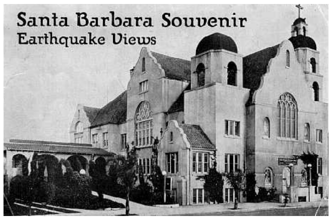

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Regional Correlations of V_{S30} and Velocities Averaged Over Depths Less Than and Greater Than 30 m

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ABSTRACT

Velocity models from sites in Japan, California, Turkey, and Europe, show that the time-averaged shear-wave velocity to 30 m (V_{S30}), used as a proxy for site amplification in recent ground-motion prediction equations and building codes, is strongly correlated with average velocities to depths less 30 m (V_{SZ}, with z being the averaging depth). The correlations for the sites in Japan show that V_{S30} is systematically larger for a given V_{SZ} than for sites in California, Turkey, and other sites in Europe. The difference largely results from the placement of the KiK-net stations locations on rock and rock-like sites, whereas stations in the other regions are generally placed in urban areas underlain by sediments. We discuss the uncertainty in ground motions that results from the uncertainty in predicting V_{S30} from V_{SZ}. We also find that V_{S30} is correlated with V_{SZ} for z as great as 400 m for sites of the KiK-net network. This final observation provides some support for using V_{S30} to statistically model the site response in ground-motion prediction equations at periods whose wavelengths far exceed 30 m.

INTRODUCTION

The time-averaged shear-wave velocity to 30 m (V_{S30}) has a number of applications, the principal ones being its use as an explanatory variable for site effects in a number of recent GMPEs (*e.g.*, Abrahamson *et al.*, 2008) and as the basis for specifying site classes in building codes (*e.g.*, Dobry *et al.*, 2000; BSSC, 2003; CEN, 2004; ASCE, 2010). V_{S30} is a simple metric that can be obtained at relatively low cost compared to more detailed descriptions of site characteristics, and it is correlated with site amplification (*e.g.*, Boore *et al.*, 1994, Figure 2). V_{S30} cannot, of course, capture all of the physics controlling site amplification (*e.g.*, Mucciarelli and Gallipoli, 2006; Castellaro *et al.*, 2008; Lee and Trifunac, 2010), and a significant amount of unexplained variation of ground motion remains after removing the site effect predicted by V_{S30} (as shown, for example, by Boore, 2004a, section 4.1.2, and Bragato, 2008).

For a number of reasons, shear-wave velocity profiles are often not available to a depth of 30 m. The reasons include technique-related limitations or environmental issues, as well as exceeding pre-determined velocity thresholds or budgetary constraints. For example, shallow penetration depth from non-intrusive active-source measurements or the presence of coarse materials in seismic cone penetrometer measurements are physical limitations often encountered. Boore (2004b) developed equations for estimating V_{S30} from V_{SZ}, where z is some depth less than 30 m. These equations were based on profiles in California. Other studies have used velocity profiles based on borehole measurements at KIBAN-Kyoshin Network (KiK-net) sites in Japan to derive similar relations. These studies include Kanno *et al.* (2006), Figini (2006) (as described in Cauzzi and Faccioli, 2008), and Cadet and Duval (2009).

Boore *et al.* (2011) expanded upon this work, by including an extensive set of shear-wave velocity profiles from Turkey and a smaller number of profiles from other areas in Europe, provided equations for more depths than in previous studies, and recognized that there are significant differences between the equations developed from different regions. This paper is an abridged version of Boore *et al.* (2011) in which we analyze these equations in terms of the uncertainty of the ground motions that results from the uncertainty in estimating V_{S30} from V_{SZ}. Additionally, we discuss correlations of V_{S30} with V_{SZ} for values of z greater than 30 m.

THE IMPACT OF UNCERTAINTY IN PREDICTED V_{S30} ON GROUND-MOTION ESTIMATES

One of the main uses of V_{S30} is for characterizing site response in GMPEs. Even though there is a strong correlation between V_{S30} and V_{SZ}, the variability of individual values of V_{S30} for a given value of V_{SZ} can have an impact on site-specific predictions of ground motions if the equations developed by Boore *et al.* (2011) are used to estimate V_{S30} at sites for which velocity profiles do not extend to 30 m (as for stations of the K-NET network). Note that here we are not concerned with errors in the velocity profiles obtained from the borehole measurements (e.g., Moss, 2008) or the effect of those errors on GMPE development (e.g., Moss, 2011), but rather with the impact of uncertainties in V_{S30} when used with previously developed GMPEs. The extrapolated values of V_{S30} will be of little use if their uncertainty is so large that ground-motion estimates using the extrapolated values are also highly uncertain. To evaluate the impact of the uncertainty in estimates of V_{S30} on predicted ground motions we use some recent GMPEs for which V_{S30} is a site variable.

Figure 1 shows the standard deviation of the observations about the regression fit as a function of averaging depth z. As expected, the standard deviation decreases monotonically to zero as z approaches 30 m. The simplest relation between a ground-motion parameter Y and V_{S30} was introduced by Joyner and Fumal (1985):

$$\log Y \propto b_{LIN} \log V_{S30} \, . \tag{1}$$

This equation was used in the GMPEs of Boore *et al.* (1994, 1997), where typical values of b_{LIN} range from -0.23 to -0.75, depending on period (*e.g.*, Boore and Atkinson, 2008). From this equation, the relation between the standard deviations of predicted motions and V_{S30} is given by

$$\sigma_{\log Y} = \left| b_{LIN} \right| \sigma_{\log V_{S30}} \, . \tag{2}$$

Taking the largest value of b_{LIN} in Boore and Atkinson (-0.75 for a period of 4 s) and the largest and the standard deviation of the residuals (σ_{RES}) reported in Figure 1 of Boore et al. (2011) for $\sigma_{\log V s30}$ gives $\sigma_{\log Y} = 0.09$ (a factor of 1.2). This is a relatively small uncertainty, given that we've chosen values of b_{LIN} and σ to maximize the uncertainty.

But the above estimate of uncertainty does not reflect the more complex role of V_{S30} in a number of recent GMPEs, in which V_{S30} appears in nonlinear amplification terms as well as implicitly in sediment-depth factors (through correlations of V_{S30} and sediment depth if the latter are not available when evaluating the GMPEs—generally, lower values of V_{S30} are associated with deeper depths of sedimentary deposits; examples of such correlations are eq. 17 in Abrahamson and Silva (2008) and eq. 1 in Chiou and Youngs, (2008)).

To give a more complete view of the sensitivity of ground motions to the uncertainty in V_{S30}, we used four recent GMPEs derived as part of the Pacific Earthquake Engineering Research Institute's Next Generation Attenuation (PEER NGA) project (the references for the specific GMPEs are given in the figure caption). We evaluated the GMPEs for values of V_{S30} corresponding to plus and minus one standard deviation of 0.12 in the predicted values of $\log(V_{S30})$ around V_{S30} values of 300 m/s and 600 m/s. This standard deviation is close to the maximum standard deviation found in the regression fits (for a 5 m averaging depth). Figure 2 uses the plus/minus one standard deviation V_{S30} values along with an earthquake magnitude of 7, a vertical strike-slip fault, and an R_{JB} distance of 20 km and plots the ratios of predicted pseudo-absolute response spectral acceleration (PSA) for the low and high values of V_{S30} about each central value (the actual values of V_{S30} are indicated in the figure, and the ratios of V_{S30} are shown by the horizontal lines, to provide a reference for the relative uncertainty in PSA and V_{S30}, expressed as multiplicative factors). We used the relations between V_{S30} and sediment depth recommended by each GMPE developer (only the Boore and Atkinson GMPEs do not involve sediment depth).

To give an idea of how the results would change for a smaller uncertainty, in the left graph we show results for two GMPEs for an uncertainty of 0.04 in $\log(V_{S30})$, the value for a depth near 20 m . Figure 2 also shows the PSA ratios for the linear amplification given by equation 1, with b_{LIN} taken from Boore and Atkinson (2008, Table 3, which are modified from Choi and Stewart, 2005).

The difference in the response spectral ratios for the purely linear site response and the site response of the GMPEs is largest for V_{S30}=300 m/s (left graph). Note that the ratios for most of the GMPEs approach unity for periods less than about 0.2 s for V_{S30}=300 m/s, but this is not true for V_{S30}=600 m/s. We think that this is a coincidence in which the larger linear amplification at the lower V_{S30} being offset by greater nonlinear deamplification.

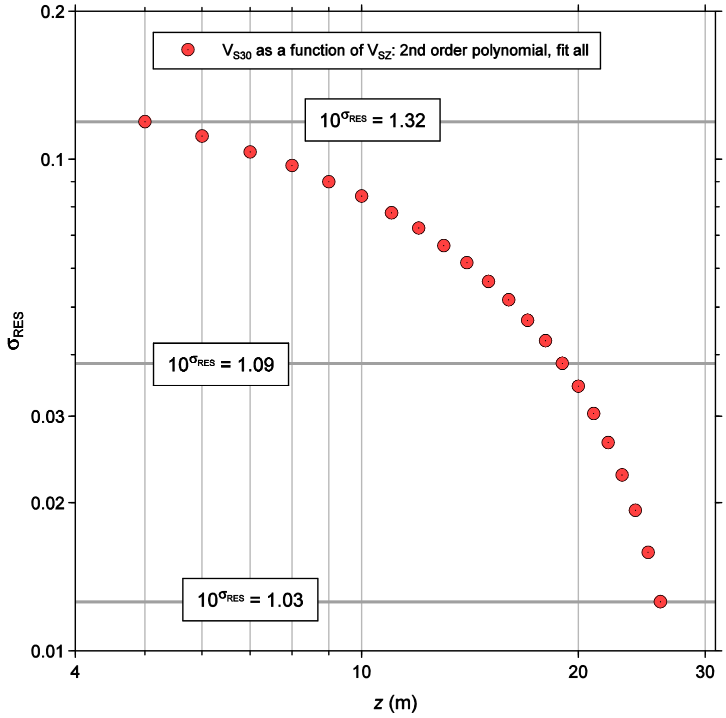

Fig. 1. The depth dependence of the standard deviation of log(V_{S30}) residuals relative to the fit of a 2nd order polynomial in log(V_{SZ}) for depths less than 30 m. For the convenience of the reader, the equivalences of the standard deviations to multiplicative factors are shown by the horizontal gray lines.

For periods less than about 2 s, Figure 2 shows that the uncertainty in the ground motions is significantly less than the uncertainty in V_{S30} for both median values of V_{S30}. For example, the uncertainty factor of 1.74 in V_{S30} (corresponding to an averaging depth of 5 m) results in less than a factor of 1.2 uncertainty in ground-motion intensity for periods less than 0.2 to 0.4 s. Because of the muting effect of soil nonlinearity discussed above, at short periods equation 2 can be used to give a quick (and conservative) estimate of the uncertainties for situations not included in Figure 2 (*e.g.*, different magnitudes, distances, and V_{S30} values). As an example, consider an uncertainty in V_{S30} of a factor of 1.5 for plus and minus $\sigma_{\log Vs30}$, analogous to the V_{S30} ratios in Figure 2 of 1.73. This ratio equates to $\sigma_{\log Vs30}$=0.09, which is close to σ_{RES} for a depth of 10 m (see Boore *et al.*, 2011, Table 2). For periods less than about 0.2 s, $|b_{LIN}|$ is close to 0.3 (Boore and Atkinson, 2008). The uncertainty in Y is then a factor of about $(1.5)^{0.3}$=1.13.

The V_{S30} sensitivity of ground motions predicted from the NGA GMPEs increases with period (Figure 2). This is due to at least three factors: 1) the magnitude of site effects generally increases as period increases (*e.g.,* for linear amplification $|b_{LIN}|$ increases with period), 2) the longer period motions are more sensitive to sediment depth than the motions at shorter periods, and 3) the muting effects of soil nonlinearity are less important at long periods than at short periods. We caution that these conclusions are based on the NGA GMPEs and may not be a global feature—certainly at some long period the ground motions will no longer be sensitive to surficial geology and the site response will then decrease toward unity as period increases (*e.g.,* starting at some period, $|b_{LIN}|$ should begin to decrease for linear amplification).

The results in Figure 2 suggest that considerable uncertainty exists in predicting ground motions at long periods when using V_{S30} values estimated from velocity profiles that only extend to 5 or 10 m. Because of the increasing accuracy of V_{S30} for greater values of the averaging depth z, however, the uncertainties in predicted motions due to the estimation of V_{S30} will obviously decrease with increasing maximum depth of the velocity profile for $z < 30$ m (for example, for a depth of about 20 m, the uncertainties in predicted motion will generally be less than 20% for all periods).

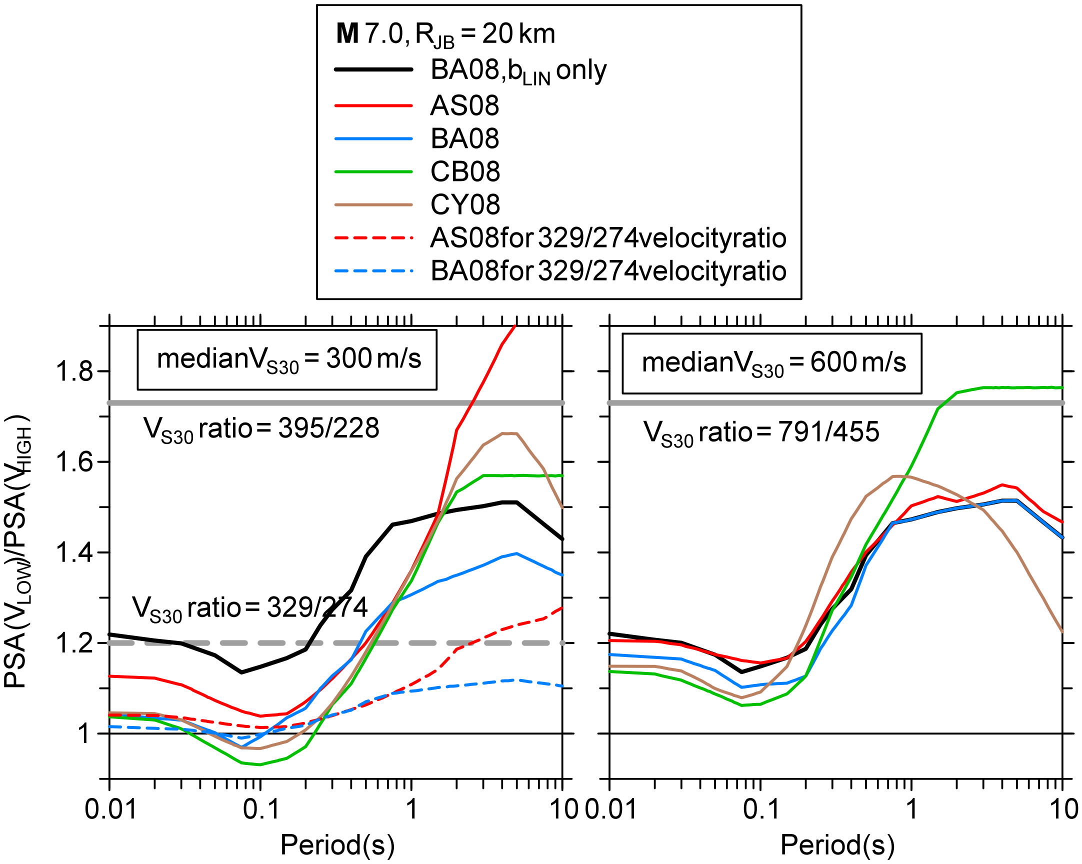

Fig. 2. Ratio of PSA from the Abrahamson and Silva (2008: AS08), Boore and Atkinson (2008: BA08), Campbell and Bozorgnia (2008: CB08), and Chiou and Youngs (2008: CY08) ground-motion prediction equations for ranges of V_{S30} centered about 300 and 600 m/s. Also shown is the ratio of response spectra using only the linear amplifications of BA08. The ranges correspond to the log of the center velocity plus and minus 0.12 log units (except for the lower ratios of AS08 and BA08 in the left graph, which correspond to plus and minus 0.04 log units). The ratio of high to low velocities is the same in all graphs, as shown by the horizontal gray lines (the high and low values are given for each ratio); these lines provide a reference for the relative uncertainty in PSA and V_{S30}, expressed as multiplicative factors. The PSA values were computed using the Fortran program described in Kaklamanos et al. (2010).

CORRELATIONS OF V_{S30} WITH V_{SZ} FOR $z > 30$ m

One criticism of V_{S30} as a site response parameter in GMPEs is that the averaging depth of 30 m is too shallow to reflect the velocity structure that can affect periods longer than a few tenths of a second. The basis for this is shown in Figure 3, which plots the depth corresponding to a quarter wavelength for various periods. Each symbol in the plot represents a particular velocity profile. For each profile the period T for which z_{MAX} is a quarter wavelength was computed using the equation

$$T = 4z/V_{SZ}\,, \tag{3}$$

where $z=z_{\mathrm{MAX}}$. One interpretation of Figure 3 is that it gives the minimum required depth of the profile such that the depth is a quarter wavelength at the specified period. Note that there is considerable scatter of the depths for a given period, due to the different velocity profiles. For example, the two California points at about 3.5 s are from boreholes penetrating very different geologic materials, the Varian hole being in Tertiary rock near Parkfield, California, and the Long Beach Water Treatment hole being in the Los Angeles Basin. Assuming that site amplification is controlled by velocities within a quarter wavelength of the surface (*e.g.*, Joyner *et al.*, 1981; Day, 1996; Boore, 2003a), the figure also can be used to estimate the minimum depth required to provide site amplification information for a given period. For example, it would seem that profiles must generally extend to at least 100 m if they are to be used to estimate amplifications at periods as long as 2 s. Another interpretation of Figure 3 is that velocities known only to 30 m are relevant for site amplifications at periods less than 1 s (being most useful for periods between about 0.1 to 0.6 s).

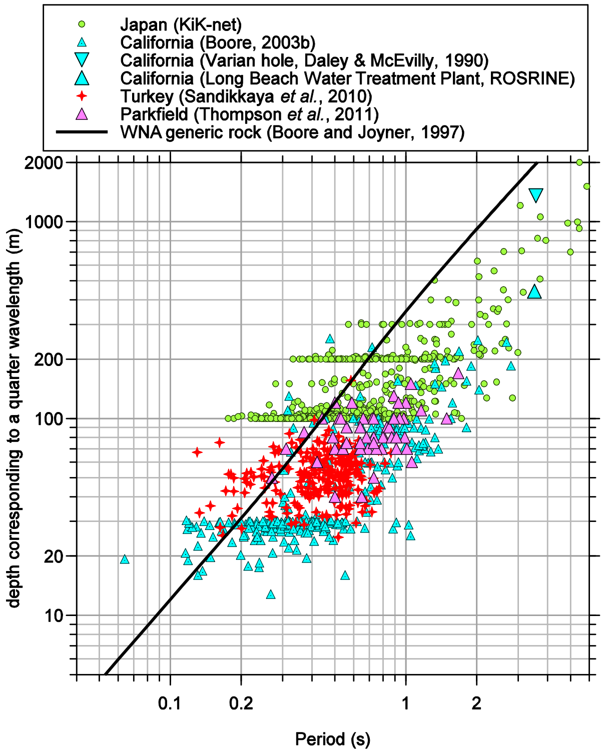

Fig. 3. The depth that equals one-quarter wavelength of an S-wave of the specified period traveling vertically in a uniform material with a velocity equal to the time-averaged velocity between the maximum depth of the profile and the surface. Each symbol represents the velocity profile at an individual site. For comparison, the black line shows the relation between depth and period for the generic rock shear-wave velocity profile of Boore and Joyner (1997).

Suggestions have been made that more accurate ground-motion predictions can be obtained if site classifications are based on depths commensurate with the period of ground motion being estimated (*e.g.*, Joyner *et al.*, 1981; Douglas *et al.*, 2009). Implied in this suggestion is that V_{S30} does not correlate well with V_{SZ} for depths greater than 30 m. Most of the velocity profiles used earlier in this article extended to depths considerably greater than 30 m, and we have taken advantage of this to look at the correlation of V_{S30} with V_{SZ} for depths as great as 600 m. The results for a representative set of depths are shown in Figure 4. The figure shows that the correlation of V_{S30} with V_{SZ} is significant even for depths many times 30 m. The correlations for the four regions are subjectively similar, at least for those depths reached by the velocity profiles in the various regions.

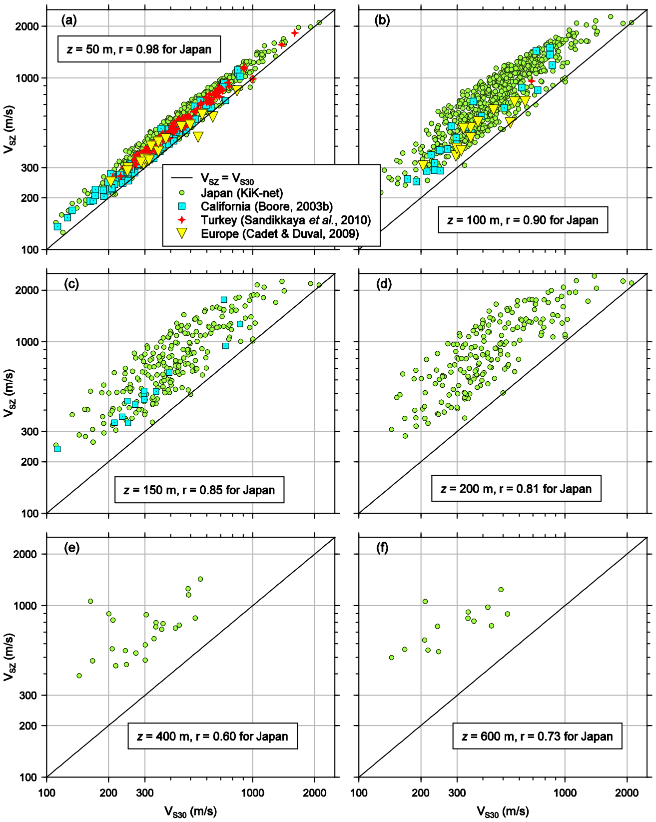

Fig. 4. Correlation of V_{S30} and V_{SZ} from shear-wave velocity profiles for averaging depths z of 50, 100, 150, 200, 400, and 600 m (not all profiles extended to all depths, thus explaining the absence of points for all but the Japan profiles for the deeper depths). The Pearson correlation coefficient r between $\log V_{SZ}$ and $\log V_{S30}$ for the Japan dataset is given in the comment box for each graph.

Only the dataset from Japan has velocity profiles extending to depths of 200 m and greater. It is interesting to consider if the correlation for the other regions would be similar to that from Japan for the depths below the maximum depths for the profiles in each region. We can speculate on this for California, for which several studies have found an inverse correlation between V_{S30} and basin depths greatly exceeding 200 m, such as the references between basin depth and V_{S30} mentioned earlier, as well as Figure 14 in Boore and Atkinson (2008). This suggests that the correlation of V_{S30} with V_{SZ} for Japanese data shown in Figure 4 might also hold for California data, at least qualitatively, with lower values of V_{S30} corresponding to lower values of V_{SZ} at a given depth.

Not surprisingly, the correlation between V_{S30} and V_{SZ} decreases with depth, at least up to about 150 m, but for greater depths the variability is approximately constant. Boore *et al.* (2011) fit the equation

$$\log V_{SZ} = c_0 + c_1 \log V_{S30} \tag{4}$$

to the KiK-net data (note that here we are interested in predicting V_{SZ} from V_{S30} for $z > 30$ m, rather than the other way around, as earlier in this article). Predicted values of V_{SZ} for a representative value of V_{S30}=300 m/s are shown as a function of averaging depth in Figure 5, along with the standard deviation of the residuals to the fit and the number of points in the fit (a 2nd order polynomial gave similar results). Note that the small range of velocity values at greater depths (*e.g.*, 600 m) makes it difficult to conclude much about the correlation between the velocities. But the consistent trends of the predicted values of V_{SZ} suggest that the correlation of V_{SZ} and V_{S30} persists to depths in excess of several hundred meters. The correlation of V_{S30} with V_{SZ} shown in Figure 4 provides some justification for the use of V_{S30} as the site response predictor variable in GMPEs for periods longer than several tenths of a second. Of course, it is possible that more accurate predictions of ground-motions can be made if the empirically based GMPEs used V_{SZ} with z commensurate with the oscillator period of interest. This requires a velocity profile extending to sufficient depths below each site providing ground-motion observations. To our knowledge, the only GMPEs that use V_{SZ} with z different than 30 m are those of Joyner and Fumal (1985).

SUMMARY AND DISCUSSION

The time-averaged shear-wave velocity to 30 m (V_{S30}), used as a proxy for site amplification in recent GMPEs and building codes, is strongly correlated with average velocities to depths less than and greater than 30 m (V_{SZ}, with z being the averaging depth). These correlations are both regionally dependent and network dependent; the KiK-net stations in Japan have systematically greater V_{S30} for a given V_{SZ} than for profiles from California, Turkey, and other sites in Europe. Furthermore, there are different trends in the velocity profiles for the KiK-net and K-net stations within Japan. We attribute both the regional and network differences to be largely the result of siting criteria for the stations rather than regional differences in geology or geomorphology: the KiK-net sites were intended to be on rock-like materials because they are co-located with the High Sensitivity Seismograph Network (Hi-net) stations, whereas the velocity profiles used here from other regions are primarily from strong-motion sites in urban regions underlain by sediments.

The standard deviations of the residuals in the equations relating V_{S30} to V_{SZ} decreases with depth (for $z < 30$ m), but even for an averaging depth of 5 m an uncertainty of plus and minus one standard deviation in $\log V_{S30}$ (a factor of 1.7 in V_{S30}) maps into less than a 20% uncertainty in short-period ground motions predicted by recent GMPEs, although the sensitivity of the ground motions to V_{S30} uncertainty is considerably larger at long periods (but is less than a factor of 1.2 for averaging depths greater than about 20 m).

We also find that V_{SZ} is correlated with V_{S30} for depths greater than several hundred meters, with the standard deviation of the scatter in $\log V_{SZ}$ for a given $\log V_{S30}$ being about 0.1 for z near 160 m; this is equivalent to the scatter in $\log V_{S30}$, given $\log V_{SZ}$ at a depth of 5 m. This provides some justification for the use of V_{S30} as a proxy for site amplification for periods for which a quarter wavelength far exceeds 30 m. This does not invalidate efforts to improve site amplification estimates in GMPEs by adding information about the depth of sediments or the presence of strong impedance contrasts (as inferred, for example, from the presence of resonant periods at sites). Even though there is a clear dependence of ground-motion amplification on V_{S30}, there is a large amount of variability in ground motions remaining after correcting for V_{S30}. An important task is to reduce this variability by introducing other site-response variables that can be obtained without a large amount of time or expense.

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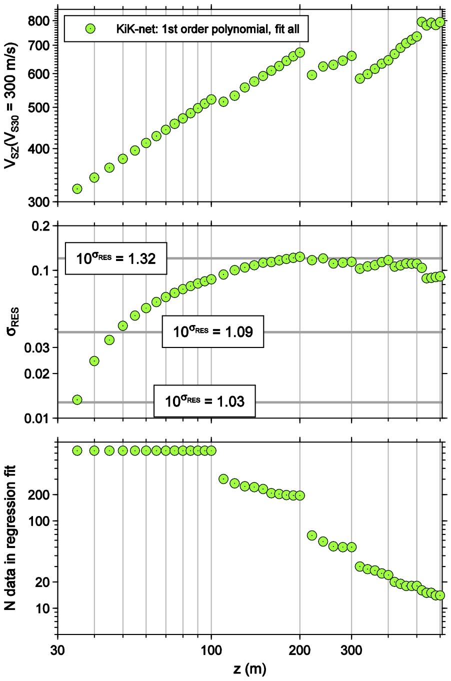

Fig. 5. Some results of fitting V_{SZ} as a function of V_{S30} for KiK-net velocity profiles for averaging depths ranging from 35 m to 600 m: (top) predicted V_{SZ} for V_{S30}=300 m/s; (middle) standard deviation of residuals; (bottom) number of points in the regression.

REFERENCES

Abrahamson, N.A. and Silva, W.J. [2008]. "Summary of the Abrahamson & Silva NGA ground-motion relations", Earthquake Spectra, Vol. 24, pp. 67-97.

Abrahamson, N., G. Atkinson, D. Boore, Y. Bozorgnia, K. Campbell, B. Chiou, I. M. Idriss, W. Silva, and R. Youngs [2008]. "Comparisons of the NGA ground-motion relations", Earthquake Spectra, Vol. 24, pp. 45-66.

ASCE (American Society of Civil Engineers) [2010]. "Minimum Design Loads for Buildings and Other Structures", Standards ASCE/SEI 7-10, ISBN 9780784410851.

Boore, D. M. [2003a]. “Prediction of ground motion using the stochastic method”, Pure and Applied Geophysics, Vol. 160, pp. 635-676.

Boore, D. M. [2003b]. “A compendium of *P*- and *S*-wave velocities from surface-to-borehole logging: Summary and reanalysis of previously published data and analysis of unpublished data”, *U. S. Geological Survey Open-File Report 03-191*, 13 pp.

Boore, D. M. [2004a]. “Can site response be predicted?”, J. Earthquake Engineering, Vol. 8, Special Issue 1, pp. 1-41.

Boore, D. M. [2004b]. “Estimating $\bar{V}_S(30)$ (or NEHRP Site Classes) from shallow velocity models (depths < 30 m)”, Bull. Seism. Soc. Am., Vol. 94, pp. 591-597.

Boore, D. M. and G. M. Atkinson [2008]. “Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s”, Earthquake Spectra, Vol. 24, pp. 99-138.

Boore, D. M. and W. B. Joyner [1997]. “Site amplifications for generic rock sites”, Bull. Seism. Soc. Am., Vol. 87, pp. 327-341.

Boore, D. M., W. B. Joyner, and T. E. Fumal [1994]. “Estimation of response spectra and peak accelerations from western North American earthquakes: An interim report, Part 2”, *U.S. Geological Survey Open-File Report 94-127*, 40 pp.

Boore, D. M., W. B. Joyner, and T. E. Fumal [1997]. “Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: A summary of recent work”, Seismol. Res. Letters, Vol. 68, pp. 128-153.

Boore, D. M., E. M. Thompson, and H. Cadet (2011). Regional correlations of V_{S30} and velocities averaged over depths less than and greater than 30 m, Bull. Seism. Soc. Am. Vol. 101, (in press).

Bragato, P. L. [2008]. “Limits for the improvement of ground-motion relations in Europe and the Middle East by accounting for site effects”, Bull. Seismol. Soc. Am., Vol. 98, pp. 2061-2065.

BSSC (Building Seismic Safety Council) [2003]. *Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, Parts: Provisions*, Report No. FEMA-450, Federal Emergency Management Agency, Washington D.C.

Cadet, H. and A.-M. Duval [2009]. “A shear wave velocity study based on the KiK-net borehole data: A short note”, Seismol. Res. Letters, Vol. 80, pp. 440-445.

Campbell, K.W. and Bozorgnia, Y. [2008]. “NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s”, Earthquake Spectra, Vol. 24, pp. 139-171.

Castellaro, S., F. Mulargia, and P. L. Rossi [2008]. “Vs30: Proxy for seismic amplification?”, Seismol. Res. Letters, Vol. 79, pp. 540-543.

Cauzzi, C. And E. Faccioli [2008]. “Broadband (0.05 to 20 s) prediction of displacement response spectra based on worldwide digital records”, J. Seismol., Vol. 12, pp. 453-475.

CEN (European Committee for Standardization) [2004]. “Eurocode 8: design of structures for earthquake resistance - part 1: general rules, seismic actions and rules for buildings”. Bruxelles.

Chiou, B.S.J. and Youngs, R.R. [2008]. “An NGA model for the average horizontal component of peak ground motion and response spectra”, Earthquake Spectra, Vol. 24, pp. 173-215.

Choi, Y. and J. P. Stewart [2005]. “Nonlinear site amplification as function of 30 m shear wave velocity”, Earthquake Spectra, Vol. 21, 1-30.

Daley, T.M. and T.V. McEvilly [1990]. “Shear-wave anisotropy in the Parkfield Varian well VSP”, Bull. Seismol. Soc. Am., Vol. 80, pp. 857-869.

Day, S.M. [1996]. “RMS response of a one-dimensional halfspace to SH”, Bull. Seismol. Soc. Am., Vol. 96, pp. 363-370.

Dobry, R., R.D. Borcherdt, C.B. Crouse, I.M. Idriss, W.B. Joyner, G.R. Martin, M.S. Power, E.E. Rinne, and R.B. Seed [2000]. "New site coefficients and site classification system used in recent building seismic code provisions", Earthquake Spectra, Vol. 16, pp. 41-67.

Douglas, J., P. Gehl, L. F. Bonilla, O. Scotti, J. Régnier, A.-M. Duval, and E. Bertrand [2009]. "Making the most of available site information for empirical ground-motion prediction", Bull. Seismol. Soc. Am., Vol. 99, pp. 1502-1520. doi: 10.1785/0120080075

Figini R [2006]. "Analisi degli effetti di sito sui lunghi periodi degli spettri di risposta di spostamento" (Master's Thesis). Politecnico di Milano.

Joyner, W. B. and T. E. Fumal [1985]. "Predictive mapping of earthquake ground motion", in *Evaluating Earthquake Hazards in the Los Angeles Region*, J. I. Ziony, Editor *U.S. Geol. Surv. Profess. Paper 1360*, pp. 203-220.

Joyner, W. B., R. E. Warrick, and T. E. Fumal [1981]. "The effect of Quaternary alluvium on strong ground motion in the Coyote Lake, California, earthquake of 1979", Bull. Seismol. Soc. Am., Vol. 71, pp. 1333-1349.

Kaklamanos, J., D. M. Boore , E. M. Thompson, and K. W. Campbell (2010). Implementation of the Next Generation Attenuation (NGA) Ground-Motion Prediction Equations in Fortran and R, *U. S. Geological Survey Open-File Report2010-1296*, 47 pp.

Kanno, T., A. Narita, N. Morikawa, H. Fujiwara, and Y. Fukushima [2006]. "A new attenuation relation for strong ground motion in Japan based on recorded data", Bull. Seism. Soc. Am., Vol. 96, pp. 879-897

Lee, V. W. and M. D.Trifunac [2010]. "Should average shear-wave velocity in the top 30m of soil be used to describe seismic amplification?", Soil Dyn. Earthq. Eng., Vol. 30, pp. 1250-1258.

Moss, R. E. S. [2008]. "Quantifying measurement uncertainty associated with thirty meter shear wave velocity (V_{S30})", Bull. Seismol. Soc. Am., Vol. 98, pp. 1399-1411.

Moss, R. E. S. [2011]. "Reduced sigma of ground-motion prediction equations through uncertainty propagation", Bull. Seismol. Soc. Am., Vol. 101, pp. 250-257.

Mucciarelli, M, and M. R. Gallipoli [2006]. "Comparison between Vs30 and other estimates of site amplification in Italy", *First European Conference on Earthquake Engineering and Seismology, a joint event of the 13th European Conference on Earthquake Engineering and 30th General Assembly of the European Seismological Commission*, Geneva, Switzerland, 3–8 Sept., paper no. 270. (available from http://www.earth-prints.org/handle/2122/1945)

Sandıkkaya, M. A., M. T. Yılmaz, B. S. Bakır, and Ö. Yılmaz [2010]. "Site classification of Turkish national strong-motion stations", J. Seismol., Vol. 14, pp. 543-563.

Thompson, E. M., L. G. Baise, R. E. Kayen, E. C. Morgan, and J. Kaklamanos [2011]. "Multiscale site-response mapping: a case study of Parkfield, California", Bull. Seismol. Soc. Am., Vol. 101, pp. 1081-1100.