m-digital-elevation-database-v41?start=2.

Luke, B. (2007). Shallow velocity database for Las Vegas basin. http://agc.unlv.edu/lv_archives/index.html.

McDonald, G., and Ashland, F. (2008). Earthquake site conditions in the Wasatch Front urban corridor, Utah. CD electronic resource, Utah Geological Survey.

McMillan, M., Heller, P., and Wing, S. (2006). History and causes of post-Laramide relief in the Rocky Mountain orogenic plateau. *GSA Bulletin* **118:3/4**, 393-405.

NEHRP (1994) Recommended Seismic Provisions for Seismic Regulations for New Buildings and Other Structures. Federal Emergency Management Agency, Report No. FEMA 222A, Washington, D.C.

NEHRP (1997) NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures. Federal Emergency Management Agency, Report No. FEMA 302, Washington, D.C.

Page, W., Lundstrom, S., Harris, A., Langenheim, V., Workman, J., Mahan, S., Paces, J., Dixon, G., Rowley, P., Burchfiel, B., Bell, J., and Smith, E. (2005). Geologic and geophysical maps of the Las Vegas 30' x 60' quadrangle, Clark and Nye counties, Nevada, and Inyo county, California. *U.S. Geological Survey Scientific Investigations Map 2814*, http://pubs.usgs.gov/sim/2005/2814/.

Pancha, A., Anderson, J., and Louie, J. (2007). Characterization of near-surface geology at strong-motion stations in the vicinity of Reno, Nevada. *Bulletin Seismological Society America* **97:6**, 2096-2177.

Power, M., Chiou, B., Abrahamson, N., Bozorgnia, Y., Shantz, T., and Roblee, C. (2008). An overview of the NGA project. *Earthquake Spectra* **24:1**, 3-21.

Rehels, M. (1999). Extent of Pleistocene lakes in the western Great Basin. *Miscellaneous Field Studies Map MF-2323*, U.S. Geological Survey, Washington D.C., 1 plate.

Reid, H.F. (1910). The California earthquake of April 18, 1907. *The Mechanics of the Earthquake*, Carnegie Inst. of Washington, Publ. 87, 21.

Rinne, E.E. (1994). Development of new site coefficients for building codes. *Proc. Fifth U.S. Nat. Conf. On Earthquake Engineering*, Chicago **3**, 69-78.

Scott, J., Clark, M., Rennie, T., Pancha, A., Park, H., and Louie, J. (2004). A shallow shear-wave velocity transect across the Reno, Nevada area basin. *Bulletin Seismological Society America* **94:6**, 2222-2228.

Silva, W., Thompson, E., and Wills, C. (2011). Development of a Vs(30m) map for central and eastern North America (CENA): median estimates and uncertainties. To be published, 60 pp.

Tchakerian, V., and Lancaster, N. (2002). Late Quaternary arid/humid cycles in the Mojave Desert and western Great Basin of North America. *Quaternary Science Reviews* **21**, 799-810.

Uniform Building Code (1997) Uniform Building Code. Published by the International Conference of Building Officials, Whittier, California.

USGS (2009). Earthquake density maps for the United States. http://earthquake.usgs.gov/earthquakes/states/us_density.php.

Wald, D., and Allen T. (2007). Topographic slope as a proxy for seismic site conditions and amplification. *Bulletin Seismological Society America* **97:5**, 1379-1395.

Wills, C., and Clahan, K. (2004). NGA: Site condition metadata from geology. PEER project 1L05.

Wills, C., and Clahan, K. (2006). Developing a map of geologically defined site-condition categories for California. *Bulletin Seismological Society America* **96:4A**, 1483-1501.

Wills, C., and Silva, W. (1998). Shear wave velocity characteristics of geologic units in California. *Earthquake Spectra* **14:3**, 533-556.

Wood, H. (1908). Distribution of apparent intensity in San Francisco, in the California earthquake of April 18, 1906. *Report of the State Earthquake Investigation Commission*, Washington D.C.: Carnegie Institute **1**, 220-245.

Yong, A., Hough, S., Abrams, M. Cox, M., Wills, C., and Simila, G. (2008). Site characterization using integrated imaging analysis methods on satellite data of the Islamabad, Pakistan, Region. *Bulletin Seismological Society America* **98:6**, 2679-2693.

Yong, A., Hough, S., Braverman, A., and Iwahashi, J. (2010). A terrain-based Vs30 estimation map of the contiguous United States. *Seismological Research Letters* **81:2**, 294.

Yong, A., Hough, S., Iwahashi, J., and Braverman, A. (2012). A terrain-based site characterization map of California with implications for the contiguous United States. *Bulletin Seismological Society America* **102:1**, 114-128.

Yu, T., and Silva, W. (2011). Development of Vs(30m) estimates for sites which recorded the May 12, 2008 **M** 7.9 Wenchuan earthquake, 2011. Report to PEER, in preparation.