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Site-specific seismic hazard analysis

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ABSTRACT :

Probabilistic seismic hazard analysis has traditionally been calculated using rock conditions and modifying the rock hazard results using deterministic site-specific amplification factors. Results by McGuire et al (2001, 2002) and Bazzurro and Cornell (2004) have shown that nonlinearities in site response and uncertainties in the response are important in estimating site-specific hazard. Previous studies demonstrate that convolution of rock seismic hazard with non-linear site response gives accurate estimates of site hazard. To achieve this accuracy, several uncertainties in site-amplification calculations for hazard applications are important. In addition, the introduction of filters that remove non-damaging ground motions results in constraints on how the site-amplification calculations can be implemented.

KEYWORDS: Seismic hazard, site amplification, site response, damaging ground motions

1.INTRODUCTION

Probabilistic seismic hazard analysis (PSHA) that accounts for site amplification factors has become more refined in recent years. Traditional PSHA accounted for site conditions by using ground motion equations (GMEs) that predicted the effects of local soils, often using broad categories for local site conditions or by incorporating empirical site amplification factors. Site-specific amplification factors developed based on site-specific properties were often used in a deterministic manner to multiply uniform hazard response spectra (UHRS) on rock in order to estimate equivalent UHRS that includes site-specific site-response effects. More recent analyses (e.g. Risk Engineering, Inc., 2001, 2002; Bazzurro and Cornell, 2004) recognized the value of incorporating site-specific amplification factors in a manner that accounts for both uncertainties in rock motion and uncertainties in site amplification given a level of rock motion. Several details of this process are not widely understood, however, and deserve elaboration so that unbiased estimate of seismic hazard can be made.

2. SITE RESPONSE

Among methods of calculating site response to earthquake shaking, the assumption of vertically propagating shear waves in a horizontally layered medium is most popular, because of its simplicity and because it is applicable to a majority of sites for critical facilities. The examples presented here come from applications where this model is used. Other models such as 2- and 3-dimensional models of wave propagation, and models of basin effects, may be appropriate in certain situations, and the comments made here apply to site-amplification calculations from those models as well.

For vertically propagating shear waves, an equivalent-linear formulation is often used instead of a nonlinear formulation, because software (e.g. SHAKE and its derivatives) is readily available for these calculations and because this formulation has been shown to agree with observations. A popular alternative to SHAKE-type programs is a formulation using Random Vibration Theory (RVT), which is equivalent to SHAKE except that the input ground motion is specified in terms of its power spectrum and duration, thereby avoiding the need to use multiple time histories of motion as input.

However the site response is calculated, an accurate representation of site characteristics, including associated uncertainties, is essential. Figure 1 illustrates a set of 10 synthetic shear wave velocity V_S profiles representing uncertainties in this parameter for a site that is well-studied by drill-hole data and nearby geophysical measurements. Important characteristics whose uncertainty should be represented when performing site response studies are stratigraphy (i.e. number of layers and their thickness), V_S for each layer, and correlation between the V_S of consecutive layers, stiffness degradation (G/G_{max}) vs. strain, damping vs. strain. Models of site response that incorporate non-vertically propagating waves or basin effects will contain a number of additional parameters and associated uncertainties, including the direction of incoming waves. Further details on the probabilistic model for Vs at horizontally-layered sites are provided in Toro (1996). This model is modified, as appropriate, to incorporate site-specific information.

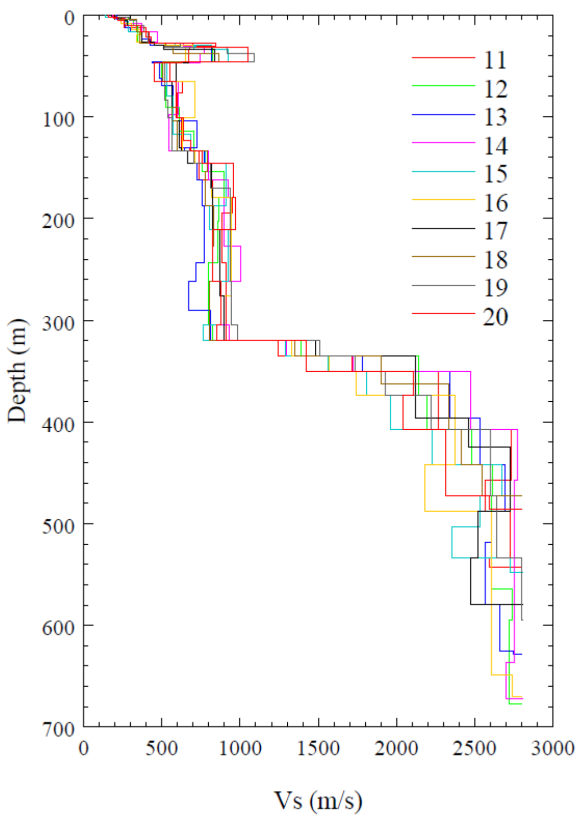

Figure 1: Example of 10 V_S profiles vs. depth

Figures 2 and 3 illustrate 60 synthetic G/G_{max} and damping vs. strain curves, which represent uncertainty in degradation properties for an example site. Often mean G/G_{max} and damping curves must be adopted from a few laboratory tests or from generic results, and uncertainties must be adopted to reflect unknown conditions. In Figure 3, damping curves have been truncated at 15% damping to conform to regulatory limitations. The degradation curves in Figures 2 and 3 have negative correlation. That is, a higher than average G/G_{max} curve is likely associated with a lower than average damping curve.

Quantitative treatment of these uncertainties and correlations in Vs and in degradation curves requires the generation of multiple synthetic profiles and their degradation curves, calculation of site response for each profile and its associated curves, and calculation of the distribution of site response over all synthetic profiles (the results from this calculation will be shown in Figure 5).

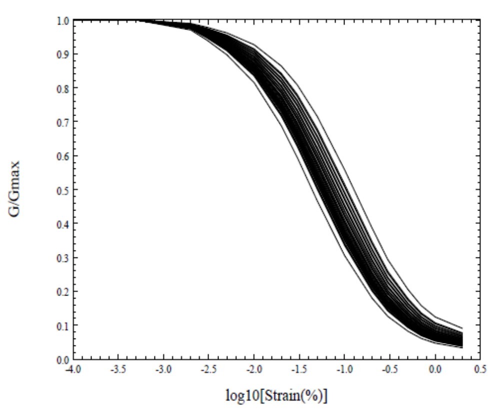

Figure 2: Example of uncertainties in G/G_{max} curves

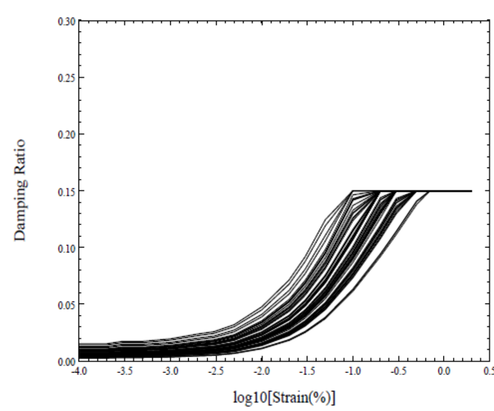

Figure 3: Example of uncertainties in damping curves

3. INPUT ROCK MOTIONS

Site response calculations must be made for discrete input rock motions, and these must span the range of motions that are critical for the final PSHA calculations. For example, for critical facilities, site motions at annual frequencies of exceedence of 10^{-4} and 10^{-5} are often required for design. In this case, rock input motions corresponding to annual frequencies from 10^{-3} to 10^{-6} should be used. If the return period of interest is 475 years, we might wish to use rock input motions corresponding to return periods of 100 to 5000 years. At low levels of motion, site response can be expected to remain linear, so fewer calculations of site response may be appropriate.

At many sites, and for the ground motions of interest for design, high-frequency (HF) response (f$\simeq$10 Hz) will be dominated by small-magnitude earthquakes occurring close to the site, and low-frequency (LF) response (f$\simeq$1 Hz) will be dominated by larger earthquakes at longer distances. Risk Engineering, Inc. (2002) recommended using the dominant earthquake for 10 Hz (represented by a mean moment magnitude **M** and distance R) for HF motions, and the dominant earthquake for 1 Hz for LF motions. Figure 4 illustrates 10^{-4} and 10^{-5} UHRS where the HF and LF spectral shapes have been derived to represent their respective **M** and R, and where the amplitudes have been scaled to the HF and LF (respectively) UHRS amplitudes. The use of multiple spectra in this way recognizes that HF and LF motions equal to the UHRS amplitudes likely will not occur during the same earthquake, and that using a broad-banded spectrum as input to the site amplification calculations would be unrealistic and potentially unconservative.

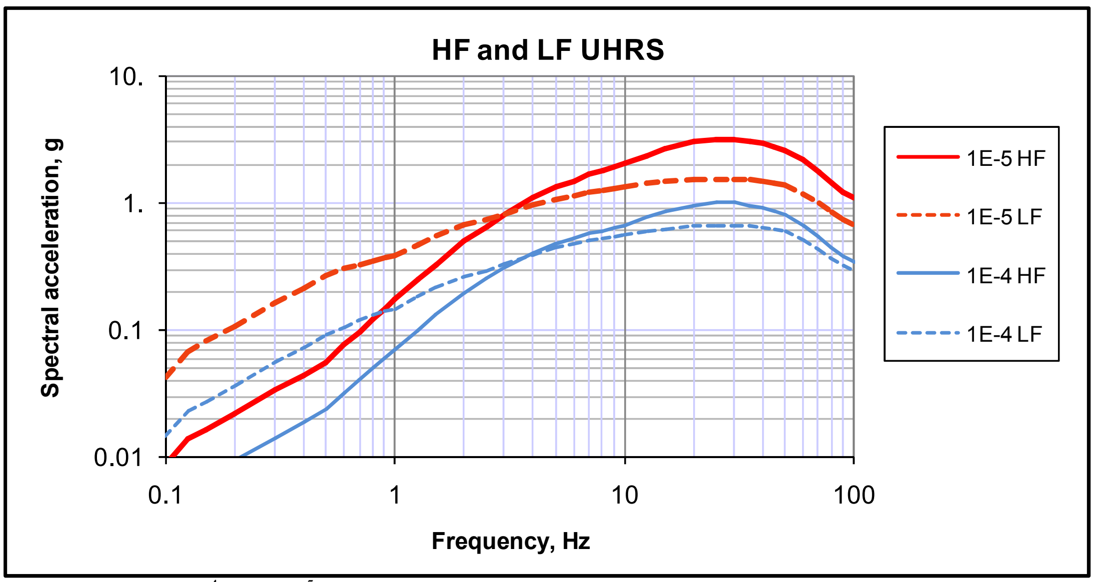

Figure 4: Example of 10^{-4} and 10^{-5} HF and LF spectra scaled to the UHRS in their respective frequency ranges.

4. SEISMIC HAZARD CALCULATIONS

The most accurate way to calculate site-specific seismic hazard is to conduct a site-response analysis for each earthquake considered in the PSHA, and include the site amplification effect (and its uncertainty) within the hazard integral. This would be computationally inefficient, and Risk Engineering, Inc. (2002) and Bazzurro and Cornell (2004) have shown that **M** and R have a secondary effect on site amplification, given the rock amplitude and mean **M** (for that amplitude). This conclusion allowed closed-form solutions to be developed to estimate site-specific hazard and UHRS from the equivalent hazard and UHRS on rock (Risk Engineering, Inc., 2002, and Bazzurro and Cornell, 2004). For typical hazard curve slopes and site-amplification uncertainties, these closed-form solutions indicate that using a deterministic amplification of rock motion such as the median values shown in Figure 5 or the associated mean values (that is, ignoring uncertainties in site response), could underestimate UHRS amplitudes by 18% or more (see McGuire, 2005). Where site-amplification uncertainties are larger, this underestimation will be greater.

Because site amplification depends primarily on the amplitude of the input motion and the **M** of the dominant earthquake, it is still computationally efficient to include site amplification (and its uncertainty) within the hazard integral. This allows more generality in applying site-amplification calculations to hazard computations, as described in the next Section.

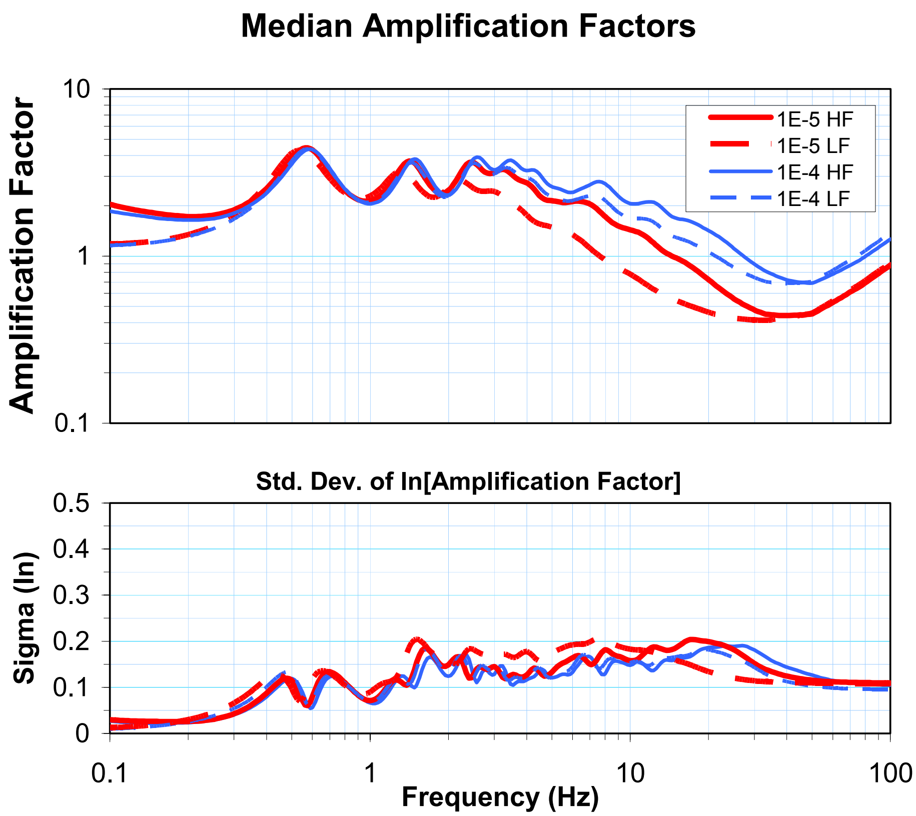

Figure 5: Median amplification factors and logarithmic standard deviations for HF and LF input motions for deep-soil site. Note: because these amplification factors represent ratios of response-spectral amplitudes, they depend on the shape of the rock input spectrum (particularly in their concave, high-frequency, portion). This spectral shape depends on **M** and on the dynamic characteristics of the upper crust.

5. GROUND MOTION DAMAGEABILITY

For seismic design of nuclear power plants in the US, the damageability of ground motions has been studied by EPRI (2006). This study used the concept of Cumulative Absolute Velocity (CAV) to determine whether ground motions will be damaging to engineered facilities. A model has been calibrated to estimate the fraction of ground motions, for a given **M** and amplitude, that will not exceed a certain CAV criterion (which is 0.16 g-sec). This fraction of non-damaging ground motions are removed from the PSHA calculation, leading to hazard curves that represent only potentially damaging shaking. This model for determining damaging motions has been accepted for use at US nuclear power plants (USNRC, 2007).

The estimate fraction of earthquakes to remove as non-damaging depends on the amplitude at which the PSHA calculation is being done, on **M** of the earthquake, on the duration of shaking (which can be estimated from

M), and on V_{S30}, the shear-wave velocity in the top 30m at the site. Thus site conditions affect the CAV calculation in two ways: through the amplitude of the ground motion at the surface and through V_{S30}. Because of this dependence on site conditions, a rock hazard with CAV cannot be conducted and then modified to account for local site conditions; the site amplification and CAV calculation must be done simultaneously within the hazard integral, using results such as those in Figure 5 to represent the site response and its uncertainty.

The CAV calculation has an important effect on the distribution of **M** and R that contribute to hazard. This is illustrated in Figures 6 and 7, which show the deaggregation of PGA at 0.2g for a site located within a rectangular area source that can produce earthquakes with **M** up to 7.0. The non-CAV hazard **M**-R deaggregation (Figure 6) shows that 50% of the hazard comes from **M** in the range 5.0 to 5.5, and R within 15 km. The CAV hazard **M**-R deaggregation (Figure 7) shows that, for damaging ground motions producing PGA=0.2g, only 20% of motions come from that **M**-R bin, and 80% of the hazard results from larger earthquakes and longer distances. The mean **M** from the CAV hazard calculation is 5.9, whereas it is 5.5 for the non-CAV hazard calculation.

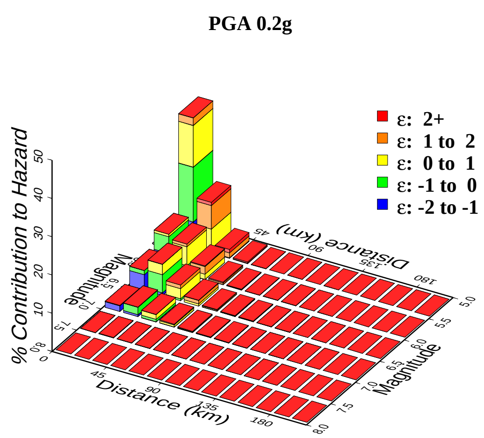

Figure 6: Example M-R deaggregation for non-CAV hazard

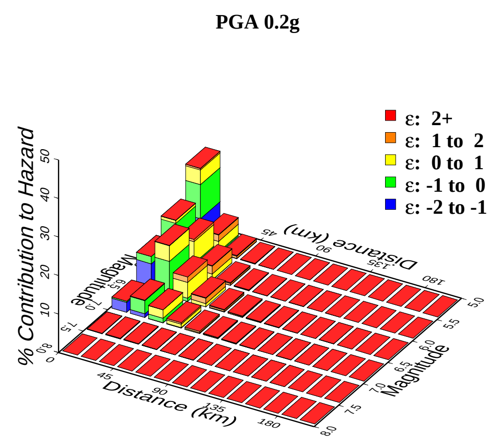

Figure 7: Example M-R deaggregation for CAV hazard

6. SUMMARY

Site-specific hazard calculations can be made using rock hazard calculations as a basis, if site-amplification calculations include all uncertainties in site characteristics and site response. For each rock amplitude at which site-amplification calculations are made, it is necessary only to know the mean **M** of the causative earthquake. Closed-form solutions are available to calculate site-specific hazard and ground motion, knowing rock hazard and ground motion and the site amplification and its uncertainty.

If methods are used to account for the damageability of ground motion such as the Cumulative Absolute Velocity (CAV) filter, then site amplifications must be incorporated into the hazard integral. In other words, rock hazard curves or UHRS cannot be transformed into site-specific hazard curves or UHRS, because the damageability filter incorporates characteristics of the site such as amplification and V_{S30}. These effects must be accounted for within the hazard calculations. However, doing so is straightforward, once site-specific amplification factors have been derived for a range of input rock motions: log-log interpolation of amplification factor (and standard deviation) vs. rock amplitude is appropriate and accurate.

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