Site Response Effects on Partially Ergodic PSHA

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ABSTRACT

Near surface materials play an important role in modifying seismic waves, hence the uncertainty in their properties is significant to the surface ground motion uncertainty. A partially non-ergodic approach that removes the uncertainty associated with site response from the ergodic ground motion prediction equation, and then accounts for the epistemic site response uncertainty within a particular site is presented. Probabilistic seismic hazard analyses (PSHA) results show that for better characterized sites the uncertainty on surface ground motion can be drastically reduced with respect to the ergodic prediction. This effect is stressed when long return periods are examined. The presented approach also produces a reduction on the ground motion prediction bias due to the site-specific modeling of site response.

INTRODUCTION

Probabilistic seismic hazard analysis (PSHA) is the preferred tool used to deal with the uncertainty involved in predicting earthquake intensities. This uncertainty is due to our limited understanding of earthquake phenomena and to the random nature of the seismic process. This paper presents a methodology to consider partially ergodic PSHA as an alternative to the typical (i.e. fully ergodic) PSHA analyses. This relaxation of the ergodic assumption allows for the consideration of local site effects without double counting its uncertainty.

Ground Motion Prediction Equations and Ergodicity: A traditional PSHA uses ground motion prediction equations (GMPE) that are developed with surface data. Because there is not enough data to constrain statistical models to specific regions, faults, or sites, parameterizations are used to account for path effects (typically divided into distance and a site terms), and source effects. Ground motion uncertainty is computed assuming that the ground motion uncertainty at a site is the same as the uncertainty computed from a large data set that includes ground motions from different sources and sites, this is referred to as the *ergodic assumption* (Anderson and Brune, 1999).

While a fully non-ergodic approach would minimize the uncertainty in the prediction of ground motion intensities, the limitation for such a model is the lack of data. In the absence of non-ergodic models, ergodic models such as the Next Generation Attenuation Relationships (Abrahamson et al. 2008) are generally used. These GMPE are developed with a large database that includes site-to-site variability. For the case where site-specific seismic hazard analyses are computed using site response analyses and including site response uncertainty (that comes from uncertainty in soil properties and behavior) a "double counting" of uncertainty results, at least for part of the uncertainty due to site response.

EVIDENCE AGAINST AN ERGODIC ASSUMPTION

To assess the effects of a non-ergodic, or partially ergodic, GMPE and therefore PSHA with reduced uncertainty, sites that have recorded a significant number of events, ideally from the same source (i.e. fault or fault section), are required. A set of ground motions that satisfies these requirements are the ground motion records from the KiK-net (Kiban-Kyoshin, 2010) network. The main results shown on this paper are based on the study of this database. However, other publications, such as Lin et al. (2010), Chen and Tsai (2002), Atkinson (2006), and Bindi et al. (2000), have analyzed the cases for Taiwan, Southern California, and Italy. Table 1 presents the comparison of single-site residual standard deviations versus standard deviations of the residuals from a fully ergodic GMPE obtained from the KiK-net database. These standard deviations are computed for residuals of the logarithm of the pseudo-spectral accelerations. Similar results are observed in other regions (Rodriguez-Marek et al. 2010).

Table 1. Single-site versus Ergodic Standard Deviations.

Period (sec)	Single-site σ	Ergodic σ
PGA	0.6725	0.8181
0.06	0.6655	0.8248
0.1	0.6800	0.8939
0.3	0.6582	0.8537
1	0.6122	0.7558
1.36	0.6095	0.7472

As shown on Table 1, the differences in the standard deviations for the ergodic and non-ergodic cases are significant. The residuals for the non-ergodic case are the true deviations from the mean estimate, when repeatable site effects at each site are accounted for, and when used on a PSHA exercise result in a much lower hazard (Montalva, 2010). Hence site specific information helps shift some of the total uncertainty (from an ergodic model) to a deterministic value. However, these measures of the uncertainty are only available at the ground motion station sites. An important consideration is whether there are fundamental grounds to use lower than the ergodic sigma values for sites that have not recorded enough ground motions to constrain the repeatable site effects, or that simply don't have a ground motion station. The authors believe that reducing epistemic uncertainty (i.e. sigma) is possible when more knowledge (e.g. site investigation) is incorporated into the prediction of the site-specific ground motion; if no additional information or understanding is available then the use of ergodic sigmas would be unavoidable from a theoretical point of view.

PARTIALLY NON-ERGODIC GMPE'S

The KiK-net database is particular in that it has recordings both at surface and at depth, which allow for empirical (and of course analytical) consideration of site effects. This makes possible the development of GMPE's for the surface, at depth, and a combined GMPE that uses ground motion records from surface and borehole simultaneously. These three models are explained in detail in Montalva (2010); only the main characteristics are briefly described herein. The selection of the functional form was based on its ability to be constrained by data (some models require intensive seismological modeling, along with recorded data, to constrain their model parameters). The selected functional form is the one proposed by Boore and Atkinson (2008), and the general form is given by,

$$y = \mu + \delta W_{es} + \delta B_e \quad (1)$$

where, μ is the median estimate of the logarithm of the ground motion intensity (pseudo-acceleration), δW_{es} is the within event residual, and δB_e is the between events residual. The median model is composed of a magnitude term, a distance term, and a site term. The within event residual can be partitioned into a site-to-site residual ($\delta S2S$) and a within site residual (δWS_{es}) as shown in the equations below.

$$\mu = F_m + F_d + F_{site} \quad (2)$$

$$\delta W_{es} = \delta S2S + \delta WS_{es} \quad (3)$$

Figure 1 shows the comparison of the total standard deviation for the ergodic model (i.e. the standard deviation of $\delta = \delta W_{es} + \delta B_e$) and for the non-ergodic or single-site (i.e. the standard deviation of $\delta WS_{es} + \delta B_e$). Notably, if the between event uncertainty is removed, the standard deviation for the single-site case are remarkably similar for very different regions of the world (see Lin et al., 2010; Rodriguez-Marek et al., 2010). The difference between the two sets of curves on Figure 1 is the site-to-site variability which we can consider epistemic uncertainty as it can be reduced with increased site investigation.

The relaxation of the ergodic assumption is possible by acknowledging the fact that $\delta S2S$ is epistemic, then the site-to-site residual at the ground surface (superscript G) can be divided into site-to-site residual at the borehole (superscript B) and a site amplification residual.

$$\delta S2S^G = \delta S2S^B + \delta S2S^{AMP} \quad (4)$$

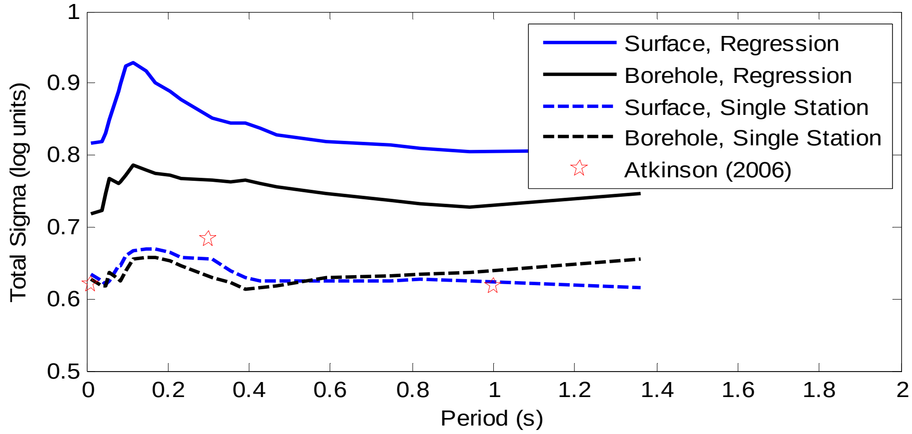

Figure 1. Comparison of total standard deviation for ergodic and non-ergodic GMPE's for surface and borehole. Results from Atkinson (2006) are shown for reference.

The partition of $\delta S2S^G$ allows for the use of the ergodic GMPE *at the borehole* (or at depth), which has lower variability than the surface regression, and the use of site response analyses to compute $\delta S2S^{AMP}$. The latter gives the possibility to lower variability by conducting thorough site investigation and site response analyses, and to reduce the site-to-site bias of the ergodic GMPE for the surface (i.e. μ^G).

EFFECTS ON HAZARD CALCULATIONS

To illustrate the effects of a PSHA conducted using the ergodic versus the partially ergodic model herein proposed, an example PSHA is studied. The seismicity affecting a fictitious sample site is defined as follows,

- Areal Source of seismicity of 100 by 100 kilometers.
- Activity rate of 0.38, for Mw between 4 and 7
- Truncated exponential Mw distribution (with parameter $\lambda = 0.8$).

The average shear-wave velocity (Vs30) of the site is set to 400 (m/s) and the Bazzurro and Cornell (2004) methodology is used to compute the nonlinear site response. Two types of scenarios were studied within the same base case, the first assuming the site is perfectly characterized, and the second one assuming uncertain Vs30 with a 10% coefficient of variation. For the case of no uncertainty on the site profile, the hazard was calculated for a range of return periods. Where the hazard is expressed as the mean annual rate of exceedance of the pseudo-acceleration (Sa) at a period of 0.1 seconds in units of "g" (gravity). This results are presented in Figure 2, were the ergodic PSHA is also shown for comparison.

To include the epistemic uncertainty on site response, uncertainties on the site's Vs30 and on the profile itself were considered. The latter one was considered when calculating the Bazzurro and Cornell parameters, the uncertainty on the site's Vs30 was included within a logic tree framework. Then different hazard curves were calculated for each Vs30 value. Note that the Bazzurro and Cornell nonlinear site response parameters are calculated separately for each Vs30 realization. Figure 3 shows the calculated hazard curves for 5 different Vs30 values.

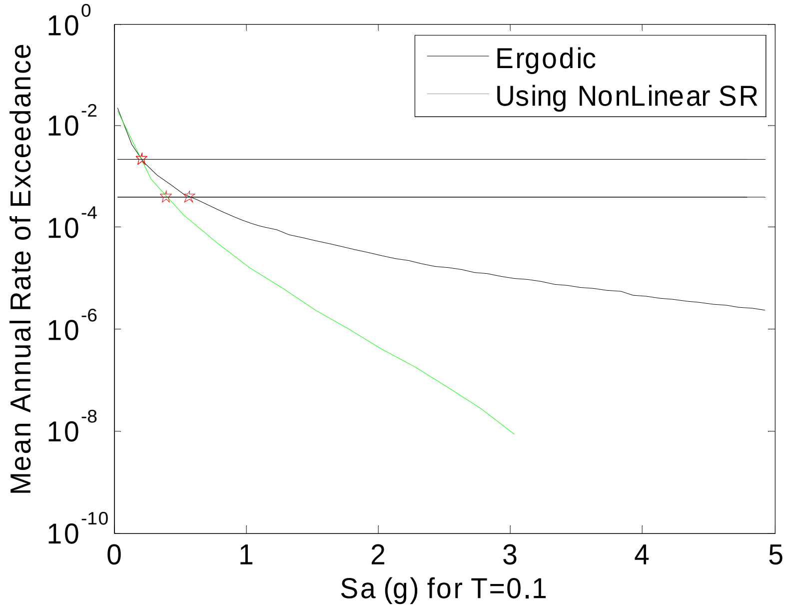

Figure 2. Hazard curve for the case of no epistemic uncertainty on site response.

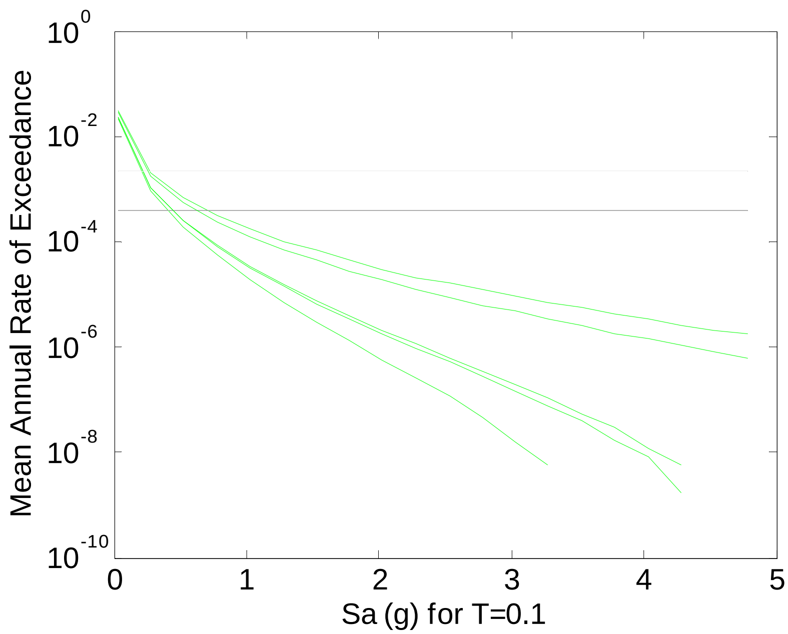

Figure 3. Hazard curves for different site scenarios (i.e. uncertainty on site characteristics)

Each hazard curve in Figure 3 corresponds to one value of Vs30 that comes from the 10% coefficient of variation assumption (a detailed study of the uncertainty in Vs30 measurements can be found in Moss 2008). Since Vs30 uncertainty is assumed to be epistemic, each hazard curve in Figure 3 has a weight for the computation of the mean hazard that reflects how far from the median estimate it is. The median Vs30 value was taken to be the same 400 (m/s). The mean hazard curve obtained for the case of uncertain Vs profile is compared to the cases without uncertainty and the ergodic model in Figure 4. Note all these hazard calculations are done using the GMPE's developed with the KiK-net database (Montalva, 2010).

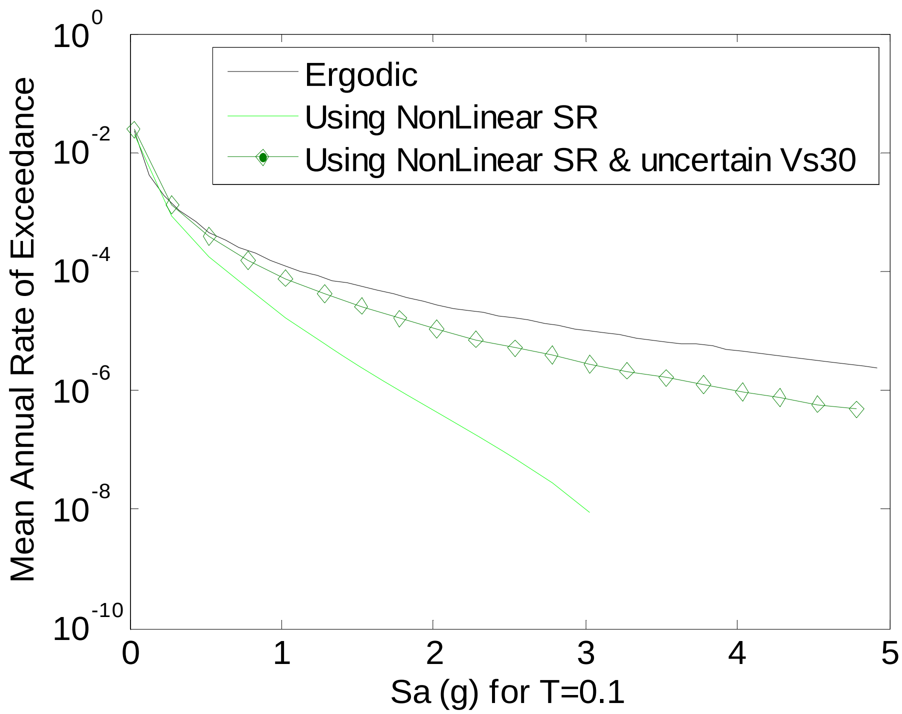

Figure 4. Hazard curves for the sample scenario, comparing ergodic, partially-ergodic, and partially-ergodic plus site uncertainty cases.

CONCLUSIONS

The main contribution of this work is the procedure for computing partially ergodic site-specific PSHA. The authors believe the methodology to be realistic, in the sense that does not use the high standard deviations drawn from ergodic regressions that are not seen on specific sites (i.e. ground motion stations). We acknowledge that we cannot directly use the median ground motion estimate for specific sites and single-site standard deviation unless we have an instrument at the site of interest.

In addition it is shown that site conditions and the degree of certainty on them, is extremely relevant to hazard calculations. Note that the 10% coefficient of variation assumed in the example is a conservative value, typical SASW uncertainty is in the order of 6%. This fact could be used as ground for seismic codes to reward thorough site investigations, because of the lower uncertainty on the expected behavior of those structures.

ACKNOWLEDGMENTS

This research was supported by the U. S. Geological Survey (USGS), Department of Interior, under USGS award numbers 08HQGR0086 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.

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