Title

Site effects in parametric ground motion models for the GEM-PEER Global GMPEs Project

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Site Effects in Parametric Ground Motion Models for the GEM-PEER Global GMPEs Project

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SUMMARY:
We review site parameters used in ground motion prediction equations (GMPEs) for various tectonic regimes and describe procedures for estimation of site parameters in the absence of site-specific data. Most modern GMPEs take as the principal site parameter the average shear wave velocity in the upper 30 m of the site (V_{s30}) either directly or as the basis for site classification into categories. Three GMPEs developed for active regions also use basin depth parameters. We review estimation procedures for V_{s30} that utilize surface geology, terrain-based site categories, ground slope, or combinations of these. We analyze the relative efficacy of those procedures using a profile data set from California assembled in a recent NGA project. The results indicate that no single procedure is most effective and that prediction dispersion is lower for young sediments than for stiff soils or rock.

Keywords: Ground motion studies, shear wave velocity, site amplification

1. INTRODUCTION

The Global Earthquake Model (GEM) project is providing tools for hazard analysis and risk assessment on a world-wide basis (http://www.globalquakemodel.org/). A key component of GEM is the selection of appropriate models for ground motion estimation, which is undertaken in the "Global Ground Motion Prediction Equations" (GMPEs) project. This paper describes work within the GEM-GMPE project in which we seek to identify protocols for evaluating the site parameters used in GMPEs from data that are available on a global scale.

We begin by reviewing the site parameters employed in the world-wide GMPEs selected for consideration within the GEM-GMPE project. This work establishes that the time-averaged shear wave velocity in the upper 30 m (V_{s30}) is a required input parameter for global application. Basin depth is also a parameter used in some relations, but is not discussed here for brevity. We briefly review procedures for estimation of V_{s30} from information such as geologic categories, geotechnical site classifications, and topographic metrics. We describe a process by which the relative efficacy of various V_{s30}-estimation procedures can be analyzed using measured velocity profiles for a target study region, which is illustrated for California using a profile data set assembled in a recent Next Generation Attenuation (NGA) project.

2. SITE CLASSIFICATION METHODS IN GMPES

As shown in Table 1, Douglas et al. (2012) present a list of GMPEs for consideration in the GEM-GMPE project organized by tectonic regime, with most being in stable continental regions, subduction zones, or active tectonic regions. Table 1 lists those GMPEs, describes the site parameters included in the models, and provides some details on the site amplification model. The final set of selected GMPEs were not yet available at the time this paper was written.

Table 1 distinguishes between site classification methods based on discrete categories or continuous variables. Discrete categories are most often described by the NEHRP criteria given in Table 2, which relate to V_{s30}. Site parameters defined as continuous variables include V_{s30} and parameters describing the depth to a shear wave isosurface (Z_x) having a velocity $V_s = x$ km/s. Values of x that have been used include 1.0 km/s and 2.5 km/s. Section 3 of this paper describes procedures that can be used to estimate V_{s30}; procedures for estimation of basin depth are reviewed in Stewart et al. (2012). While site period is used in some GMPEs for site classification, it is not directly used as a continuous variable.

As shown in Table 1, most GMPEs utilize linear site terms, meaning that the site amplification is constant with respect to the amplitude of ground shaking. The reference site condition listed in Table 2.1 is the condition for which the site amplification is unity. This condition generally corresponds to rock site conditions.

3. ESTIMATION OF V_{S30}

3.1. Estimation Based on Surface Geology and Geotechnical Categories

Correlations have been developed to link surface geologic units and geotechnical categories to V_{s30}. Some of these correlations are well documented and based on large inventories of V_s profiles; these tend to be based on surface geology. The correlations for geotechnical categories tend to be relatively poorly documented and often use proprietary data sets.

Correlations utilizing surface geology are available for California and Italy. For such correlations to be effective, variations of velocities within the broad geological categories typically shown in geological maps (e.g., Quaternary alluvium, Qa) need to be captured. This can be accomplished by either using relatively detailed categories, (e.g., separating thin and deep Qa), region-specific categories (e.g., for alluvium in the Imperial Valley and Los Angeles basin), or geologic information coupled with geomorphological data (e.g., slope or other terrain descriptors).

For California, correlations based on 19 relatively detailed geological categories (including region-specific categories) are provided by Wills and Clahan (2006), which were used in the NGA project database (Chiou et al., 2008). Medians and standard deviations of V_{s30} are provided for each category. Current recommendations are to use the Wills and Clahan values for rock sites (i.e., geologic age that is Tertiary or older), and to use relations based on ground slope for Quaternary sediments (Wills and Gutierrez, 2008), as shown in Figure 1. The alluvial ground slope correlation shows an increase of velocity with slope, which follows expected trends because flatter slopes tend to be in mid-basin areas having relatively fine-grained alluvium with slow velocities. Figure 1 also shows that the standard deviation of velocities decreases as V_{s30} decreases.

The applicability of the Wills and Clahan correlations to Italy was investigated by Scasserra et al. (2009), who found that the median velocities for Quaternary categories are unbiased relative to Italian data. For rock sites, the California categories were not descriptive of Italian geology, and distinct correlations therefore were developed for appropriate geologic rock categories.

Table 1. Site parameters and site amplification information for GMPEs selected in Task 2 of GEM-GMPE project (Douglas et al., 2012). GMPE references given in Douglas et al. (2012).

	Reference	Application Region	Site Parameters		Site Amplification Function	
			Discrete categories[1]	Continuous Variables[2]	Non-linearity	Reference site condition[2]
Stable continental regions	Atkinson (2008), Atkinson & Boore (2011)	CEUS	NEHRP B/C only	-	na	NEHRP B/C
	Atkinson & Boore (2006, 2011)	CEUS	Hard rock; NEHRP B/C	V_{s30}	Yes	Hard rock (V_s>2000 m/s); B/C (V_{s30}=760 m/s)
	Campbell (2003)	CEUS	Hard rock only	-	na	Hard rock (V_s=2800 m/s)
	Douglas et al. (2006)	So. Norway	Hard rock only	-	na	Hard rock (V_s=2800 m/s)
	Frankel et al. (1996)	CEUS	Hard rock; NEHRP B/C	-	na	Hard rock (V_s=2800 m/s)
	Raghu Kanth & Iyengar (2006, 2007)	Peninsular India	Hard rock; NEHRP A-D	-	Yes	Hard rock (V_s=3600 m/s)
	Silva et al. (2002)	CEUS	Hard rock only	-	na	Mid-cont., V_s=2830 m/s; Gulf cst V_s=2310 m/s)
	Somerville et al. (2009)	Australia	Rock only	-	na	Rock (V_s=865 m/s)
	Pezeshk et al. (2011)	CEUS	Hard rock only	-	na	Hard rock (V_s>2000 m/s)
	Toro et al. (1997); Toro (2007)	CEUS	Hard rock only	-	na	Hard rock (V_s=2800 m/s)
Subduction zones	Abrahamson et al. (2012)	Global	-	V_{s30}	Yes	V_{s30}=1000 m/s
	Atkinson & Boore (2003)	Global	NEHRP B-E	-	Yes	NEHRP B
	Garcia et al. (2005); Arroyo et al. (2010)	Mexico	NEHRP B only	-	na	NEHRP B
	Zhao et al. (2006); Zhao (2010)	Japan	*Four*: hard rock to soft soil	-	No	Not defined
	Kanno et al. (2006)	Japan	-	V_{s30}	No	V_{s30}≈300 m/s
	Lin & Lee (2008)	Taiwan	*Two*: rock & soil	-	Yes	Not defined
	Mc Verry et al. (2006)	New Zealand	*Five*: strong rock to v soft soil	-	Yes	Strong rock and rock
	Youngs et al. (1997)	Global	*Three*: GMX A, B, D	-	No	Not defined
Active tectonic regions	Abrahamson & Silva (2008)	Global	-	V_{s30}, $Z_{1.0}$	Yes	V_{s30} = 1100 m/s
	Akkar & Bommer (2010)	Europe & Middle East	*Two*: rock, stiff & soft soil	-	No	Rock
	Boore & Atkinson (2008, 2011)	Global	-	V_{s30}	Yes	V_{s30}=760 m/s
	Campbell & Bozorgnia (2008)	Global	-	V_{s30}, $Z_{2.5}$	Yes	V_{s30} = 1100 m/s
	Cauzzi & Faccioli (2008); Faccioli et al. (2010)	Global	CEN A-D	V_{s30}	No	CEN A
	Chiou & Youngs (2008)	Global	-	V_{s30}, $Z_{1.0}$	Yes	V_{s30}=1130 m/s
	Kanno et al. (2006)	Japan	-	V_{s30}	No	V_{s30}≈300 m/s
	McVerry et al. (2006)	New Zealand	*Five*: strong rock to v soft soil	-	Yes	Strong rock and rock
	Zhao et al. (2006)	Japan	*Four*: hard rock to soft soil	-	No	Not defined
Volcanic regions	McVerry et al. 2006	New Zealand	Five: strong rock to v soft soil	-	Yes	Strong rock and rock
	Zhao (2010)	Japan	*Four*: hard rock to soft soil	-	No	Not defined
Vran-cea	Sokolov et al. 2008	Romania	Hard rock only	-	No	Hard rock (V_s = 3800 m/s)

[1] NEHRP categories in Table 2; GMX categories (used by Youngs et al., 1997) in Table 3; CEN categories similar to NEHRP, but one letter lower (e.g., CEN D = NEHRP E)

[2] Reference site condition defined as having no site modification in the GMPE. 'Not defined' indicates separate regression coefficients evaluated for different site conditions (no specific site term)

Table 2. NEHRP site categories (Dobry et al., 2000)

Class	V_{s30} Range (m/s)	Profile type
A	>1500	Hard rock
B	760-1500	Rock
C	360-760	Very dense soil/soft rock
D	180-360	Stiff soil
E	< 180	Soft soil
F	Special soils requiring site-specific evaluation	

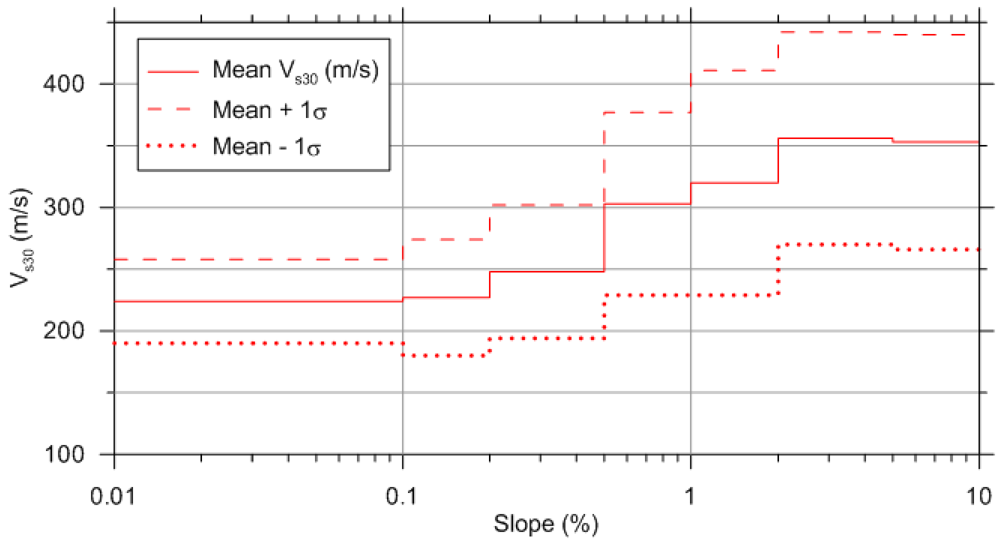


Figure 1. Variation of V_{s30} with ground slope within basins. Adapted from Wills and Gutierrez (2008).

The principal geotechnical site categorization scheme that has been used in previous ground motion studies and correlated to V_{s30} is attributed to the former consulting firm Geomatrix (GMX). The GMX scheme has three letters, the last of which represents site condition. The GMX third letters and the corresponding site conditions are shown in Table 3. The values of V_{s30} in Table 3 are based on a proprietary data set and were used in the original NGA project as the basis for V_{s30} estimation when surface geological information was not available but Geomatrix 3rd letter classifications were available.

Table 3. Geomatrix 3rd letter site categories and recommended V_{s30} values (Chiou et al., 2008)

Geomatrix Third Letter	***Description***	***Median V_{s30} (m/s)***	***σ_{ln}***	***Mean V_{s30} (m/s)***	***σ***
A	Rock. Instrument on rock (V_s > 600 mps) or <5m of soil over rock.	659.6	0.416	720.2	324.2
B	Shallow (stiff) soil. Instrument on/in soil profile up to 20m thick overlying rock.	424.8	0.431	464.3	211.0
C	Deep narrow soil. Instrument on/in soil profile at least 20m thick overlying rock, in a narrow canyon or valley no more than several km wide.	338.6	0.203	345.4	70.4
D	Deep broad soil. Instrument on/in soil profile at least 20m thick overlying rock, in a broad valley.	274.5	0.335	291.4	110.5
E	Soft deep soil. Instrument on/in deep soil profile with average V_s < 150 mps.	191.3	0.29	199.4	61.4

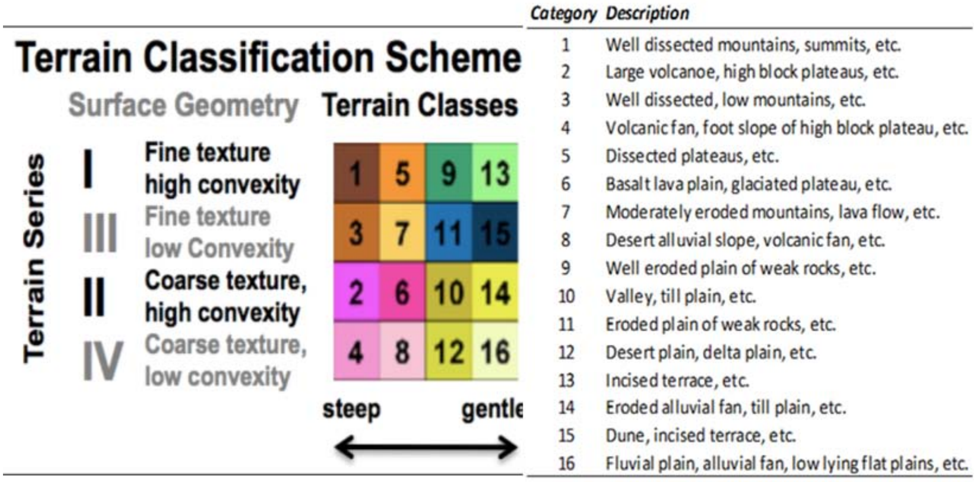
3.2. Estimation Based on Topography or Geomorphology

Correlations have been developed to link surface topographic features to V_{s30}. The most well known of these correlations relate topographic slope to V_{s30} (Wald and Allen, 2007; Allen and Wald, 2009) for application in active tectonic regions with shallow crustal earthquakes and stable continental regions. Techniques in which V_{s30} is estimated based on geomorphology-based categories have been presented by Yong et al. (2012) for California and Matsuoka et al. (2006) for Japan. Another technique that has been used locally for Taiwan stations correlates V_{s30} to elevation within Geomatrix categories (Chiou and Youngs, 2008b). We briefly review here the slope and geomorphology-based techniques.

The motivation behind development of the V_{s30} – slope correlation is that topographic data are globally available and slope can be anticipated to be an indicator of near-surface morphology and lithology (http://earthquake.usgs.gov/hazards/apps/vs30/custom.php). Steep terrain is expected in mountains, indicating rock, whereas nearly flat slopes occur in basins, indicating soil. Transition zones would be expected to have moderate slopes involving weathered rock and potentially older sediments near basin boundaries. Wald and Allen (2007) developed a correlation between ground slope and measured V_{s30}. Separate slope-V_{s30} correlations were developed for active and stable continental regions that indicate increasing V_{s30} with increasing topographic slope. Data exists for gradients < 7%, corresponding to a 4 degree slope. Equations relating V_{s30} to slope were not provided; rather, stepped relationships of slope tied to discrete velocity bands were provided. Elevation was found to not provide additional predictive power for V_{s30} beyond ground slope.

The Yong et al. (2012) procedure for V_{s30} considers slope along with geomorphological factors including convexity and texture. This technique utilizes the same globally available SRTM 30 arc sec surface models employed by Wald and Allen (2007). Hence, for a given location (latitude, longitude), the slope parameters used in the two models should be identical. The convexity element of the classification scheme is intended to distinguish convex-upward topography (characteristic of lowland terraces and alluvial fans) from concave-downward topography (broad valleys and foothills). The texture elements distinguish relatively smooth terrain from terrain having pits and peaks. These textural descriptions should not be confused with soil texture (e.g., fine, course) used in some sediment classification schemes (e.g., Fumal and Tinsley, 1985).

Ground slope, convexity, and texture are jointly analyzed using an automated topography classification scheme by Iwahashi and Pike (2007) to segregate terrain types into 16 categories, which are depicted in Figure 2. As one moves to the right in the matrix ground slope is decreasing, whereas moving down in the matrix produces less convexity and smoother texture. We note that the classification scheme has relatively fine discretization of rock conditions (rock categories include 1-7, 9, 11, and 13) but limited discretization of soil (e.g., there is no category that would seem to encompass lacustrine or marine clays, which produce the largest site amplification).



Category	Description
1	Well dissected mountains, summits, etc.
2	Large volcanoe, high block plateaus, etc.
3	Well dissected, low mountains, etc.
4	Volcanic fan, foot slope of high block plateau, etc.
5	Dissected plateaus, etc.
6	Basalt lava plain, glaciated plateau, etc.
7	Moderately eroded mountains, lava flow, etc.
8	Desert alluvial slope, volcanic fan, etc.
9	Well eroded plain of weak rocks, etc.
10	Valley, till plain, etc.
11	Eroded plain of weak rocks, etc.
12	Desert plain, delta plain, etc.
13	Incised terrace, etc.
14	Eroded alluvial fan, till plain, etc.
15	Dune, incised terrace, etc.
16	Fluvial plain, alluvial fan, low lying flat plains, etc.

Figure 2. Variation of slope, texture, and convexity with terrain categories of Yong et al. (2012).

Matsuoka et al. (2006) provide V_{s30} values for categories within the "Japan Engineering Geomorphologic Classification Map (JEGM)." The JEGM actually utilizes geomorphology, surface geology, slope angle, and relative relief to classify locations into geomorphologic units. The empirical correlations are based on shear wave velocity profiles from 1937 sites. The categories and their median values of V_{s30} are indicated in Figure 3 (indicated as 'AVS30' in the figure). Categories 1-4 correspond approximately to rock conditions, 5-7 are transitional categories, and categories of 8 and above represent variable soil conditions. Matsuoka et al. (2006) provide intra-category regressions against elevation for categories 8-13, against slope for categories 3, 5, and 8-11, and against distance from hill for categories 8, 10, 13, 15, and 18-19.

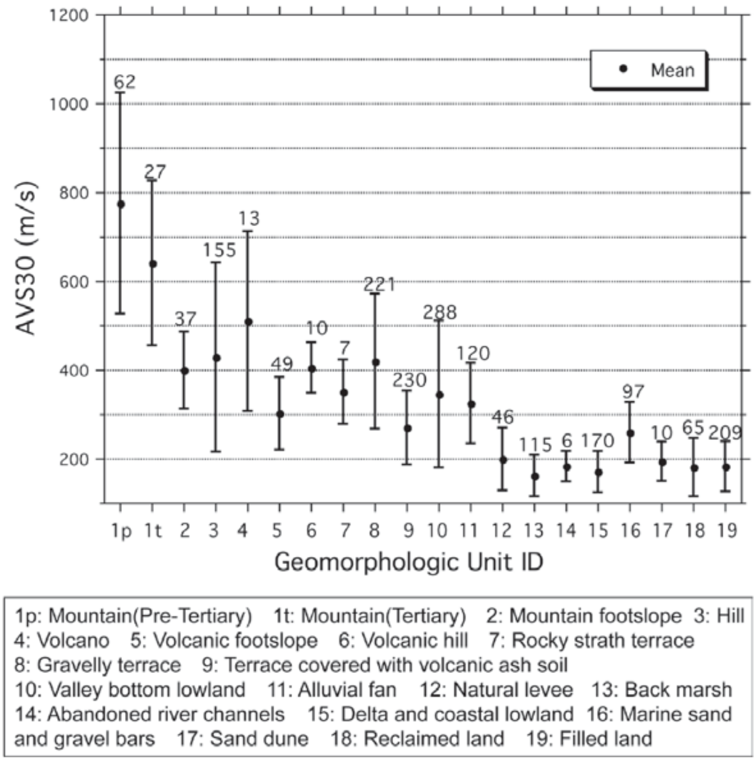


Figure 3. Mean values of V_{s30} (indicated as 'AVS30') for geomorphologic categories in JEGM. From Matsuoka et al. (2006).

3.3. Proxy Evaluation Using California Data Set

While it is clear that V_{s30} is most reliably obtained with high-quality geophysical measurements at the site of interest, no consensus exists regarding how it should be estimated in the absence of such measurements. In many cases, practical considerations may dictate the choice of method to be applied in a given area; for example, in the absence of geological maps, topography or terrain-based methods are the only viable option. However, when the available information does provide options (e.g., when both high quality geological and topographic information are available), which method should be selected? Ideally this decision would be made on the basis of local or regional studies of the efficacy of these techniques to the region. We investigate the relative reliability of the techniques described above through comparative analysis against a California data set.

We utilize the site database compiled as part of the NGA-West2 project (http://peer.berkeley.edu/ngawest2/) (i.e., a database of sites that have produced usable recordings), from which we have identified 222 sites with V_{s30} values based on measurements within CA. We use data from sites with geophysical measurements to depths $z > 20$ m. For sites with $z = 20 – 29$ m, we compute time-averaged velocity to the profile depth (V_{sz}) and then use the Boore (2004) V_{sz} to V_{s30} extrapolation technique.

We calculate V_{s30} residuals as follows:

$$R = \ln(V_{s30})_{meas} - \ln(V_{s30})_{proxy} \tag{1}$$

where $(V_{s30})_{meas}$ is a measured value and $(V_{s30})_{proxy}$ is estimated based on a correlation relationship. Note that by taking the natural log of the data, we assume the velocities to be log-normally distributed. Model bias can be estimated from the median of the residuals (μ_{lnV}). The standard deviation of residuals (σ_{lnV}) can be calculated for the entire set of residuals or sub-sets having certain conditions (e.g., sites within a particular category). Standard deviation term σ_{lnV} represents epistemic uncertainty on velocity, which should be considered in ground motion estimation. Boore et al. (2011) describe procedures by which this uncertainty can be considered in ground motion evaluation from GMPEs.

Figure 4 presents histograms of residuals from the geology proxy of Wills and Clahan (2006) and Wills and Gutierrez (2008) (in which geology is used in combination with ground slope for alluvium). We note that the bias is small (less than 0.1 in natural log units) and the standard deviation increases from approximately 0.25 for alluvium to about 0.5 for older bedrock units. When all data are combined together, the median is -0.03 and the standard deviation is 0.35.

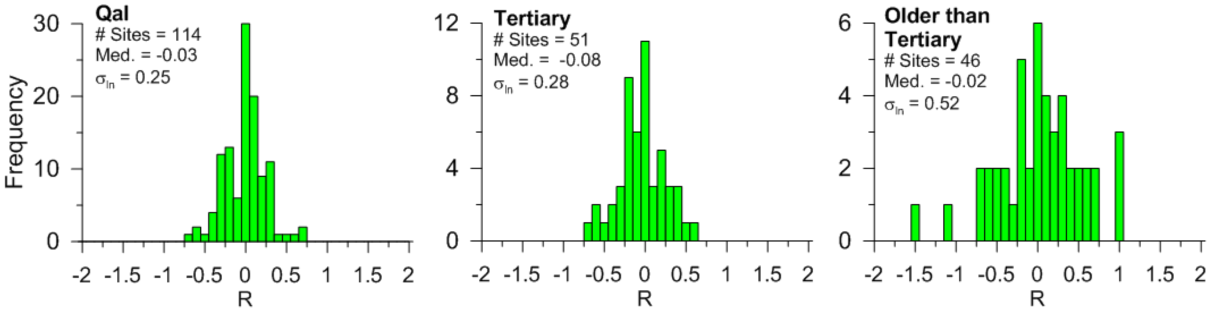


Figure 4. Residuals of V_{s30} from estimates based on the geology proxy using the methods of Wills and Gutierrez (2008) for alluvium and Wills and Clahan (2006) for all other conditions.

Figure 5 presents histograms based on the Geomatrix third letter (Chiou et al., 2008). The bias is negligible except for category E. Standard deviations range from 0.23 for soft soils to about 0.5 for rock. When all data are combined together, the median is -0.04 and the standard deviation is 0.34.

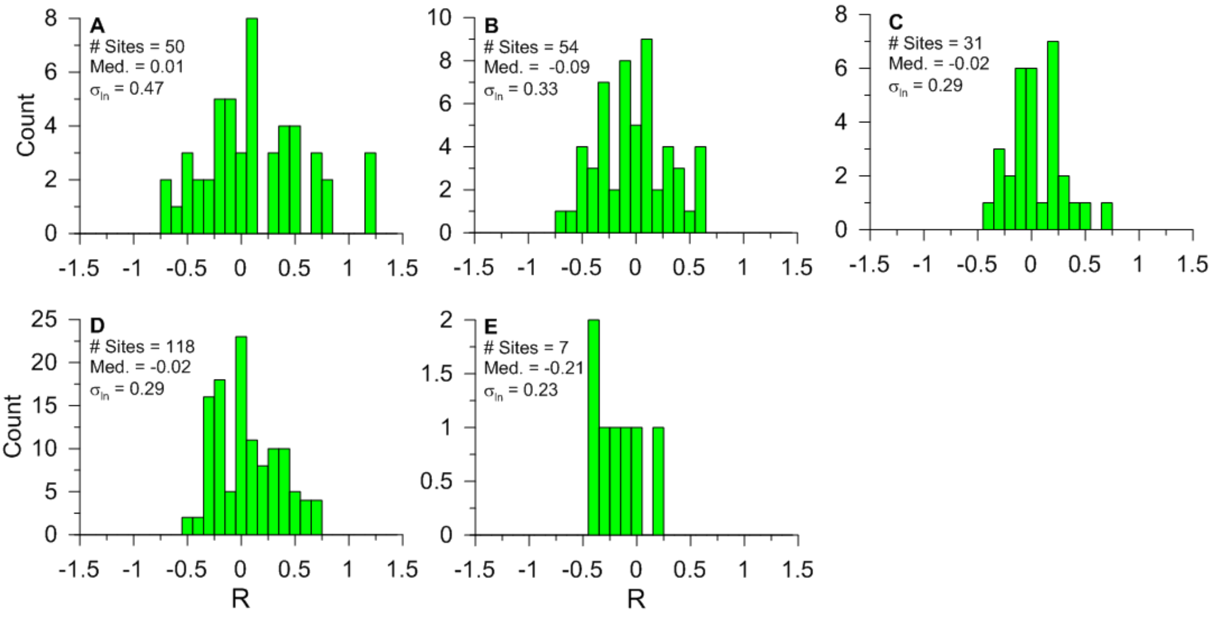


Figure 5. Residuals of V_{s30} from estimates based on the geotechnical proxy (Geomatrix third letter) using the methods of Chiou et al. (2008). Based on V_{s30} measurements and V_{sz}-V_{s30} relations.

Figure 6 presents V_{s30} data plotted versus slope along with the recommended ranges from Wald and Allen (2007). The proxy estimates reasonably well the data median for slopes under about 5% (0.05 m/m) and over-predicts approximately from 5-15% (0.05-0.15 m/m). There is practically no data for steeper slopes. The overall median of residuals is -0.09 and the standard deviation is 0.45.

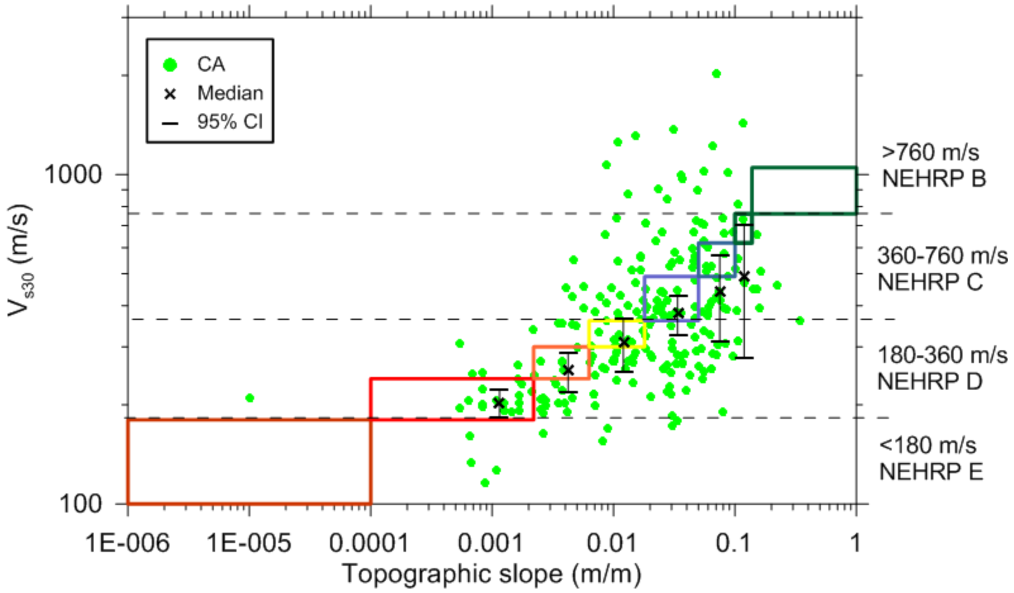


Figure 6. V_{s30} versus slope from California data and estimates from Wald and Allen (2007) for active tectonic regions. Color coded polygons correspond to slope ranges within NEHRP classes.

Residuals for the terrain-based method were evaluated, although the data is not adequate to constrain statistically significant medians or standard deviations for most categories. Categories with results considered to be reliable are indicated in Table 4. There is relatively little bias except for category 16, and standard deviations range from about 0.2 for softer geology to 0.5-0.6 for harder rock categories. Looking across all categories, the median of residuals is -0.14 and standard deviation is 0.43.

Table 4. Terrain-based categories by Yong et al. (2012) and corresponding V_{s30} statistics

Category	***Description***	***# V_{s30} meas.***	***$\mu_{\ln V}$***	***$\sigma_{\ln V}$***
1	Well dissected mountains, summits, etc.	19	-0.12	0.41
3	Well dissected, low mountains, etc.	25	-0.06	0.59
4	Volcanic fan, foot slope of high block plateau, etc.	24	0.1	0.45
7	Moderately eroded mountains, lava flow, etc.	25	-0.1	0.52
8	Desert alluvial slope, volcanic fan, etc.	41	-0.06	0.32
12	Desert plain, delta plain, etc.	16	-0.09	0.21
16	Fluvial plain, alluvial fan, low lying flat plains, etc.	36	-0.18	0.18

The relative efficacy of the different proxy-based estimation techniques can be judged on the basis of bias and standard deviation of residuals, as shown in Figure 7. Bias is generally small for the proxies investigated with the aforementioned exceptions. The standard deviation results were separated by categories when practical as indicated in Figure 7. For comparison, Figure 7 also shows standard deviations for measurements of V_{s30} at single sites with multiple V_s measurements. Measurement-based COVs would be expected to be higher than those given by Moss when the site geology is highly heterogeneous and V_s measurements are widely spaced relative to the scale of the site variability. For example, the NGA site spreadsheet from the original NGA project (Darragh, personal communication, 2011) allows a borehole to be associated with a ground motion station for separation distances up to 300 m, and assigns dispersion to the value of V_{s30} ranging from 0.05 for soft soil to 0.3 for firm rock.

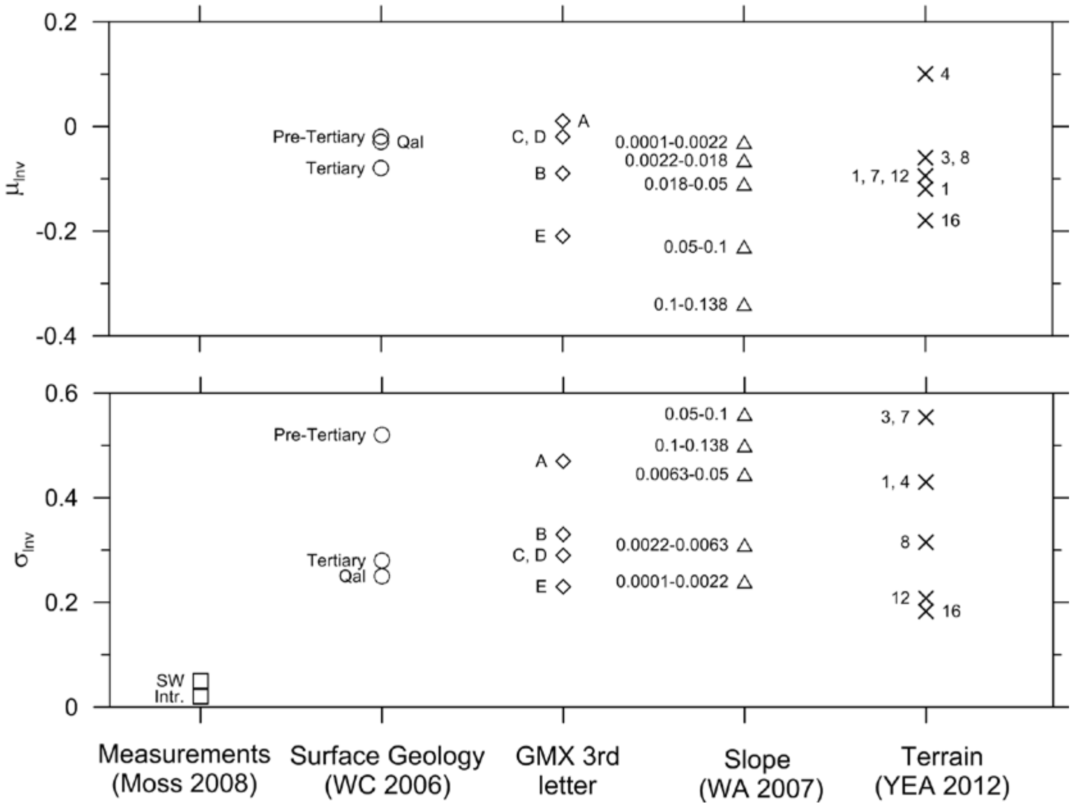


Figure 7. Median and dispersion of V_{s30} prediction residuals for California in natural log units based on the analyses in this study. Results from Moss (2008) are COVs taken as approximately equal to σ_{lnV}. Explanation of codes. *Measurements*: SW = surface wave methods, Intr = intrusive methods (borehole). *GMX*: A-E, see Table 3. *Slope:* slope categories within various NEHRP classes. *Terrain*: numbered categories, see Figure 2. WC 2006 = Wills and Clahan (2006), WA 2007 = Wald and Allen (2007), YEA 2012 = Yong et al. (2012).

As expected, none of the estimation techniques are able to reproduce the low dispersions from measurement. We generally see lower dispersion for softer sites, represented by Quaternary geology, Geomatrix soil categories (C-E), and terrain categories 12 and 16. The general dispersion levels provided by the four considered proxies are generally similar, suggesting that no single method is clearly preferred.

4. CONCLUSIONS

In this article, we review the site parameters used in GMPEs world-wide for various tectonic regimes and describe procedures for estimation of site parameters in the absence of site-specific data. Most modern GMPEs use either V_{s30} directly as a continuous variable site parameter or as the basis for site classification into discrete categories. Accordingly, the V_{s30} parameter is emphasized in this paper.

For site-specific applications, we recommend that V_{s30} be developed from on-site geophysical measurements. When those measurements extend to a depth $z_p < 30$ m, V_{s30} can be estimated using extrapolation methods described by Boore (2004) and Boore et al. (2011).

In the absence of on-site geophysical data, or for regional ground motion studies, estimation of V_{s30} from geological or topographic data will generally be required. Geologic, geotechnical, and terrain-based correlations are available (Wills and Clahan, 2006; Chiou et al., 2008; Wills and Gutierrez, 2008; Yong et al., 2012) that are calibrated against California data. Ground slope correlations are available that utilize additional data sources from specific regions world-wide (Wald and Allen, 2007).

Previous work has shown that applying V_{s30} correlations for one region to another can be problematic, as demonstrated for example for bedrock conditions in Italy by Scasserra et al. (2009) and for Wenchuan, China, sites generally by Yu and Silva (2011, personal communication with R. Darragh). Accordingly, we recommend local verification (and perhaps re-calibration) of V_{s30} estimation procedures when they are applied outside of the original study area.

When correlation relationships are used to estimate V_{s30}, there is a large epistemic uncertainty in the mean estimate, as represented by the σ_{lnV} term shown in Figure 7. This epistemic uncertainty should be considered in ground motion hazard analysis.

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