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Probabilistic versus Deterministic Implementation of Nonlinear Site Factors in Seismic Hazard Analysis

Christine. A. GOULET and Jonathan. P. STEWART

ABSTRACT

In engineering practice, it is common for the ground motion intensity measures used in design to be estimated using a combination of probabilistic and deterministic procedures. Formal probabilistic seismic hazard analyses are performed to estimate intensity measures (*IMs*) for rock site conditions. This is followed by a deterministic modification of the rock *IMs* to account for site effects, which is typically done using prescribed site factors available in the literature or in seismic code provisions. In this article we investigate the extent to which ground motions estimated using this semi-probabilistic approach approximate ground motions evaluated in a fully probabilistic context in which the nonlinear site response is integrated into the hazard calculations. Using two existing California sites as examples, we demonstrate that the deterministic application of nonlinear site factors underestimates the ground motions evaluated using a formal probabilistic approach. This misfit arises from multiple sources including different standard deviation terms for rock and soil sites and different controlling earthquakes. In particular, sites having a significant nonlinear site response tend to attract larger contributions from distant earthquakes than do rock sites. Fortunately, a new set of ground motion prediction equations developed through the Next Generation Attenuation project directly incorporate nonlinear site response effects, and hence as those models are integrated into hazard codes, there will be no need to continue in practice the semi-probabilistic approach for ground motion estimation.

INTRODUCTION

Probabilistic seismic hazard analyses (PSHA) are performed using empirical ground motion prediction equations (GMPEs) in combination with earthquake source models. The GMPEs provide estimates of the median and standard deviation of a ground motion intensity measure (*IM*) conditioned on various source, path, and site parameters.

It is common practice to apply amplification factors such as those provided in the NEHRP Provisions (BSSC, 2003) to *IMs* developed using PSHA at a target probability level for a rock site condition (Figure 1). Because this approach involves a deterministic modification of a probabilistically estimated *IM*, it is termed a semi-probabilistic approach for the purpose of this paper.

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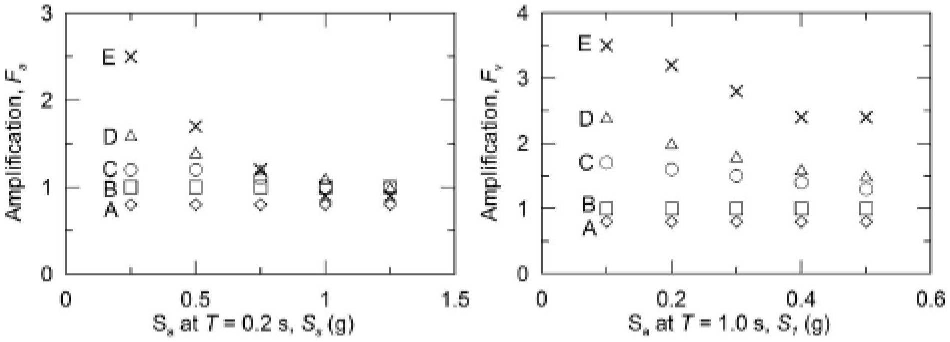

Figure 1. Site factors F_a, for low period range (T=0.1–0.5 s), and F_v, for mid-period range (T=0.4–2.0 s) as given in the *NEHRP Provisions* (BSSC 2003).

In this paper, we illustrate the difference between *IMs* evaluated using a fully probabilistic procedure that includes formal consideration of nonlinear site response and *IMs* evaluated using the semi-probabilistic approach. The nonlinear site amplification factors provided in Choi and Stewart (2005) are used. These site amplification factors (*AFs*) are a function of the average shear wave velocity of the top 30 meters of the soil column at the site of interest (V_{s30}). While the model is straightforward to apply deterministically, it can also be readily utilized in PSHA using the web-based software package OpenSHA (Field et al., 2005).

FULLY PROBABILISTIC ESTIMATION OF GROUND MOTION INTENSITY MEASURES

We have selected two soil sites from California (Table 1). Both sites have been characterized with detailed boring logs and shear wave velocity profiles. The Emeryville site is located along the margins of the San Francisco Bay just north of Oakland and is situated between the highly active San Andreas and Hayward Fault systems. The Sepulveda site is located in the San Fernando Valley portion of Los Angeles. This area is approximately 70 km away from the San Andreas fault, but also has many nearby thrust faults including the Northridge fault that was responsible for the 1994 Northridge earthquake.

Table 1. Sites information

Location and site name	**Location: (lat., long.)**	**V_{s30} (m/s)[1]**	**Geology**
Emeryville, Pacific Park Plaza	37.844°N, -122.295°W	198	Marine Clay
Los Angeles, Sepulveda VA	34.249°N, -118.477°W	370	Deep alluvium

[1] Average shear wave velocity in upper 30 m of site

Within OpenSHA, we used the probabilistic analysis option with the Frankel 2002 source model and a time span of one year. Background seismicity is excluded. Complementary information on the hazard characterization of these sites is presented in Goulet et al. (2007). The reference site condition is the rock case for the Abrahamson and Silva (1997) GMPE.

Figure 2 shows the hazard curves for the reference rock condition (Abrahamson and Silva 1997) and the soil site conditions (using Choi and Stewart 2005) as computed within OpenSHA.

Because the *AFs* are included within the GMPE, the hazard for Choi and Stewart is computed properly within the hazard integral. Figure 2*a* shows the large soil nonlinearity at the Emeryville site for *PGA*: there is amplification of the ground motions at low *PGA* values and de-amplification at larger *PGA* values with the neutral point ($AF = 1$) around PGA=0.21g. The level of nonlinearity for a spectral period of 1 s is much less important for the same site (Figure 2*b*), although the level of amplification is large. As shown in Figure 2*c*, for the Sepulveda site, the levels of *PGA* amplification/de-amplification are much smaller. This occurs because the site geology consists of stiff soils having a V_{s30} value (370 m/s) that is relatively close to the reference (rock) velocity for *PGA*. For the 1.0 sec S_a Sepulveda case (Figure 2*d*), the site amplification is nearly linear at a higher amplification level than for *PGA*.

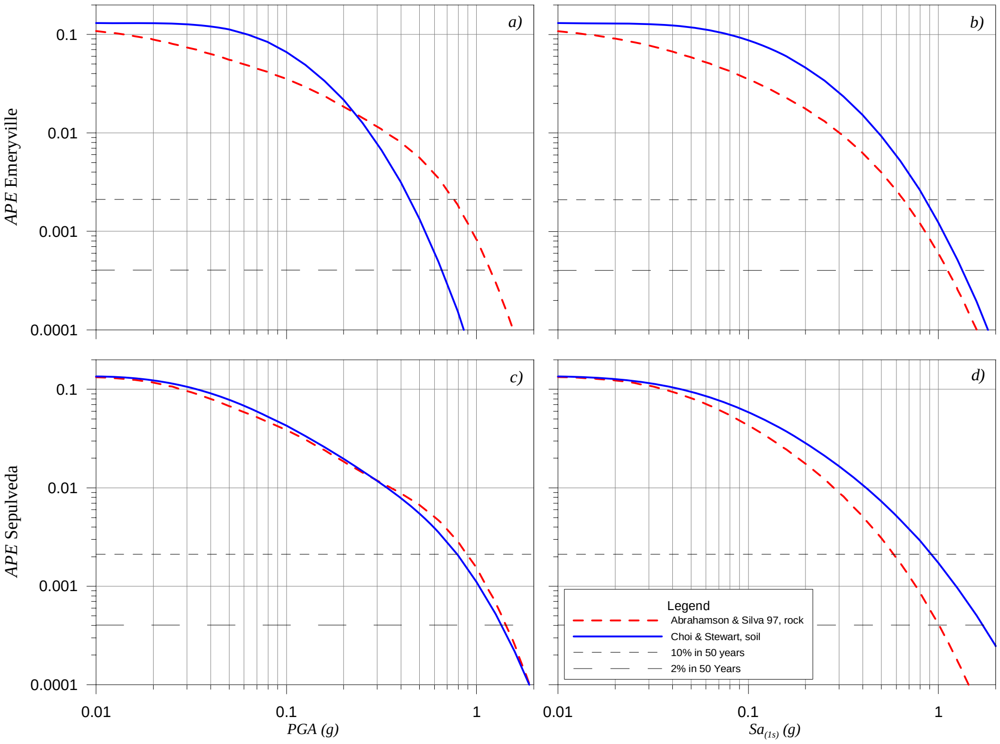

Figure 2. Hazard curves showing the annual probability of exceedance (*APE*) for Emeryville (*a* and *b*) and Sepulveda (*c* and *d*) site profiles for *PGA* and 1.0 sec S_a.

SEMI-PROBABILISTIC ESTIMATION OF GROUND MOTION INTENSITY MEASURES

The next step in our comparison is to compute the *AFs* that will be applied to the reference rock hazard curves in a deterministic fashion (*outside* of the hazard integral). To accommodate the limited length of the paper, we will only focus on *AF(PGA)* for both sites. We obtain the following relation for the Median *AF*:

$$AF(PGA) = \exp(c\ln\left(\frac{V_{s30}}{V_{ref}}\right) + b\ln\left(\frac{PGA^r}{0.1}\right) \tag{1}$$

Table 2. Choi and Stewart (2005) coefficients for PGA (Equation 1)

Site	***b***	***c***	V_{ref} ***(m/s)***
Emeryville[2]	-0.64	-0.36	418
Sepulveda	-0.14	-0.36	418

[2] Emeryville is considered a *soft soil* according to Choi and Stewart's classification

We now plot the *AFs* as a function of PGA^r (*PGA* on rock) in Figures 3*a* and 3*b* for both sites. Figures 3*c* and 3*d* show the hazard curves from above against the semi-probabilistic hazard curve computed as the rock hazard multiplied by the *AFs* deterministically. At the 10% probability of exceedance in 50 years hazard level, the *PGA* results on soil are very different for the Emeryville case. For example, at an APE of 0.0021 (corresponding to 10% probability of exceedance in 50 years), the *PGA* evaluated probabilistically is 0.44 g on soil and 0.76 g on rock. The deterministic modification of the 0.76 g rock motion is around 0.35, leading to an estimated soil motion of 0.27 g, which is much smaller than the "correct" value of 0.44 g. The problem is similar at the 2% in 50 years level. For the Sepulveda case, the amplification function has a much flatter slope (Figure 3*b*). Therefore the rock hazard is much less amplified and de-amplified (Figure 3*d*). We can still observe an unconservative reduction of *IM* for the semi-probabilistic estimation (0.67 g) relative to the fully probabilistic case (0.79g) at the 10% in 50 years hazard level.

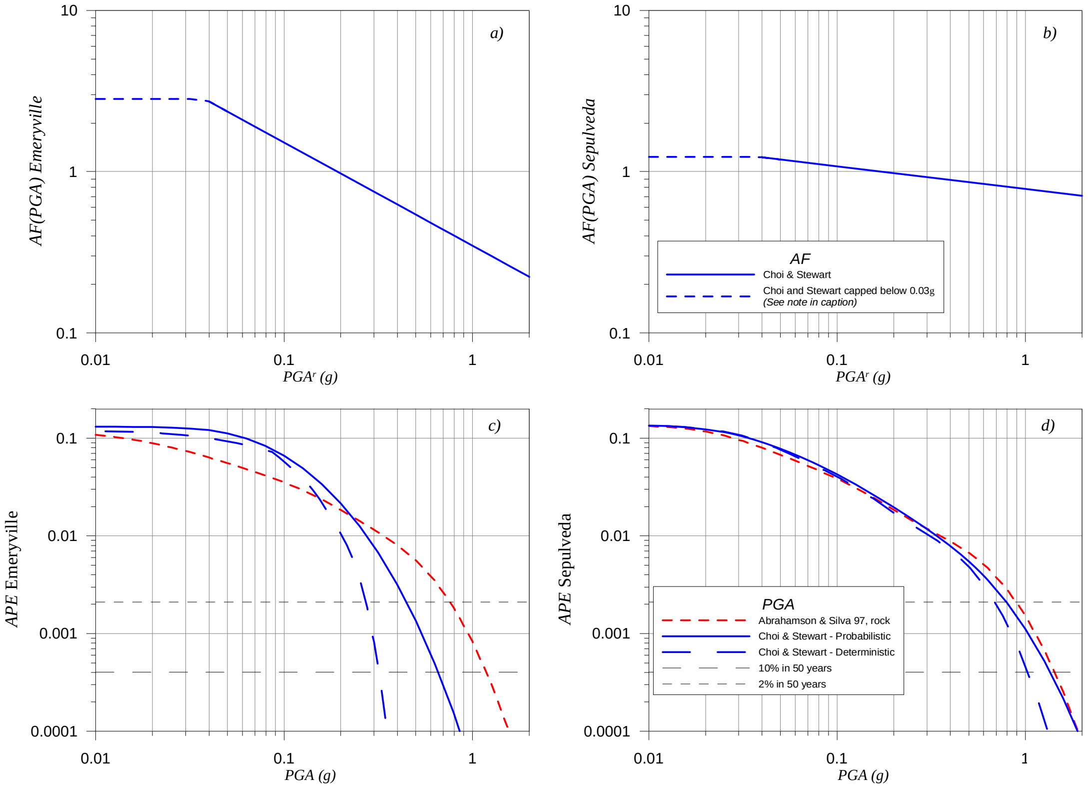

Figure 3. *PGA* median amplification functions (*a* and *b*) and hazard curves (*c* and *d*) for the Emeryville and Sepulveda sites. Note: Choi and Stewart *AFs* were developed with PGA^r data values above 0.03 g. The dashed line below that value represents an extrapolation.

INTERPRETATION

In this section, we evaluate the causes of the mismatch between the probabilistic and semi-probabilistic hazard results. To understand these differences, it is essential to consider the causes of the different probabilistic hazard results for the rock and soil site conditions. For a given magnitude and distance, the rock and soil GMPEs produce difference medians and standard deviations, but the characteristics of the contributing sources are also different. For example, Figure 4 shows rock and soil disaggregation results for Emeryville PGA at the 0.0021 APE level. Weighted average values of magnitude, distance, and epsilon (denoted $\overline{M}$, $\bar{r}$, and $\bar{\varepsilon}$) are indicated in the figure. Epsilon is a property of the ground motion record introduced by Baker and Cornell (2005), and is defined by:

$$\varepsilon = \frac{\ln\left(S_a\right)_{data} - \ln\left(\mu_{Sa}\right)}{\sigma_{Sa}} \tag{2}$$

where $(S_a)_{data}$ is the spectral acceleration of the recording and μ_{Sa} and σ_{Sa} are predicted values of the median and logarithmic standard deviation of S_a from a GMPE. The physical interpretation of ε is the offset (in number of standard deviations) between the value of the record's *IM* and the expected value from a ground motion prediction equation. An *IM* evaluated from PSHA with a very low probability of exceedance will tend to have high epsilon values, whereas *IMs* frequently exceeded could have negative epsilon.

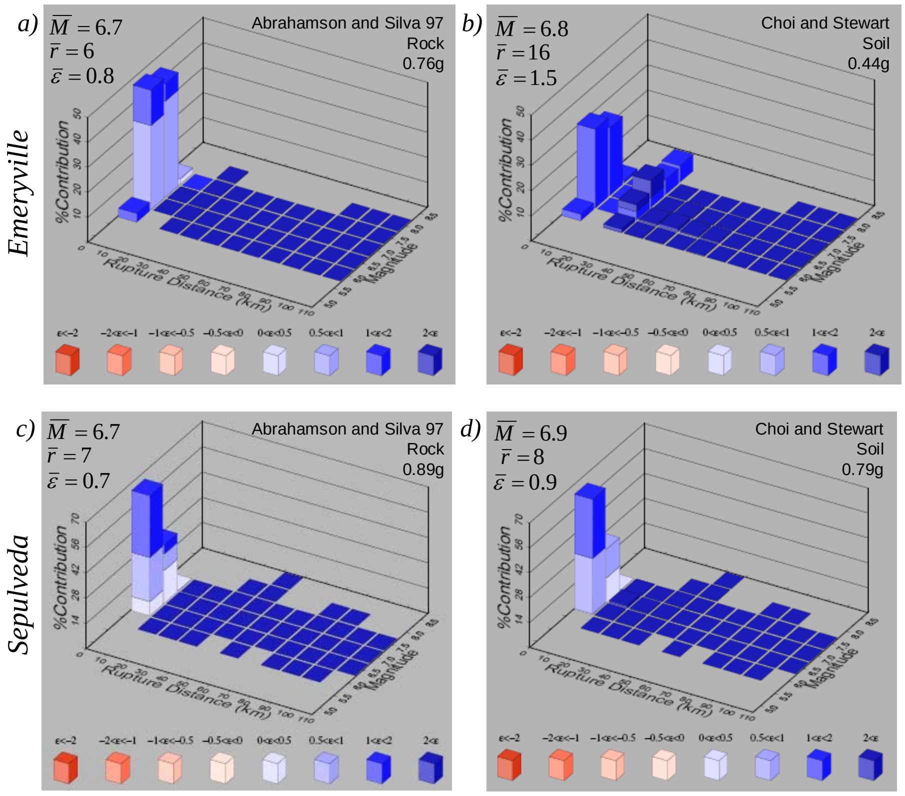

Figure 4. Comparison of hazard disaggregation results for the 10% in 50 years *PGA* hazard, Emeryville and Sepulveda sites.

Let us first look at the Emeryville case (Figure 4*a* and 4*b*). The *PGA* rock disaggregation results show a fairly narrow range of controlling magnitudes and distances (i.e., more than 95 % of the overall hazard comes from $M = 6.5\text{-}7.0$ and $r = 0\text{-}10$ km), while the epsilon values are generally between 0.5 and 1.0. On the other hand, the PGA soil disaggregation shows the controlling sources to be more broadly distributed (about only 60% of the hazard comes from $M = 6.5\text{-}7.0$, $r = 0\text{-}10$ km), especially in terms of distance (i.e., significant contributions occur to distances out to 30 km). This is due to large soil amplification of relatively weak rock input motions, such as those generated by earthquakes at large distances. Moreover, the epsilon values are higher than for the rock case, suggesting that more rare realizations of ground motions (well above the median) control the hazard on soft soil.

For the case of Sepulveda, the disaggregation results for soil and rock are more similar. We observe only a slight increase in controlling distance and epsilon for the soil case. This is consistent with the results presented previously showing similar hazard results.

The question remains, what factors control the different ground motion estimates for a given hazard level for rock versus soft soil. There are three principal possibilities: (1) different median motions (resulting from the amplification factor for soil); (2) different standard deviation terms for rock and soil; and (3) different controlling sources, as noted above. We illustrate the impact of these factors with a numerical example. Using the OpenSHA Attenuation Relationship applet, we obtain a median μ and standard deviation σ of *PGA* both for rock and soil for equivalent single-source scenarios defined from disaggregation ($\overline{M}$, $\bar{r}$), as shown in Table 3. We then compute a deterministic *PGA* value combining the median, the standard deviation, and the mean epsilon value as follows:

$$PGA = \mu e^{\bar{\varepsilon}\sigma} \tag{3}$$

Results of this computation are shown in Table 3. Despite the crudeness of the approximation of a hazard curve ordinate by these single-source scenarios, the deterministic *PGA* values are within 15 % of the probabilistic *PGA* values for Emeryville.

Table 3. Deterministic computation of *PGA* at the 10% in 50 years hazard level

GMPE, Site	PGA^1 (PSHA)	$\mu = F(\overline{M}, \bar{r})$	$\sigma = F(\overline{M}, \bar{r})$	$\bar{\varepsilon}$	PGA^2
a) Rock, Emeryville	0.76	0.49	0.47	0.8	0.71
b) Soil, Emeryville	0.44	0.19	0.52	1.5	0.41

[1] Values reported from Figure 4, [2] Values computed with Equation 3.

Examining the results in Table 3, a significant contributor to the difference in the ground motion estimates from the rock and soil GMPEs is the different medians, especially for the case of Emeryville. The differences in the medians result from different average distances (6 km for rock vs. 16 km for soft soil, as shown in Figure 4), which produces partially offsetting effects of reduced motions for reference rock and increased site factors (increasing the soil median). The net effect of these two factors is a reduced soil median relative to rock, as shown in Table 3. We do find similar standard deviations, mostly because Choi and Stewart has a much larger inter-event variability term compensated by a smaller intra-event variability term (not shown here). This is a by-product of the different ages of the models. The soft soil median is approximately 0.4 (=0.19/0.49) of the rock median, yet the ratio of the ground motions from the hazard analysis is 0.6 (=0.44/0.76). The difference in these ratios comes from the different $\bar{\varepsilon}$ values, which are much larger for soft soil than rock. This tends to increase the *PGA* for soft soil, bringing it closer to the value for rock. Similar results are obtained for the relatively stiff soil Sepulveda site. In summary, the differences in the rock and soft soil hazard estimates result from the nonlinear site factor for soft soil, larger contributions from relatively distant sources for soft soil, and relatively large ε values for soft soil.

The hazard underprediction observed earlier with the semi-probabilistic method can be explained in part by the mismatch in the disaggregation results. The semi-probabilistic method inherently assumes that the modified soil hazard has the same disaggregation characteristics as the rock hazard. We have just seen that this is not the case. Emeryville shows a good example of this mismatch and how different seismic sources lead to different median predictions. It is important to note that for the purpose of this paper, the specific choice of GMPEs is inconsequential in the sense that the general conclusions would apply to other combinations as well.

CONCLUSIONS

Increasingly sophisticated site factors (or amplification factors) are becoming available for engineering applications. However, the hazard results themselves are not necessarily more reliable if the site factors are not implemented properly. When site factors are applied deterministically to hazard curves, there is an implied assumption that the sources and epsilon values controlling the hazard on soil are the same as the hazard on rock. We have shown that the sources contributing to the hazard are different for rock and soil and that modifying the hazard curve computed for rock can bias the estimated ground motion levels. For the two sites and hazard levels considered here, the semi-probabilistic approach (i.e., deterministic application of *AFs*) led to unconservative ground motion estimates. The degree to which the semi-probabilistic procedure is biased will in general vary from site to site and for a given site will vary with hazard level. Hence, this approach produces an arbitrary result that is hardly suitable for modern performance-based design. To avoid these problems, it is recommended that the variability of *AF* be considered properly within PSHA by incorporating it in the hazard computation, at the GMPE level. This can be easily accomplished using the Choi and Stewart (2005) GMPE in OpenSHA, or in the future, any of the GMPE's produced by the Next Generation Attenuation project (which include nonlinear site terms) once they are implemented in hazard codes.

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