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Selection of strain compatible properties for soil structure interaction analysis

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ABSTRACT: The seismic response of nuclear facilities is computed routinely through Soil Structure Interaction (SSI) analysis that defines the input motions based on the Uniform Hazard Spectra (UHS) at the ground surface. Generally, the SSI analysis models the soil as linear-elastic with strain-compatible shear moduli and damping. The selection of these properties for SSI must be performed apriori and they must be consistent with the site response analyses used to develop the surface UHS. When the surface UHS is developed using fully probabilistic approaches, it is not straight-forward to evaluate the appropriate strain-compatible properties. This paper introduces an approach that allows for the selection of strain-compatible soil properties that are consistent with a probabilistically computed UHS. The surface UHS is disaggregated at each period with respect to the contributing rock motion level and this rock spectrum is used in site response analyses with randomly varied shear wave velocity (Vs) profiles to identify the induced strain level and associated nonlinear properties consistent with the surface UHS. The approach is demonstrated using a hypothetical site and ground motion hazard.

1 INTRODUCTION

Soil-structure interaction (SSI) analysis models the dynamic interaction between the soil and the supported structure during an earthquake. The dynamic characteristics of the near-surface soils play a critical role in determining the characteristics of earthquake shaking at the ground surface and determining the dynamic response of the supported structure. For nuclear facilities, the SSI analysis commonly uses the surface Ground Motion Response Spectra (GMRS) from Uniform Hazard Spectra (UHS) to define the input motions. In many SSI computer programs used in the nuclear industry, the soil domain is modeled as linear elastic with strain-compatible shear moduli and damping. Prior to the SSI analysis, strain-compatible properties need to be selected that are consistent with the dynamic site response analyses used to develop the GMRS.

Generally for nuclear facilities, a site-specific, performance-based GMRS will be computed from the results of a probabilistic seismic hazard analysis (PSHA), which provides a framework to capture uncertainties in both the rock ground motions and site response (US. Nuclear regulatory Commission 2007, Rodriguez-Marek et al. 2014). The soil-specific PSHA incorporates the effects of the detailed site-specific soil conditions and computes the soil hazard curve by considering each rock motion amplitude, its annual rate of occurrence, and the probability that it is amplified enough to exceed a given surface motion amplitude. These effects are commonly applied using the convolution approach (Rodriguez-Marek et al. 2014) which convolves a rock hazard curve with an intensity-dependent site amplification model to produce a seismic hazard curve at the surface for each period (Figure 1) and the resulting UHS and GMRS at the surface. Within this context it is not straight-forward to evaluate the appropriate strain-compatible properties associated with the UHS or GMRS.

This paper describes an approach that allows for the selection of strain-compatible soil properties that are consistent with a UHS at the soil surface computed from the PSHA convolution approach. The proposed method disaggregates the surface soil ground motion hazard in terms of the contributing rock motion levels and selects the median rock motion at each

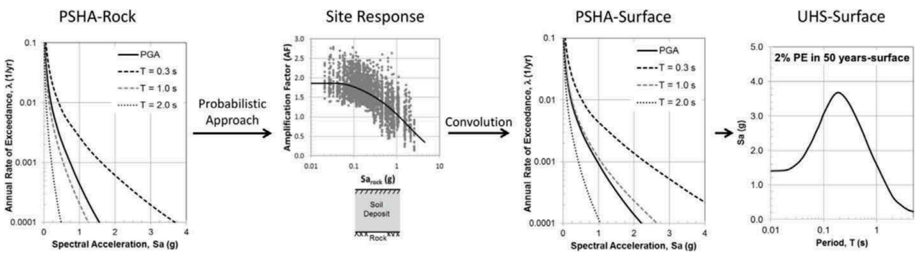

Figure 1. Probabilistic technique that incorporates intensity dependent site amplification into seismic hazard analysis through the convolution approach.

period as the controlling input motion. The controlling rock motions at each period are combined to create a rock response spectrum that is used as the input for site response analyses. This input motion is used in random vibration theory (RVT) based site response analyses with randomly varied shear wave velocity (Vs) profiles to identify the Vs profile, induced strain level, and associated strain-compatible properties consistent with the surface UHS. The approach is demonstrated using a hypothetical site and ground motion hazard.

2 PROPOSED APPROACH TO SELECT STRAIN-COMPATIBLE PROPERTIES

2.1 *Convolution approach*

The convolution approach uses a bedrock hazard curve and the site-specific, intensity-dependent, site amplification response at each period to compute a soil hazard curve (Bazzurro and Cornell, 2004, Rathje et al. 2015, Pehlivan et al. 2016). The approach convolves the rock hazard curve with the probability density function for the amplification factor (AF), which is defined as the ratio of the soil surface spectral acceleration, $Sa_{soil,}$ to the rock spectral acceleration, Sa_{rock}. Due to soil nonlinearity, the intensity of the bedrock motion influences AF. Thus, the median AF at a given period is defined as a function of the spectral acceleration on rock, Sa_{rock}, at that same period.

The mean annual rate of exceedance for soil ground motion level at spectral period T can be computed following equation (1):

$$\lambda_{soil}(z^*) = \sum_{x_j} \lambda_{soil}(z^*)_{x_j} = \sum_{x_j} P\left[AF > \frac{z^*}{x_j}|x_j\right].d\lambda_{Sa_{rock}}(x_j) \tag{1}$$

where $\lambda_{soil}(z^*)_{x_j}$ is the annual rate of exceedance of z^* for $Sa_{rock} = x_j$, which is computed from $P\left[AF > \frac{z^*}{x_j}|x_j\right]$, the probability that AF is larger than $\frac{z^*}{x_j}$ when $Sa_{rock} = x_j$, and $d\lambda_{Sa_{rock}}(x_j)$, the annual rate of occurrence for $Sa_{rock} = x_j$. The term $d\lambda_{a_{rock}}(x_j)$ can be computed by differencing a previously defined rock hazard curve. By assuming a lognormal distribution for AF, $P\left[AF > \frac{z}{x}|x\right]$ can be computed using equation (2):

$$P\left[AF > \frac{z}{x}|x\right] = \hat{\phi}\left(\frac{ln\left[\frac{z}{x}\right] - \mu_{ln_{AF|x}}}{\sigma_{ln_{AF|x}}}\right) \tag{2}$$

where $\hat{\phi}(.)$ is the standard Gaussian complementary cumulative distribution function. $\mu_{ln_{AF|x}}$ is the mean value of lnAF when $Sa_{rock} = x$, and $\sigma_{ln_{AF|x}}$ is the standard deviation of lnAF when $Sa_{rock} = x$. Both $\mu_{ln_{AF|x}}$ and $\sigma_{ln_{AF|x}}$ are obtained from a site-specific AF relationship and they are functions of bedrock amplitude x.

To use the convolution approach, site-specific amplification relationships are required that describe the change in AF with input rock motion intensity and also quantify the variability in AF. The AF relationships are developed from AF values computed via site response analyses for a range of levels of input motion intensity. These site response analyses incorporate variability in the shear wave velocity (Vs) through Monte Carlo simulations, in which multiple shear wave velocity profile realizations are statistically generated (e.g., Rathje et al. 2010, Kottke and Rathje 2009). Commonly, random Vibration Theory (RVT)-based site response analyses have been used (Rathje and Ozbey 2006, Kottke and Rathje 2009) beause this approach does not require the selection of input time series.

2.2 *Disaggregation of soil surface ground motion hazard*

Engineers are familiar with disaggregation of the rock ground motion hazard in terms of the relative contributions to different earthquake magnitudes (M) and site-to-source distances (R). When considering the disaggregation of the surface ground motion hazard, we are interested in the relative contributions of different rock motion levels (i.e. x_j, in equation 1) and this can be computed as part of the convolution analysis, as described below.

The convolution analysis starts with the rock hazard curve for a particular period being converted to $d\lambda_{Sa_{rock}}(x_j)$, the annual rate of occurrence of each $Sa_{rock} = x_j$, and using these values in equation (1) to compute the individual $\lambda_{soil}(z_k)_{x_j}$. The contribution from each value of $Sa_{rock} = x_j$ to the total $\lambda_{soil}(z_k)$ can be computed as:

$$Contribution(x_j) = \frac{\lambda_{soil}(z_k)_{x_j}}{\lambda_{soil}(z_k)} = \frac{\lambda_{soil}(z_k)_{x_j}}{\sum_{x_j} \lambda_{soil}(z_k)_{x_j}} \tag{3}$$

and epsilon of the amplification factor associated with each $Sa_{rock} = x_j$ is computed as:

$$\varepsilon_{x_j} = \frac{ln\left[\frac{z_k}{x_j}\right] - \mu_{ln_{AF|x_j}}}{\sigma_{ln_{AF|x_j}}} \tag{4}$$

An example disaggregation is shown in Figure 2 for a hypothetical site and $Sa_{soil} = 1.03$ g. Each Sa_{rock} bin contributes a portion of the surface hazard, with the maximum contribution (mode) associated with $Sa_{rock} = 0.75$ g and the median contribution associated with $Sa_{rock} = 0.97$ g. Also shown for each Sa_{rock} bin is the epsilon associated with the AF required to amplify the Sa_{rock}. For the smaller Sa_{rock}, larger epsilon are required to amplify the motion up to $Sa_{soil} = 1.03$ g, while for larger Sa_{rock}, smaller epsilon are required.

For a surface UHS, one can perform the disaggregation for each period and select the median contributing Sa_{rock} from the disaggregation data to generate a disaggregated rock spectrum that represents the rock spectrum that contributes most to the UHS at the soil surface.

2.3 *Identifying strain-compatible properties*

After determining the disaggregated rock response spectrum, a suite of site response analyses are performed to estimate the induced strain level and associated strain-compatible properties. It is important that the identified properties be consistent with the computed UHS at the surface from the convolution method. Additionally, because the amplification relationships used in the convolution method included variability in the Vs profiles, it is not obvious which properties will generate the UHS at the surface. To address these issues, a suite of analyses are performed with the baseline Vs profile varied via Monte Carlo simulation. For all of the analyses, the input motion is specified as the disaggregated rock response spectrum and the equivalent-linear site response computations are performed using the RVT approach because for RVT analysis the input motion can be specified simply as a response spectrum. The surface response spectrum is computed for each analysis and compared with the surface UHS. The shear wave velocity profiles, as well as the associated strain-compatible shear moduli and damping ratios, that provide the best fit with the surface UHS are selected as appropriate for use in the SSI analyses.

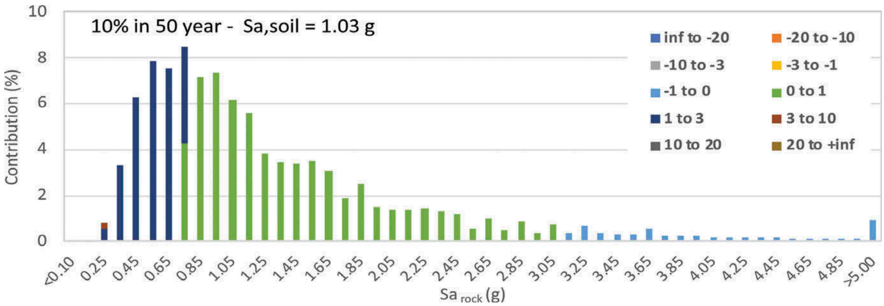

Figure 2. Example disaggregation data for Sa_{soil}= 1.03 g

3 APPLICATION OF THE APPROACH TO SELECT STRAIN-COMPATIBLE SOIL PROPERTIES

3.1 *Generation of soil surface uniform hazard spectrum*

Located in Southern California, we selected the Sylmar County Hospital site (SCH, N34.327, W118.444) in the San Fernando Valley to demonstrate the approach. The soil profile consists of 90 m of alluvium above bedrock with 4 main shear wave velocity layers ranging from 250 m/s at the surface and increasing to 700 m/s at 60 m depth (Pehlivan et al. 2016). The rock hazard curves for the site were taken from the USGS Unified Hazard tool (USGS, 2017) for NEHRP B/C site class condition (V_{s30}= 760 m/s) and consisted of seven spectral periods between T = 0.0 s and 2.0 s. Figure 3 shows the rock hazard curves for peak ground acceleration (PGA) and spectral acceleration (Sa) at T = 0.5 and 2 s.

To develop the AF relationships for the convolution method, 11 rock response spectra were developed to represent a range of input intensities for use as input into RVT site response analyses. These motions were used as input into site response analyses that incorporated Vs variability through Monte Carlo simulation with 30 Vs realizations and $\sigma_{\ln Vs}$ = 0.2 for all layers. The 330 site response analyses were performed using the program STRATA (Kottke and Rathje 2009), which computed surface response spectra and associated AF values at each period for each analysis.

The resulting AF data were used to generate site amplification functions at each period, using the approach outlined by Pehlivan et al. (2016). The AF vs. Sa_{rock} and Sa_{soil} vs. Sa_{rock} relationships for peak ground acceleration (PGA), Sa at T = 0.5 s, and Sa at 2.0 s are illustrated in Figure 4. For PGA and Sa at T = 0.5 s, the data show an decrease in AF with increasing Sa_{rock} due to the increased soil nonlinearity and damping associated with larger

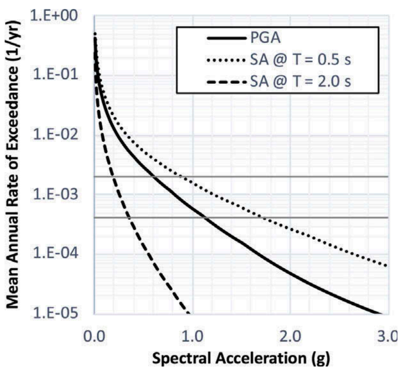

Figure 3. Rock hazard curves at three spectral period of PGA, 0.5 and 2 seconds.

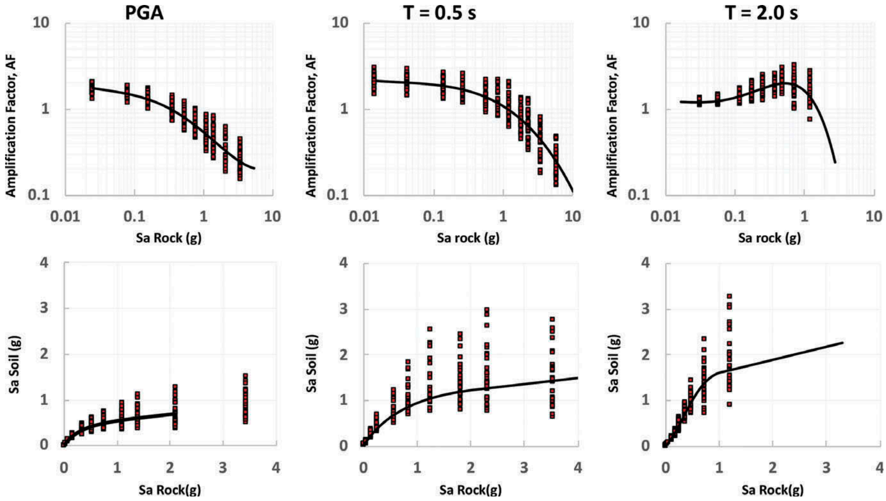

Figure 4. Amplification factor curves and spectral acceleration at the surface plots versus spectral acceleration of rock.

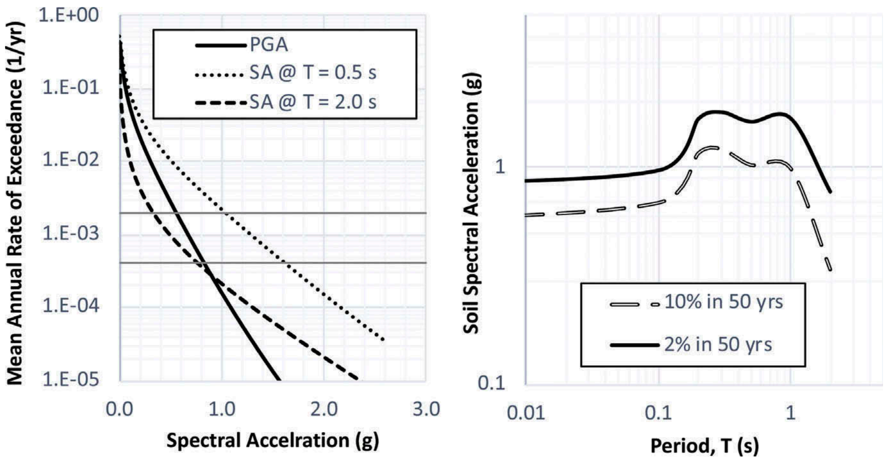

Figure 5. (a) Soil hazard curves at three spectral periods of PGA, 0.5 and 2 s; (b) Soil UHS at 10% probability of exceedance in 50 years and (b) 2% probability of exceedance in 50 years.

intensity motions. When plotted as Sa_{soil} vs. Sa_{rock}, the curve bends over and at large Sa_{rock} becomes relatively flat. For Sa at T = 2.0 s, the AF first increases with Sa_{rock} before starting to decrease at Sa_{rock} greater than 0.5 g. The resulting Sa_{soil} vs. Sa_{rock} curve shows a concave up shape at small Sa_{rock} before bending over.

Following the convolution approach (Eq. 1 and 2), soil hazard curves were computed using the rock hazard curve and AF relationships for all seven periods obtained from the USGS Unified Hazard tool. The $\mu_{ln_{AF|x}}$ for each Sa_{rock} was taken from the developed AF relationships (Figure 4), and $\sigma_{ln_{AF|x}}$ was taken as 0.4. The site-specific soil hazard curves for PGA and T = 0.5 s and 2.0 s are presented in Figure 5, along with the resulting soil UHS for hazard levels of 10% and 2% probabilities of exceedance in 50 years (i.e. λ = 0.002 and 0.0004 1/yr).

3.2 *Selection of strain-compatible soil properties*

The soil surface UHS at hazard levels of 10% and 2% in 50 years are disaggregated with respect to the contributing rock motions and epsilon of the amplification factor at each period. Figure 6 depicts the disaggregated PGA_{rock} for PGA_{soil} = 0.56 g (10% in 50 years) and for PGA_{soil} = 0.83 g (2% in 50 years). For PGA_{soil} = 0.56 g, the median contributing PGA_{rock} is 0.5 g with an associated AF of 1.12 and epsilon of 0.74. For PGA_{soil} = 0.83 g, the median contributing PGA_{rock} is 0.7 g with an associated AF of 1.18 and epsilon of 1.39. In general, the median contributing rock spectral acceleration and corresponding epsilon increase as the hazard level increases from 10% in 50 years to 2% in 50 years.

For each period, the median Sa_{Rock} from the disaggregated distributions are used to create an input motion spectrum that is used in the computer program STRATA to perform equivalent linear site response analyses. The resulting disaggregated median Sa_{Rock} spectra are shown in Figure 7 along with the UHS_{rock} directly from the rock hazard curves. The disaggregated median Sa_{Rock} spectra are smaller than the UHS_{rock} at both hazard levels.

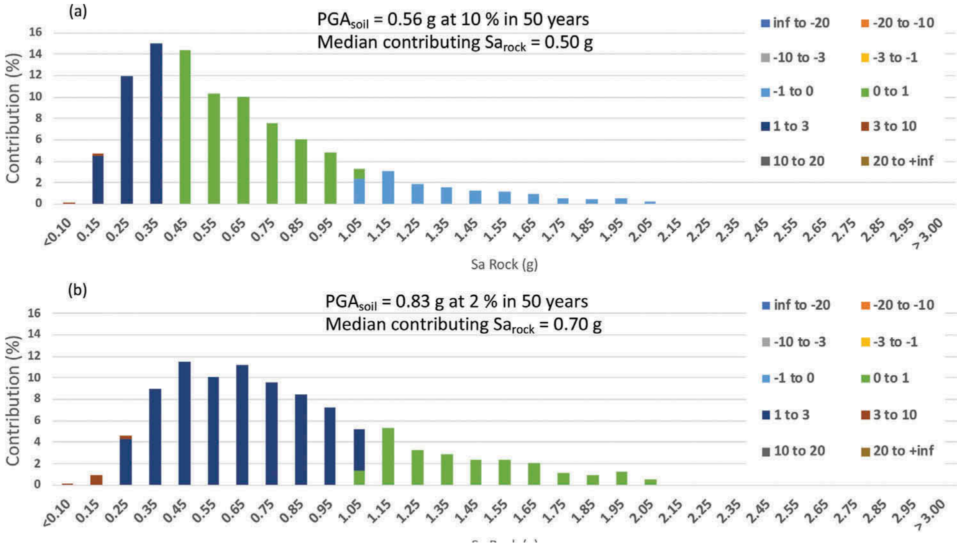

Figure 6. Disaggregation of PGA_{rock} for the PGA_{soil} associated with (a) 10% probability of exceedance in 50 years and (b) 2% probability of exceedance in 50 years.

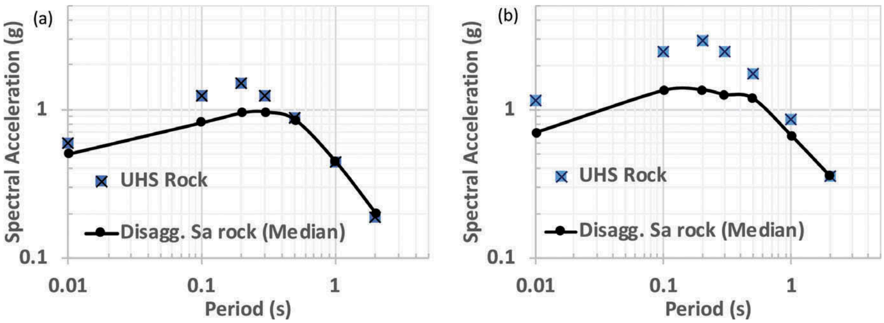

Figure 7. Disaggregated median Sa_{Rock} spectra for UHS_{soil} for (a) 10 % probability of exceedance in 50 years and (b) 2% probability of exceedance in 50 years. Also shown is UHS_{rock} directly from rock hazard curve.

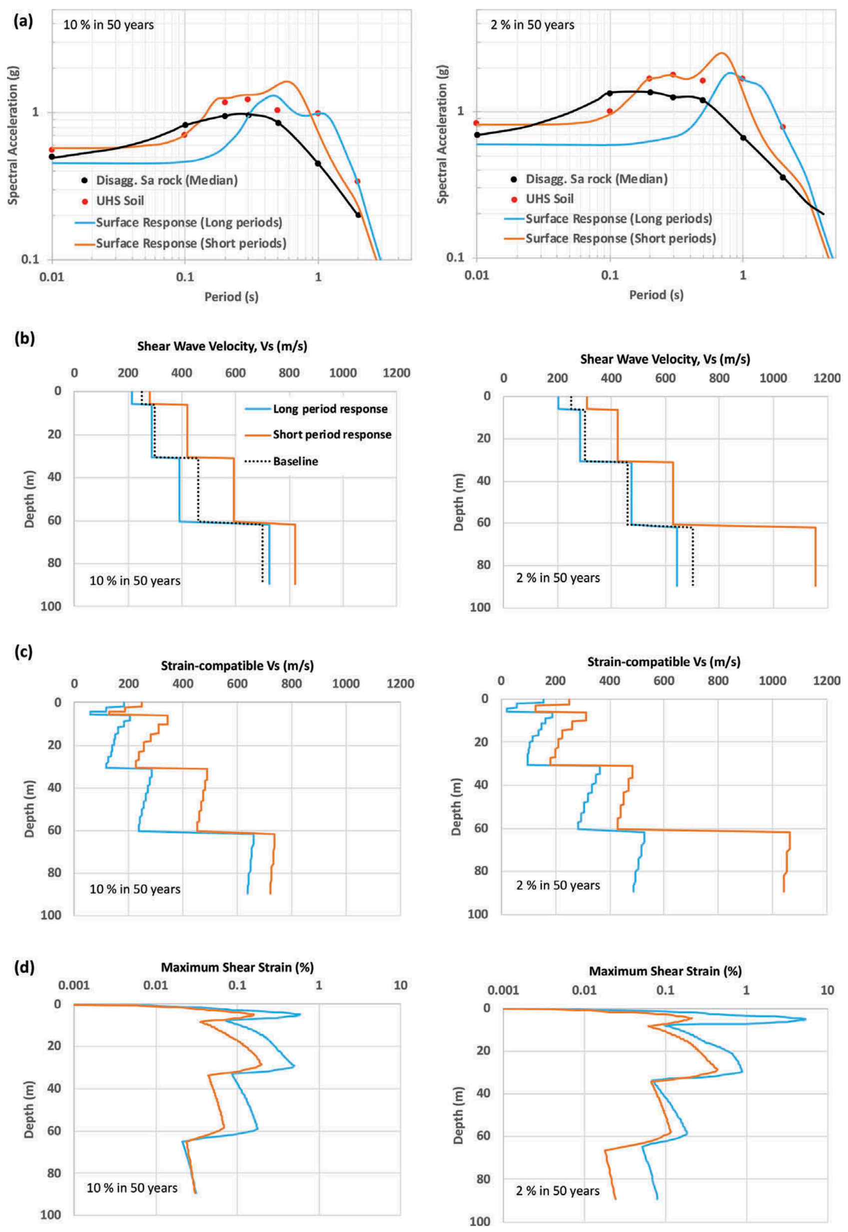

Figure 8. (a) Best-fit surface response spectra at short and long periods as compared with UHS_{soil} for 10% in 50 years and 2% in 50 years. (b) Shear wave velocity profiles, (c) strain-compatible shear wave velocity profiles, and (d) maximum shear strain profiles that provide the best fit to the UHS_{soil} at short and long periods for the two hazard levels.

The disaggregated median Sa_{Rock} spectra are used as input into site response analyses that simulate 500 realizations of the Vs profiles (with $\sigma_{\ln Vs} = 0.2$) to find the profile(s) that best match the UHS_{soil}. Multiple Vs profiles are required because the profile that provides the best fit at short periods often does not provide the best fit at long periods, and vice versa. For the example in this paper, two profiles are selected to fit the UHS_{soil}; one for short periods (i.e., less than about 0.5 s) and one for long periods (i.e., greater than 0.5 s).

The resulting surface spectra for the two hazard levels are shown in Figure 8 along with the associated Vs profiles and shear strain profiles. For both hazard levels, the profile that matches the UHS_{soil} at short periods is associated with larger values of Vs than the profile that matches at longer periods. As a result, the profile for short periods strains less. For the large shaking levels associated with the surface hazard level of 2% in 50 years, slightly different Vs profiles provide the best fit but the induced strain levels are larger. The strain-compatible Vs profiles in Figure 8, along with the associated damping profile, can then be used in SSI analyses.

4 CONCLUSIONS

Probabilistic seismic hazard analysis is generally used while designing important structures such as nuclear facilities in order to estimate design ground motions compatible to a particular hazard level at the soil surface. PSHA accounts for several important sources of uncertainty and variability associated with ground motion prediction. The convolution approach integrates site response analysis into PSHA and it is routinely used to consider the effects of local site conditions for nuclear projects. Furthermore, SSI analysis is mainly used to compute the seismic response of nuclear facilities, but often the strain-compatible soil properties for the SSI analyses need to be determined apriori and they must be consistent with the site response analyses that were used to develop the UHS and GMRS. This paper introduced a methodology that allows for selection of selecting strain-compatible properties for a UHS developed through the convolution approach. This approach disaggregates the surface soil hazard to develop a disaggregated rock spectrum that represents the rock motion levels that contribute most to the surface UHS. This input rock spectrum is used in site response analyses with the Vs varied via Monte Carlo simulation to identify the Vs profiles and induced strains that result in a surface response spectrum similar to the soil UHS. These strain-compatible properties can then be used for subsequent SSI analyses.

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