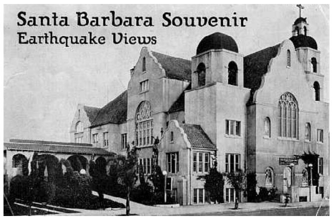

4th IASPEI / IAEE International Symposium:

Effects of Surface Geology on Seismic Motion

August 23–26, 2011 · University of California Santa Barbara

CONTRIBUTION TO GROUND MOTION UNCERTAINTY FROM SITE RESPONSE OF SHALLOW SURFACE DEPOSITS

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ABSTRACT

Various recent studies have taken advantage of the availability of large ground motion datasets to compute the standard deviation of strong ground motion at individual sites. This standard deviation is known as the single-station sigma. This study presents an extension of recent work in which ground motion variability is quantified for the Japanese KiK-net database, which has co-located strong motion stations at the surface and at borehole depth. This allows for an additional breakdown of ground motion variability into the site-to-site variability at borehole depth and the component due to record-to-record variability in the borehole-to-surface amplification factor. In this work, we quantify the contribution to overall standard deviation of the borehole-to-surface site response variability. We also evaluate how the characteristics of shallow surface deposits correlate to the variability in borehole-to-surface amplification. The quantification of this variability is important because probabilistic seismic hazard studies that remove the ergodic assumption on site response can be conducted with an overall variability that excludes the site response component. However, we observe that prediction of site response allows only for the reduction of some components of ground motion variability and does not justify the use of single-station standard deviation.

INTRODUCTION

The tools needed to conduct probabilistic seismic hazard analyses (PSHA) include methods to predict ground motions for given earthquake scenarios. These predictions must be made in probabilistic terms. This is achieved by the use of ground motion prediction equations (GMPE), which predict both median estimates of ground motion and their standard deviation (or variance). Often, the standard deviation of the predicted ground motion plays an important role in the results of PSHA.

The standard deviation predicted by a GMPE does not differentiate between spatial and temporal variability in earthquake ground motions. This assumption is known as the "ergodic assumption" (Anderson and Brune 1999). The availability of larger ground motion datasets with well recorded earthquakes and sites that have recorded multiple earthquakes, together with advanced statistical methods, permits the identification of the different contributors to ground motion variability and, at least in part, the removal of the ergodic assumption.

This study presents an extension of recent work (Rodriguez-Marek et al. 2011) in which ground motion variability is quantified for the Japanese KiK-net database, which has co-located strong motion stations at the surface and at borehole depth. This allows for the computation of the component of variability due to the shallower geological deposits. Rodriguez-Marek et al. (2011) presented results of regression analysis with the objective of quantifying single station standard deviation (e.g., the standard deviation of ground motions at a single site, that is, considering only temporal and not spatial variability). In this study, the regression analyses of Rodriguez-Marek et al. (2011) are modified in such a way that the partition of standard deviation is achieved in a single step. Moreover, this paper discusses in greater length the contribution to ground motion variability of the shallow geological deposits. Finally, the effect of different site characterizations on this variability is studied and the practical implications of these results are discussed.

GMPE RESIDUALS BREAKDOWN

The difference between observed ground motion and the median prediction of a GMPE is termed the ground motion residuals. These residuals (denoted by Δ_{es}; where the subscripts e and s denote event and station, respectively) are generally separated into between-event residuals and within-event residuals (Al-Atik et al. 2010):

$$\Delta_{\mathrm{es}} = \delta \mathrm{W}_{\mathrm{es}} + \delta \mathrm{B}_{\mathrm{e}} \tag{1}$$

The standard deviation of each of the three components are termed the total standard deviation (σ_{tot}), the within-event standard deviation (ϕ), and the between-event standard deviation (τ), for $\Delta_{\mathrm{es}}, \delta\mathrm{W}_{\mathrm{es}},$ and $\delta\mathrm{B}_{\mathrm{e}}$, respectively. Note that these residuals are computed using the logarithm of recorded and predicted ground motions. Rodriguez-Marek et al. (2011) conducted a regression analysis on the KiK-net database using both surface and borehole data. Both sets of data (surface and borehole) were used to constrain the between-event terms ($\delta\mathrm{B}_{\mathrm{e}}$), which resulted in a unique $\delta\mathrm{B}_{\mathrm{e}}$ term for surface and borehole records of a given earthquake. This permits the computation of surface within-event residuals ($\delta\mathrm{W}_{\mathrm{es}}^{\mathrm{G}}$) as simply the sum of the borehole residuals ($\delta\mathrm{W}_{\mathrm{es}}^{\mathrm{B}}$), and the residuals of the empirical amplification function between the borehole and the surface ($\Delta\mathrm{AMP}$):

$$\delta\mathrm{W}_{\mathrm{es}}^{\mathrm{G}} = \delta\mathrm{W}_{\mathrm{es}}^{\mathrm{B}} + \Delta\mathrm{AMP}_{es} \tag{2}$$

Note that this is possible because the between-event component of the residual ($\delta\mathrm{B}_{\mathrm{e}}$) is the same for the surface and borehole and hence appears on both sides of Equation 1 and thus cancels out.

For the KiK-net dataset, it is possible to compute the average residual for each of the components of the right-hand side of Equation 2 at sites that recorded multiple earthquakes. We denote these repeatable effects as the "site terms" and denote them, following the notation by Al-Atik et al. (2010), with δS2S along with a descriptive superscript:

$$\begin{gathered} \delta W_{es}^{G} = \delta S2S_{s}^{B} + \delta WS_{es}^{B} \\ \Delta\mathrm{AMP}_{\mathrm{es}} = \delta\mathrm{S2S}_{\mathrm{s}}^{\mathrm{AMP}} + \delta\mathrm{AMP}_{\mathrm{es}} \end{gathered} \tag{3}$$

And the within event residual at the surface can be written as:

$$\delta W_{es}^{G} = \delta S2S_{s}^{B} + \delta S2S_{s}^{AMP} + \delta AMP_{es} + \delta WS_{es}^{B} \tag{4}$$

Each of the terms in Equations 3 and 4 are zero-mean random variables. The δS2S terms in Equations 3 and 4 denote repeatable site effects, either at the borehole ($\delta S2S_{s}^{B}$) or in the borehole-to-surface amplification factor ($\delta S2S_{s}^{AMP}$). The two other terms are residuals that denote true aleatoric variability (an additional breakdown into repeatable source and path terms can also be achieved, thus further constraining the true aleatoric variability; this is not included in the scope of this paper).

Equation 4 is important in many respects. On one hand, the term $\delta S2S_{s}^{AMP}$ denotes the contribution to ground motion variability of the shallow geological deposits. Its standard deviation (ϕ_{S2S}^{AMP}) is the contribution to the overall standard deviation of the shallow geological deposits. We investigated how this standard deviation is a function of various parameterizations of site conditions (see the analysis of residuals section). Moreover, the term $\delta S2S_{s}^{AMP}$, being a "repeatable effect," can be predicted for a given site, either by the use of past recordings or using external means, such as site response analyses. In this case, $\delta S2S_{s}^{AMP}$ ceases to be random variable and takes a deterministic (albeit with possible epistemic uncertianty) value. This is the concept behind "partially non-ergodic" seismic hazard analyses (Anderson and Brune 1999). We quantify how much of a variance reduction is achieved by the prediction of $\delta S2S_{s}^{AMP}$ (see the application in PSHA practice section). Important in this quantification is the correlation of these residuals with the other components of Equation 4.

Mixed Effects Regression Output

The functional form of the GMPE used in this study was adopted from Boore and Atkinson (2008) and used by Rodriguez-Marek et al. (2011). The GMPE predicts the median estimate of peak ground acceleration (PGA) and pseudo-spectral acceleration at 5% damping. The general form of the model used in this study is:

$$y_{es}^{G/B} = \mu_{es}^{G/B} + \delta S2S_{s}^{G/B} + \delta WS_{es}^{G/B} + \delta B_{e} \tag{5}$$

Where, $y_{es}^{G/B}$ is the natural logarithm of the measured ground motion parameter; $\mu_{es}^{G/B}$ is the median estimation for the ground-motion parameter, δB_{e} is the between-event residual, $\delta S2S_{s}^{G/B}$ is the site term, and $\delta WS_{es}^{G/B}$ is the remaining residual component. Note that $y_{es}^{G/B}$, $\mu_{es}^{G/B}$, $\delta S2S_{s}^{G/B}$, and $\delta WS_{es}^{G/B}$ have different estimations at ground surface (G) and borehole (B).

The independent variables adopted in the prediction of the median ground motion parameter are the moment magnitude (M_w), closest distance to fault rupture (R), the average shear wave velocity over the top 30 meters of the soil profile (V_{s30}), the depth at which the shear wave velocity reached 800 m/sec (h_{800}), and the shear wave velocity at the downhole instrument (V_{shole}). For additional information on the functional form see Rodriguez-Marek et al. (2011). SAS, a commercially available statistical software, was used to perform the regression for the current study. The three residual components in Equation 5 were split in one single step. These components are manipulated using the equations shown in previous section to calculate $\delta S2S_{s}^{AMP}$ and δAMP_{es}.

The study by Rodriguez-Marek et al. (2011) obtained the residuals in Equation 5 using a two-step approach: first the Random Effects regression (Abrahamson and Youngs 1992) was used to obtain the parameters for the median model and the split of between-event and within event residual; then the within-event residual component was further split into a site specific residual component and the remaining portion. The site specific residual was calculated by averaging the within-event residual component at a specific site. In this study, the residuals are split in a single step. The advantage of splitting the three residual components all at once using SAS over the methodology adopted by Rodriguez-Marek et al. (2011) is that the site-specific residual component is being estimated using best linear unbiased predictor (BLUP). Using the BLUP assures the normal distribution for $\delta S2S_{s}$. Figure 1 shows the predicted value for δS2Ss from both studies. In general both approaches give the same trend with a substantial scatter. For the borehole observations, the absolute values of $\delta S2S_{s}$ tend in general to be smaller than the $\delta S2S_{s}$ calculated by averaging the residuals at a specific site. The $\delta S2S_{s}$ predicted from both methodologies converge towards the same value for sites with a larger number of observations. For more information about BLUP the reader is referred to Henderson (1975) and Robinson (1991).

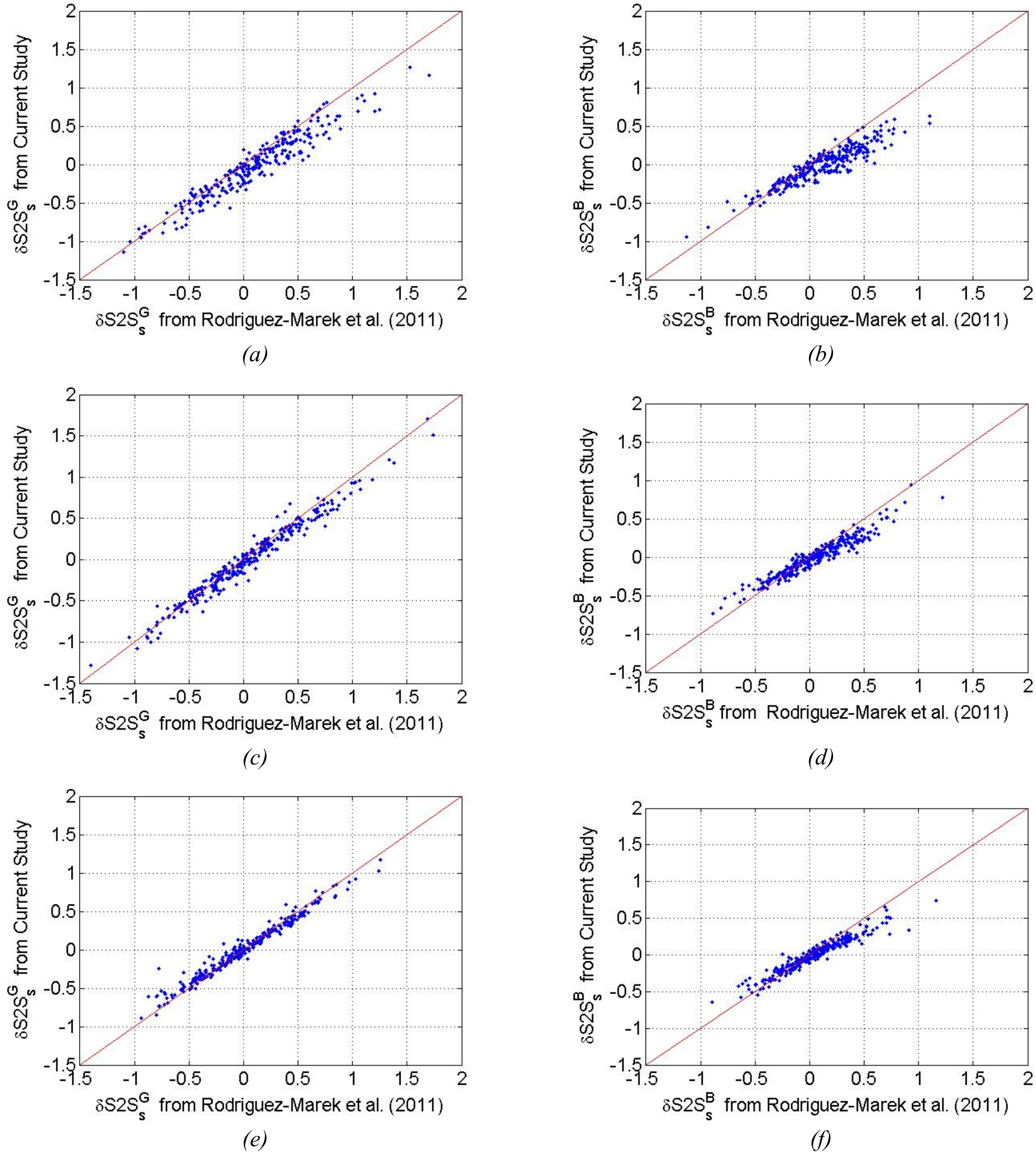


Fig. 1. The values of $\delta S2S_s$ predicted from Rodriguez-Marek et al. (2011) versus the values predicted in this study for: a) PGA at Ground Surface, b) PGA at Borehole, c) T=0.3 s at Ground Surface, d) T=0.3 s at Borehole, e) T=1.0 s at Ground Surface, and f)T=1.0 s at Borehole.

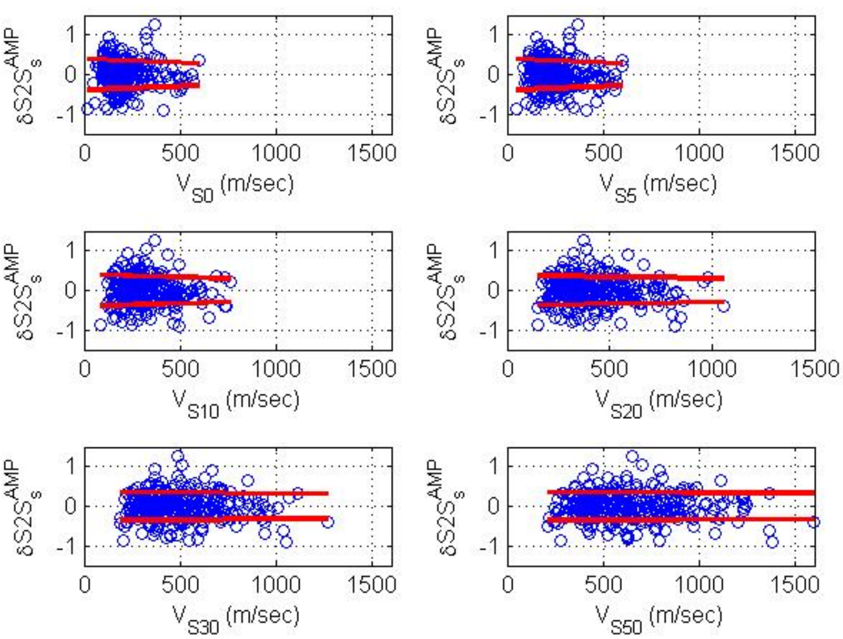
ANALYSIS OF RESIDUALS

As indicated previously, the standard deviation of the repeatable amplification term ($\delta S2S_s^{AMP}$) is denoted by ϕ_{S2S}^{AMP} and represents the contribution to the overall standard deviation of the shallow geological deposits. The effect of different soil profile parameterizations on ϕ_{S2S}^{AMP} is studied in this section. The different parameterizations used are the average shear wave velocity of the soil profile up to depths that vary from 0m to 50m measured from the ground surface, $V_{s(xx)}$. Maximum likelihood estimation (MLE) was used to estimate ϕ_{S2S}^{AMP} as a linear function of $V_{s(xx)}$. Figure 2 presents the estimated $\delta S2S_s^{AMP}$ versus the corresponding $V_{s(xx)}$ for each site at three different periods; namely, PGA, 0.3 s and 1.0 s. Two lines that represents $\pm\ \phi_{S2S}^{AMP}$ were added to Fig. 2 to show how ϕ_{S2S}^{AMP} changes with $V_{s(xx)}$.

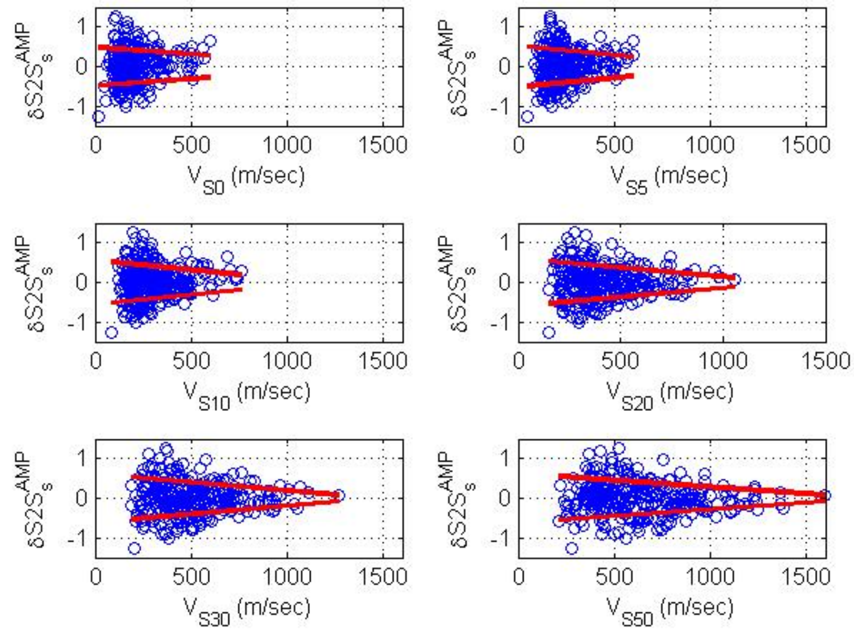
The plots in Fig. 2 show that ϕ_{S2S}^{AMP} tend, in most of the cases, to decrease with an increase of $V_{s(xx)}$. This tendency reflect the fact that the sites with small values of $V_{s(xx)}$ are sites that have transfer functions characterized by several peaks. The amplitude and location, in terms of frequency, of these peaks changes with the layering configuration at each site and hence there is large variability in the site amplification component. For this reason, the variability in $\delta S2S_s^{AMP}$ is large for soft sites. On the other hand, sites with larger $V_{s(xx)}$ tend to have a flatter transfer functions and hence a smaller variability in $\delta S2S_s^{AMP}$.

The slope in the plot of ϕ_{S2S}^{AMP} versus $V_{s(xx)}$ is an indicator of how strongly residuals depend on that particular site parameterization. In the case of short spectral periods, the steepest slope tends to appear when using the average shear wave velocity of a relatively shallow thickness of the soil profile. On the other hand, for long spectral periods the steepest slope is observed when using an average shear wave velocity of a thicker layer of the soil profile. Table 1 shows the $V_{s(xx)}$ that results in the steepest slope for each spectral period. Table 1 illustrates an interesting (albeit intuitive) concept; that shallow site response is most affected by shallow sediments within a depth that is period dependent: larger for longer periods (reflecting a deeper quarter wavelength at the fundamental mode), and shallower for shorter periods. Table 1 can be used as a guide for site parameterization for the development of code recommendations of future GMPEs. Figure 2 also illustrates that the value of ϕ_{S2S}^{AMP} to be used in site-specific PSHA analyses can be a function of the stiffness of the site. The fact that stiffer sites have lower variability also reinforces the fact that stiff bedrock sites are appropriate reference sites.

By using the MLE to estimate the standard deviation of the total residual and the different residual components; namely, Δ_{es}, $\delta S2S_s^{B}$, δWS_{es}^{B} and δAMP_{es} as a linear function of $V_{s(XX)}$, the linear functions didn't show a specific trend with $V_{s(XX)}$ and standard deviations was almost constant with respect to $V_{s(XX)}$. This suggests that the breakdown of the residuals is a good way to study the parameterizations of the site response as the breakdown was able to isolate the residual component that represents the site conditions ($\delta S2S_s^{AMP}$).



(a)



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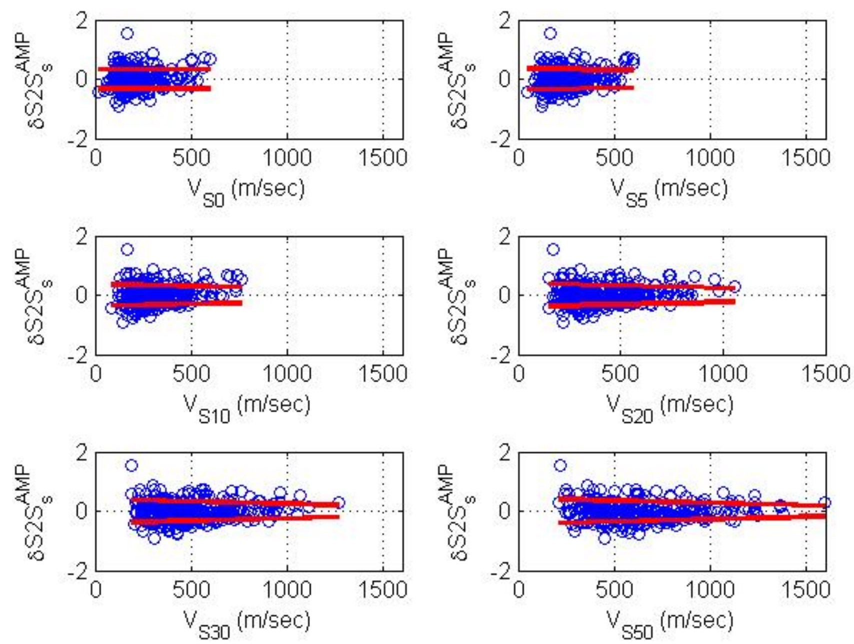

(c)

Fig. 2. $\delta S2S_s^{AMP}$ versus different $V_{s(xx)}$ including the $\pm\ \phi_{S2S}^{AMP}$ estimate as a function of $V_{s(xx)}$ calculated using MLE for: a) PGA; b)T= 0.3 s; and c)T= 1.0 s.

Table 1. The $V_{s(xx)}$ that showed the steepest slope of the ϕ_{S2S}^{AMP} versus $V_{s(xx)}$ for each spectral period.

Spectral Period	$V_{s(xx)}$ measure	Spectral Period	$V_{s(xx)}$ measure
PGA	$V_{s(5)}$	T=0.234	$V_{s(5)}$
T=0.038	$V_{s(0)}$	T=0.309	$V_{s(10)}$
T=0.048	$V_{s(0)}$	T=0.355	$V_{s(20)}$
T=0.058	$V_{s(0)}$	T=0.390	$V_{s(30)}$
T=0.077	$V_{s(0)}$	T=0.427	$V_{s(30)}$
T=0.084	$V_{s(0)}$	T=0.469	$V_{s(50)}$
T=0.097	$V_{s(5)}$	T=0.591	$V_{s(50)}$
T=0.117	$V_{s(5)}$	T=0.746	$V_{s(50)}$
T=0.147	$V_{s(5)}$	T=0.818	$V_{s(50)}$
T=0.169	$V_{s(5)}$	T=0.940	$V_{s(50)}$
T=0.204	$V_{s(5)}$	T=1.362	$V_{s(50)}$

APPLICATION IN PSHA PRACTICE

The site term at the surface, $\delta S2S_s^G$, can be obtained from the combination of the site term at borehole and the repeatable amplification site term:

$$\delta S2S_s^G = \delta S2S_s^B + \delta S2S_s^{AMP} \tag{6}$$

At a given site, this term represents epistemic rather than aleatoric uncertainty, hence it can be estimated if additional information at the site is available. Replacing this term with its estimate results in what is termed a partially-ergodic PSHA. This can be achieved in a variety of ways:

(a) Having sufficient records at the site of interest such that the site specific repeatable term can be computed directly. In this case, the within-event standard deviation that should be used is the standard deviation of the true aleatoric terms in Equation 4 [$stdev(\delta WS_{es}^B + \delta AMP_{es})$]. This standard deviation is also known as the *single-station* or *single-site* standard deviation (ϕ_{ss}).

(b) Computing $\delta S2S_s^{AMP}$ from site response analyses. In this case, the within-event standard deviation to be used in the PSHA would be the standard deviation of the residuals in Equation 4 excluding the $\delta S2S_s^{AMP}$ term [$stdev(\delta S2S_{es}^B + \delta WS_{es}^B + \delta AMP_{es})$].

(c) Other specific data such as single source or single-wave-path. This alternative is not discussed in this paper because it is rare that it can be applied in a PSHA analyses. The reader is directed to Al-Atik et al. (2010) or Lin et al. (2011).

The most realistic way to include the concept of partially-ergodic PSHA into practice is to estimate the repeatable term $\delta S2S_s^{AMP}$ from site response analyses. This process involves some epistemic uncertainty due to the site response analysis and related uncertainties; this epistemic uncertainty should be included in the PSHA. Figure 3 shows a comparison of the within-event standard deviation to be used in an ergodic PSHA (ϕ), and in partially-ergodic PSHA using options (b) above, and the single-site standard deviation (ϕ_{ss}) implicit in option (a) above. As indicated before, it is important to note that in practice the partially-ergodic sigma would need to consider additional epistemic variability, closing the gap between ergodic and partially-ergodic standard deviations. Figure 3 also ignores the correlation between different components of variability, but this correlation tends to be small (Rodriguez-Marek et al. 2011).

Applying the partially-ergodic approach into PSHA represents a lower bound to what can be achieved in practice, as no epistemic uncertainty has been considered. With this in mind we present an example application for a hypothetical site. Figure 4 compares the hazard curves, for a spectral period of 0.1 s, for the ergodic and partially-ergodic cases. Here the $\delta S2S^{AMP}$ term has been assumed to be zero, that is, the median site amplification at the site is perfectly predicted by the GMPE. In practice, a site specific analysis would have a bias that can be important at short return periods.

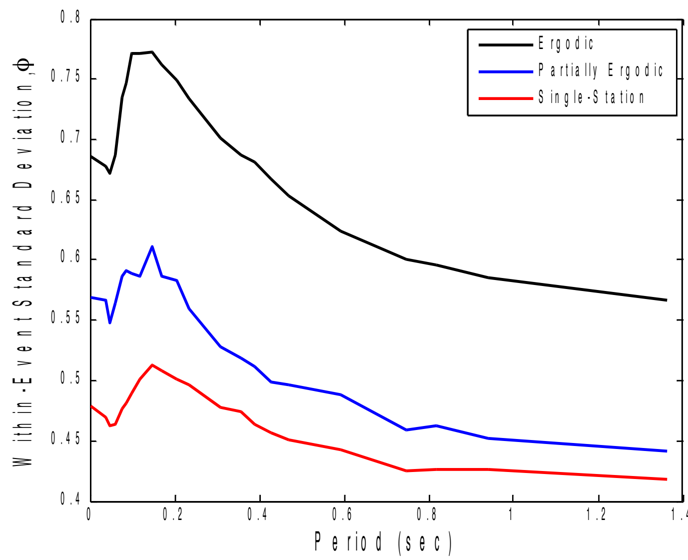

Fig. 3. Within-event standard deviation comparison for different levels of site knowledge.

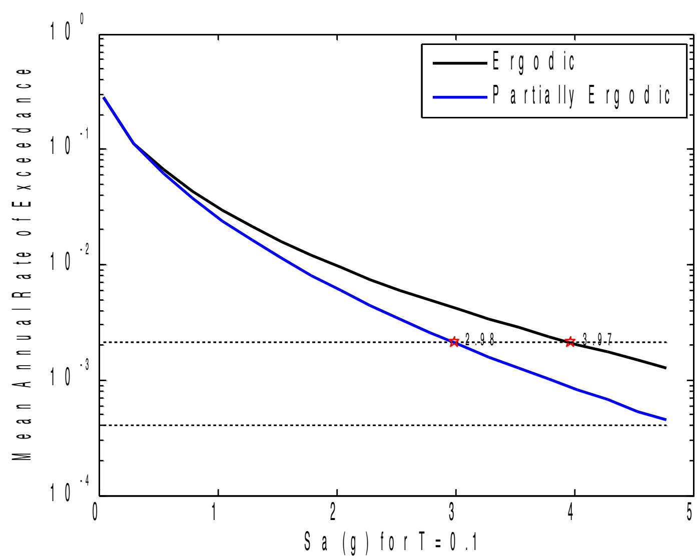

Fig. 4. Hazard curves for ergodic and partially-ergodic cases for a hypothetical case using the estimates of within-event standard deviation from the KiK-net database.

CONCLUSION

This paper presented an analysis of the ground motion residuals in the KiK-net data. The work is an extension of work presented in Rodriguez-Marek et al. (2011). In this work, an alternative statistical analysis is used to compute the GMPE and the ground motion residuals. Whereas previous work used a two-step analysis to compute residuals, in this work the various random effect terms (e.g., event-terms and site-terms) were computed in a single step. Regression results were similar using both methodologies. In addition, this paper presents an analysis of the residuals due to the shallow geological deposits. It was shown that the standard deviation of the site specific amplification residual is a function of the average shear wave velocity over a depth that changes with spectral period. Finally, the implications for PSHA practice were discussed. In particular, we highlight that additional information on site response can be used to reduce the within-event standard deviations, and this reduction can be significant. However, the use of site response analyses using information on shallow surface deposits also eliminates one component of variability, and does not justify the use of a single-station standard deviation.

ACKNOWLEDGEMENTS

This research was supported by the U. S. Geological Survey (USGS), Department of the Interior, under USGS award numbers G11AP20049 and G10AP00029. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U. S. government. Additional funding was also provided by the PEGASOS Refinement Project (PRP).

REFERENCES

Abrahamson, N. A., and R. R. Youngs [1992]. “A stable algorithm for regression analyses using the random effects model”, Bull. Seismol. Soc. Am. 82, no. 1, 505–510.

Al-Atik, L., N. Abrahamson, F. Cotton, F. Scherbaum, J. Bommer, and N. Kuehn [2010]. “The variability of ground-motion prediction models and its components”, Seismol. Res. Lett. 81, no. 5, 794–801.

Anderson, J. G., and J. Brune [1999]. “Probabilistic seismic hazard analysis without the ergodic assumption”, Seismol. Res. Lett. 70, 19–28.

Henderson, C. R. [1975]. “Best Linear Unbiased Estimation and Prediction under a Selection Model”, Biometrics, Vol. 31, No. (2), pp. 423-447.

Lin, P., B. Chiou, N. Abrahamson, M. Walling, C.-T. Lee, and C. Cheng [2011]. “Repeatable Source, Site, and Path Effects on the Standard Deviation for Empirical Ground-Motion Prediction Models”, Bull. Seismol. Soc. Am. (in press).

Robinson, G. K. [1991]. “That BLUP Is a Good Thing: The Estimation of Random Effects”, Statistical Science, 6, 15–51.

Rodriguez-Marek, A., G.A. Montalva, F. Cotton, and F. Bonilla, [2011]. “Analysis of Single-Station Standard Deviation Using the KiK-net Data”, Bull. Seismol. Soc. Am., Vol. 101, no. 3, pp. 1242–1258