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EFFECTIVE KAPPA VALUES FOR NONLINEAR SITE EFFECTS. A CASE STUDY

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ABSTRACT

In current seismic hazard assessment practice, parameter κ_0 (kappa-0) plays a very important role in the derivation of site effects, in adaptation of ground motion prediction equations (GMPE) to a specific site or in the computation of site amplification factors with respect to motion at the selected bedrock horizon. Response spectra at the surface control points show a strong dependence on the selected κ_0 for frequencies greater than about 10 Hz. In practice, values of κ_0 for a particular ground column are obtained from correlations between κ_0 and V_{s30} values, judged to be valid for the region of interest. In low-seismicity regions, it is likely that such correlations are derived using motion records corresponding to small magnitude earthquakes, which produced a small energy dissipation in the ground. Therefore, it can happen that the κ_0 values for a particular site, obtained from such correlations, are underestimated for larger magnitude earthquakes, such as the ones contributing most to the seismic risk of a nuclear power plant.

An extended practice to derive site amplification factors is that κ_0 values are assigned to a ground column, and random vibration theory (RVT) is used to compute the motions at the specified control point from the motion at a deep bedrock. Amplification factors are then obtained as ratios between motion at the control point and the motion at the bedrock. This paper presents a case study in which nonlinear effects within the ground column were considered in order to obtain "effective" κ_0 values, which were then used to compute site amplification factors dependent on the severity of the shaking. For the magnitude-distance pairs relevant for the site seismic hazard, those effective κ_0 values turned to be significantly larger than the ones derived from small magnitude earthquake records. This led to a correction of the initial hazard curves, which had been derived without consideration of non-linear effects.

INTRODUCTION

General methods for estimating strong ground motion should incorporate source, path, and site effects. This is illustrated by the so-called "stochastic method" of generation of strong ground motions (Boore, 1983), which is the simplest physically reasonable representation of these effects. In the stochastic method, the Fourier amplitude spectrum of acceleration at a site is given by:

$$a(f) = E(M_0\, f)\; P(R, f)\; G(f) \tag{1}$$

Where f is frequency, M_0 is seismic moment and R is hypocentral distance. Factors E, P and G represent source, path and site contributions, respectively. The site factor G is separated into the contribution of site amplification A and site diminution D:

$$G(f) = A(f)\; D(f) \tag{2}$$

Usually, A is amplification from an 8 km depth, or where it is assumed that the impedance is similar to the impedance at the seismic source. Amplification results from the smaller stiffness of the upper layers as well as from resonance effects. On the other hand, the most popular form for the D factor is the one empirically introduced by Anderson and Hough (1984):

$$D(f) = e^{-\pi \kappa_0 f} \tag{3}$$

Where the parameter κ_0 (kappa-0) represents the attenuation of seismic waves within the geological structure beneath the site. Site diminution factor D can be a function of the amplitude of the shaking but, typically, in the stochastic method, non-linear ground response effects are not considered. Non-linear effects are left to an additional site-response calculation (Boore, 2003).

Parameter κ_0 was introduced as a simple way to match the results of the stochastic method with actual earthquake records (Anderson and Hough, 1984). The parameter may be the result of a number of dissipative phenomena. However, consistent with the widespread engineering assumption of 1D vertically propagating seismic waves when studying site response, a physical interpretation of the parameter κ_0 in more geotechnical terms is given by (modified from Hough and Anderson, 1988):

$$\kappa_0 = \int_0^H \frac{2\,\xi(z)}{V_s(z)}\, dz \tag{4}$$

Where H is the depth of the ground column, V_s is the shear wave velocity, and ξ is the hysteretic damping ratio along the column. Consequently, following this interpretation, the parameter κ_0 depends on the hysteretic damping ratio along the ground column. For soft-medium rocks and soils, damping ratio depends on the deformation induced by the earthquake motion and, consequently, κ_0 is dependent on the level of shaking. Note that the integral in Eq. 4 extends along the whole depth H of the ground column, but the main contribution will normally come from the softer surficial layers.

In current seismic hazard assessment practice, κ_0 plays a relevant role in the consideration of site effects (Bard et al, 2020). Parameter κ_0 is used in adaptation of ground motion prediction equations (GMPE) to a target site (i.e. the so-called "V_s-kappa correction"), or in the computation of site-specific amplification factors with respect to motion at the selected bedrock horizon (Appendix B, EPRI, 2013). A common method to derive site amplification factors is that κ_0 values are assigned to a ground column, and random vibration theory (RVT) is used to compute the motions at the specified control point from the motion at a deep bedrock (e.g. $Vs > 2500$ m/s). If linear response behavior is assumed in the ground column, a transfer function can be derived between the Fourier spectrum of the motion at the bedrock and the Fourier spectrum of motion at the control point, using just the κ_0 value and the shear wave velocity and density profiles. This saves a significant effort, given the large number of computations that usually need to be performed to address uncertainty in the ground profiles. For each spectral frequency, site-specific amplification factors are obtained, for a series of magnitude-distance pairs, as ratios between response spectrum at the control point and the response spectrum at the bedrock (Fig. 1). Stochastic method simulation tools such as SMSIM (Boore, 2002) are used for this purpose.

Values of κ_0 for a particular ground column are commonly obtained from correlations between κ_0 and V_{s30} values, judged to be valid for the region of interest. In low-seismicity regions, it is likely that the κ_0 value for a particular location (i.e. with a particular V_{s30}) is obtained using correlations derived from motion records corresponding to small magnitude earthquakes, which produced a small energy dissipation in the ground. Therefore, it can happen that the κ_0 values derived from such correlations are underestimated for larger magnitude earthquakes.

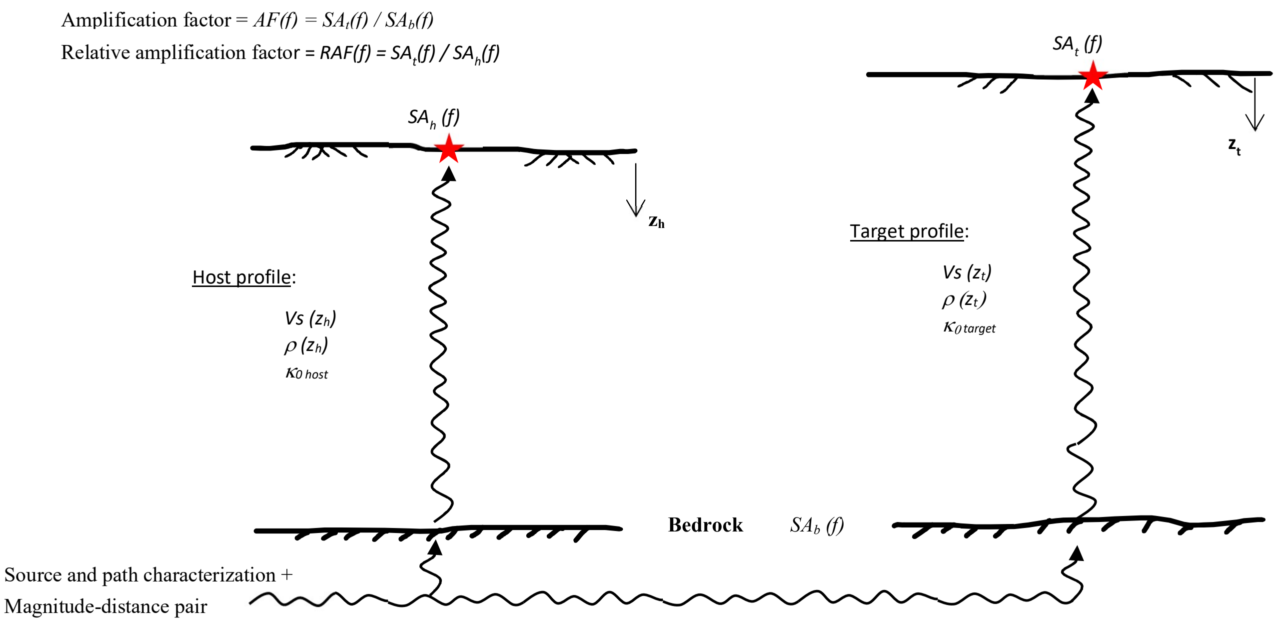

Figure 1. Site amplification factors assuming linear response behavior in the ground: *Vs*, ρ and κ_0 are assumed to be the same for every magnitude-distance pair considered in the assessment of site effects

This paper presents a case study in which non-linear effects in the response of the ground column were considered, in order to obtain "effective" κ_0 parameters dependent on the severity of the earthquake. Those effective parameters were used to feed the process of computing site amplification factors (Fig. 1). The paper focuses on the root process, without elaborating on important aspects, such as the randomization of the ground column or the consideration of uncertainties introduced by the soil degradation curves (*G/Gma*x, hysteretic damping).

SAMPLE SITE

Fig. 2 shows the upper part of shear wave velocity profiles used to consider the epistemic uncertainty in the sample site. Note that minimum shear wave velocity is in the order of 1000 m/s, very quickly increasing with depth to values around 2000 m/s at about 300 m depth. V_{s30} values are between 1033 and 1740 m/s, with an average of 1307 m/s. Hence, at first sight, one would expect a negligible influence of non-linear effects in the ground response, and a full linear response analysis would be used to assess site effects.

Using V_{s30} - κ_0 correlations considered applicable to the region of the site, a range of κ_0 values can be obtained for each profile, accounting for the epistemic uncertainty about these correlations. Table 1 provides a sample of the selected κ_0 values, five for each V_{s30} value, corresponding to five different branches in the logic tree. Central values of κ_0 are between 0.0141 and 0.0218 s. Note the large difference between the smallest and the largest values within each range. This is indicative of the level of uncertainty that is faced by the seismic hazard assessment teams (Bard et al, 2020).

Shear velocity and density profiles, together with a value of κ_0, are the only input necessary for introducing site response in the stochastic ground motion simulation using a tool such as the SMSIM package (Boore, 2002). For a given seismic source and path attenuation characterization, response spectra for different profiles can be obtained and amplification factors can be derived for a number of magnitude-distance pairs covering the range of seismic sources of interest (Fig. 1).

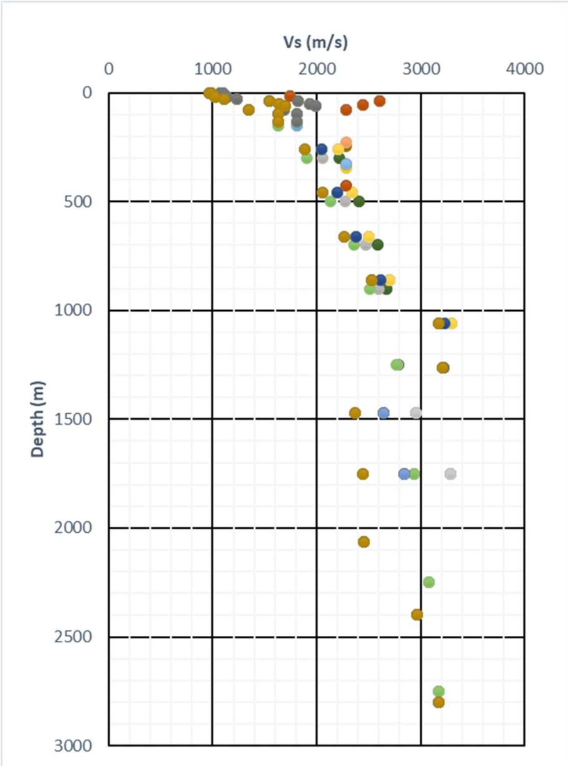

Figure 2. Sample site - Shear wave velocity profiles to capture epistemic uncertainty (36 profiles).

Table 1: V_{s30} velocities and range of κ_0 to capture epistemic uncertainty in V_{s30} - κ_0 *correlation*.

Profile ID	V_{s30} (m/s)	kappa1 (s)	kappa2 (s)	kappa3 (s)	kappa4 (s)	kappa5 (s)
…	…	…	…	…	…	…
14	1147.9	0.0056	0.0115	0.0200	0.0263	0.0357
15	1033.1	0.0061	0.0125	0.0218	0.0288	0.0390
16	1740.0	0.0040	0.0081	0.0141	0.0186	0.0253
…	…	…	…	…	…	…
52	1740.0	0.0040	0.0081	0.0141	0.0186	0.0253
53	1147.9	0.0056	0.0115	0.0200	0.0263	0.0357
54	1033.1	0.0061	0.0125	0.0218	0.0288	0.0390

When the potential influence of non-linear ground behavior on the amplification factors needs to be assessed, *G/Gmax* and hysteretic damping as a function of shear strain in the ground are also required. This allows application of the so-called “equivalent linear” response analysis method. In this work, *G/Gmax* and hysteretic damping curves have been taken from the SPID report, for firm rock (Appendix B, EPRI, 2013). The selected *G/Gmax* curves can be seen in Fig. 3. According to the SPID report, hysteretic damping should be limited to 15%.

METHODOLOGY

The methodology is based on the idea that the κ_0 parameter to be assigned to a ground profile depends not

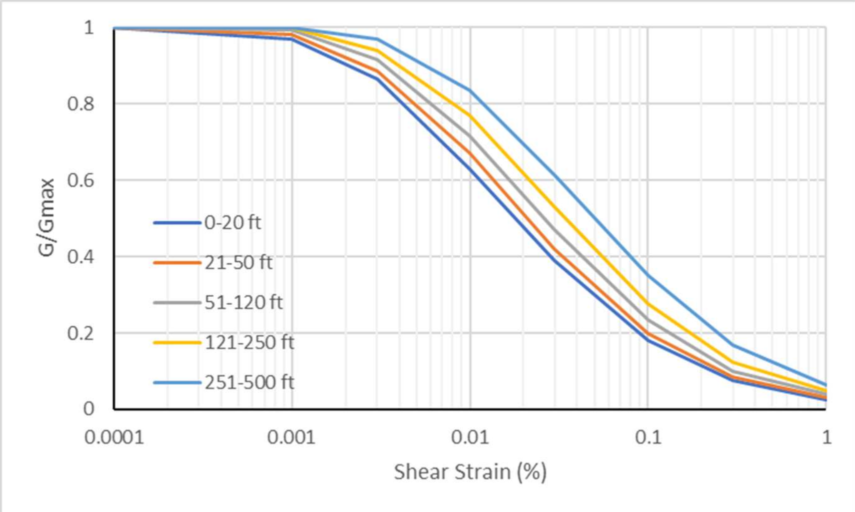

Figure 3. Generic *G/Gmax* curves for firm rock at different depths (EPRI 1025287, 2013).

only on the V_{s30}, but also on the severity of the shaking. Thus, stronger motions would lead to larger effective κ_0 parameters, since the shaking will result in more energy dissipation within the profile, especially in the more surficial layers.

To implement this idea with a minimum perturbation in the process of computing amplification factors using linear tools such as SMSIM (Boore, 2002), an effective κ_0 is derived for each magnitude-distance pair, which would substitute the κ_0 parameter derived using only V_{s30} - κ_0 correlations. The process is schematically depicted in Fig. 4, and it consists of the following steps:

1. A ground column is defined based on its shear wave velocity and density profiles. The column could be, for instance, one realization of a randomization process of a base profile.
2. Parameter V_{s30} is computed and an initial κ_0 parameter is obtained based on the applicable V_{s30} - κ_0 correlation. In low-to-moderate seismicity regions, the correlation will likely have been derived from small magnitude earthquake records.
3. Initial κ_0 is distributed as hysteretic damping ratio along the materials within the column. There are different ways to perform the distribution (see below). The only condition is that the integral of the distributed damping (Eq. 4) results in the given κ_0 parameter.
4. The column of ground is subjected to the ground motion corresponding to a given magnitude-distance pair. Amplification factors may be dependent on the strength of the shaking. Therefore, when computing amplification factors, a range of magnitude-distance pairs needs to be used, in order to cover the required range of spectral accelerations. Usually, magnitude is kept fixed, and distance is varied.
5. Degradation of shear modulus G and changes in hysteretic damping at each layer are obtained using the equivalent linear approach. To avoid generating time-histories of the motion, a program based on RVT will preferably be used. An example is the code STRATA and its Python library (Kottke and Rathje, 2009).
6. Uncertainty in the *G/Gmax* and hysteretic damping curves is considered by means of a Montecarlo approach, using for instance the dispersion parameters (ln-sigma) given in the SPID report (Appendix B, EPRI, 2013). As a result, degraded *Vs* profiles and hysteretic damping profiles are obtained.

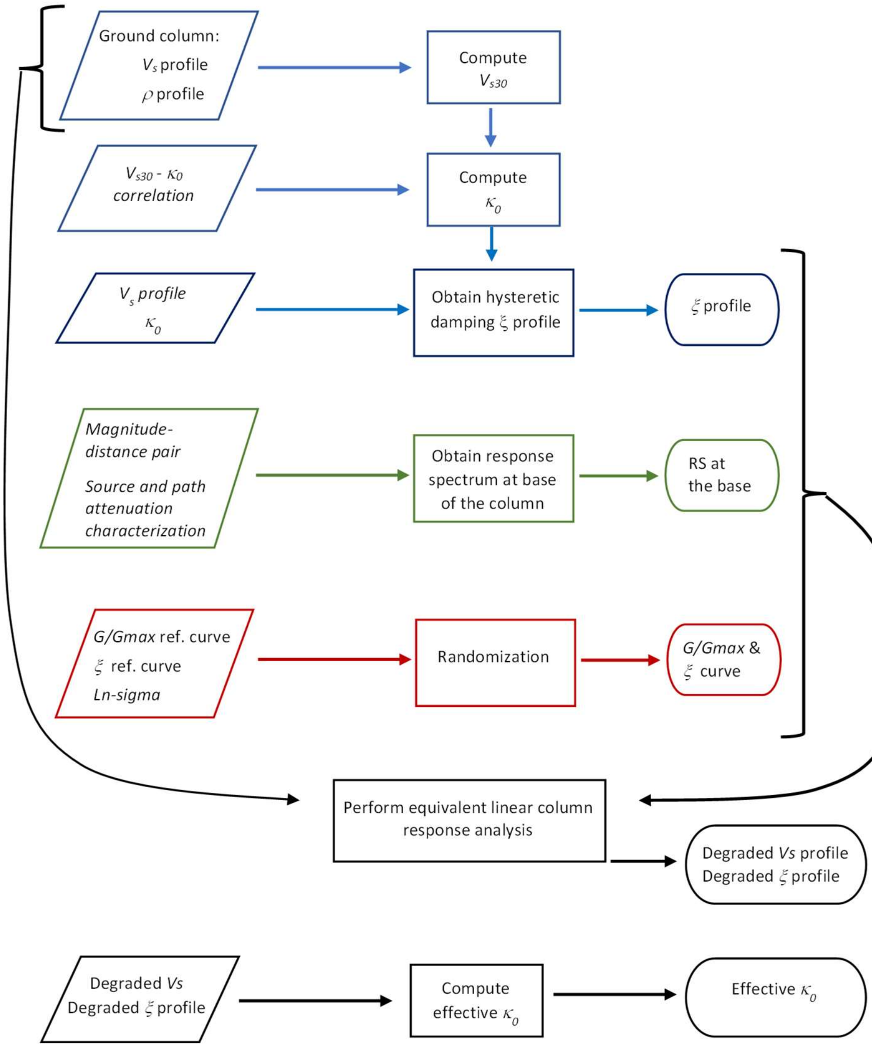

Figure 4. Schematic workflow for computing an "effective" κ_0 parameter.

7. The resulting degraded *Vs* profiles and hysteretic damping profiles are used to obtain the effective κ_0 parameter in each case, by means of the integral in Eq. 4.
8. The degraded *Vs* profiles and the computed effective κ_0 parameters are used to compute the amplification factors of the ground column for the given magnitude-distance pair using the regular approach (e.g. with SMSIM). The density profile is assumed not to change.
9. Statistics of amplification factors (median, ln-sigma) are developed for the given ground column, to be used in the overall consideration of uncertainty in the site effects.

For a given *Vs* profile and κ_0 parameter, there are different ways to build a hysteretic damping profile. The following procedure may be used. Sometimes, the so-called "quality factor" Q is used to characterize the dissipative properties of a geologic material, but it should be remembered that hysteretic damping ratio ξ and quality factor Q are related by:

$$\xi = \frac{1}{2\,Q} \tag{5}$$

For deep layers (e.g. depth larger than 3000 m), a quality factor similar to the one assumed for the seismogenic rock is usually taken (e.g. Q = 2000). For shallower layers, the quality factor of the layer is assumed to be proportional to the Vs velocity in the layer. This condition, together with the condition that Eq. 4 should yield the given κ_0 parameter, determines a profile of Q values and, therefore, the profile of hysteretic damping ratio ξ.

Note that the process 1-9 above will result in effective κ_0 parameters equal to the initial κ_0 parameter if shear strains derived from the magnitude-distance pair causes no degradation in ground stiffness.

RESULTS

Application of the methodology to a single reference profile is illustrated in the following paragraphs. Seismic hazard of the sample site is dominated by near field earthquakes. A magnitude 6.25 earthquake, at 5 km distance is selected for illustration purposes (Fig. 5). Source and path attenuation parameters were provided by the team assessing the seismic hazard at the site.

Reference profile reaches a depth of 10 km. In the reference profile (Profile ID 15 in Table 1), V_{s30} is 1033 m/s, which corresponds a central κ_0 parameter equal to 0.0218 s. Reference profile was randomized using the method by Toro (1996). The red dotted lines in Fig. 6 show the Vs and hysteretic damping profiles corresponding to one of the realizations of the randomization.

The initial profile shown in Fig. 6 (red dotted lines) was subjected to the given seismic motion for 50 random *G/Gmax* and hysteretic damping degradation curves, centered in the reference curves shown in Fig. 3. Thirty of the degraded profiles, after the equivalent linear computations, are shown in Fig. 6. If the κ_0 parameter is computed for the 50 resulting degraded profiles (Eq. 4), the resulting median κ_0 parameter is 0.0286 s. This is to be compared with 0.0218 s, originally assigned to the reference profile via the central correlation of Table 1.

Reduction in the surface response spectrum obtained for the specified magnitude-distance pair, with respect to the one obtained using the full linear, no-degradation, response of the column is shown in Fig. 7 (left). The effects of non-linearity are seen for frequencies beyond 8 Hz, there is a small displacement of the spectral shape to lower frequencies and spectral ordinates are reduced between 30 and 10%.

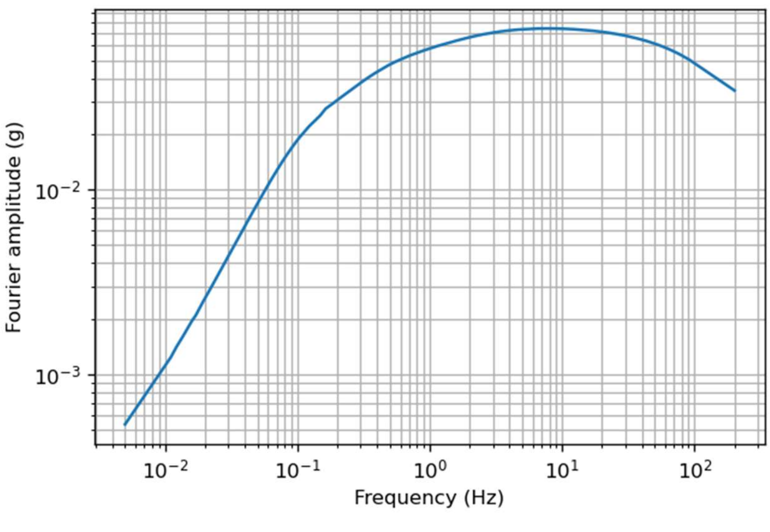

Figure 5. Fourier amplitude spectrum at the base of the ground column (M 6.25, R 5 km).

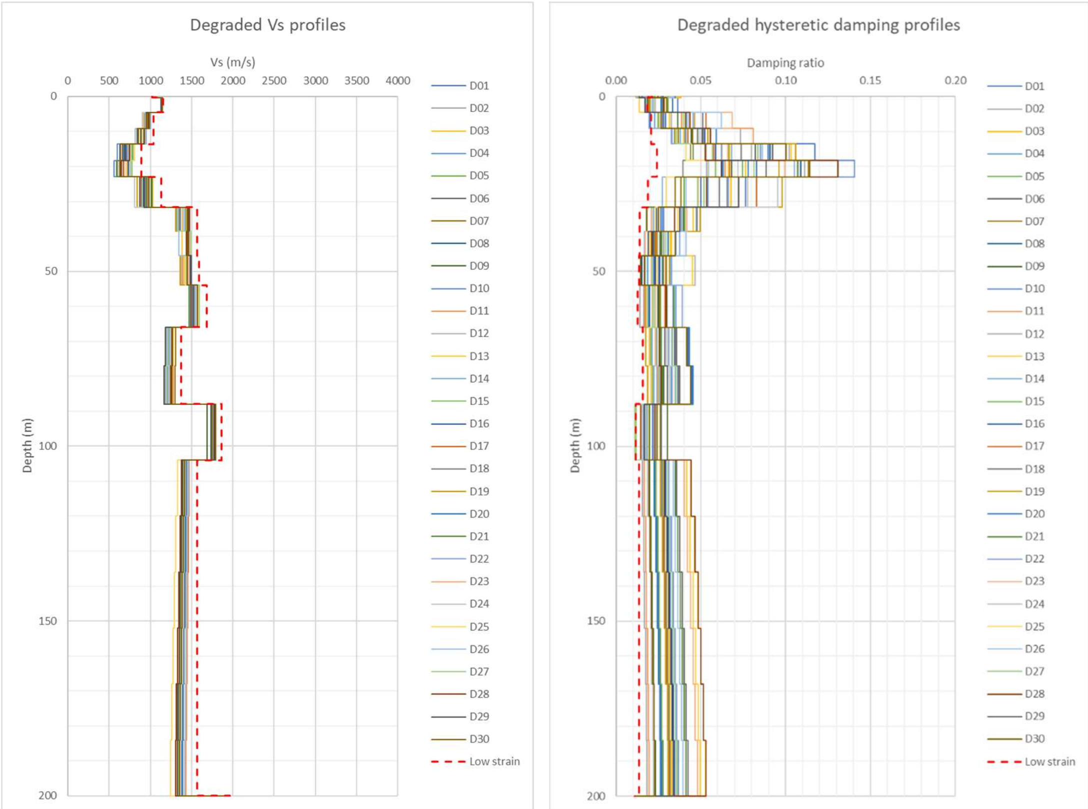

Figure 6. Upper and *Vs* and hysteretic damping profiles. Red dotted lines indicate undisturbed (low strain) profiles

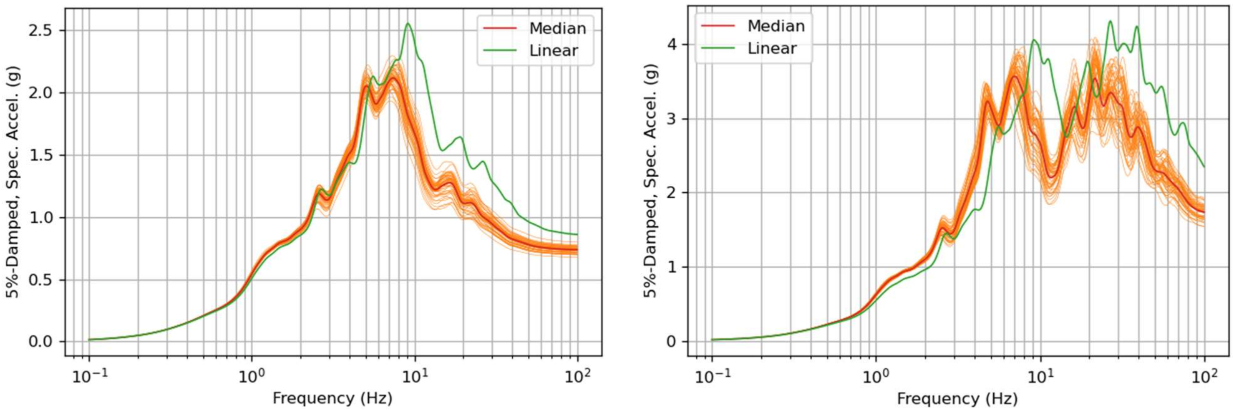

Figure 7. Comparison of response spectra at surface. Left: central V_{s30}- κ_0 correlation of Table 1 in the reference profile (κ_0 = 0.0218 s). Right: lowest V_{s30}- κ_0 correlation (κ_0 = 0.0061 s).

In the sample site, relative amplification factors between the full linear approach (green line in Fig.7) and the equivalent linear approach (red line in Fig.7) were used to transform the hazard curves based on the full linear approach to a set of hazard curves that considers non-linear effects. For this purpose, the Approach 3 of NUREG/CR-6728 (NRC, 2001), as described in Appendix B of the SPID report (EPRI, 2013), was used. Significant reductions of the mean uniform hazard response spectra at the control points

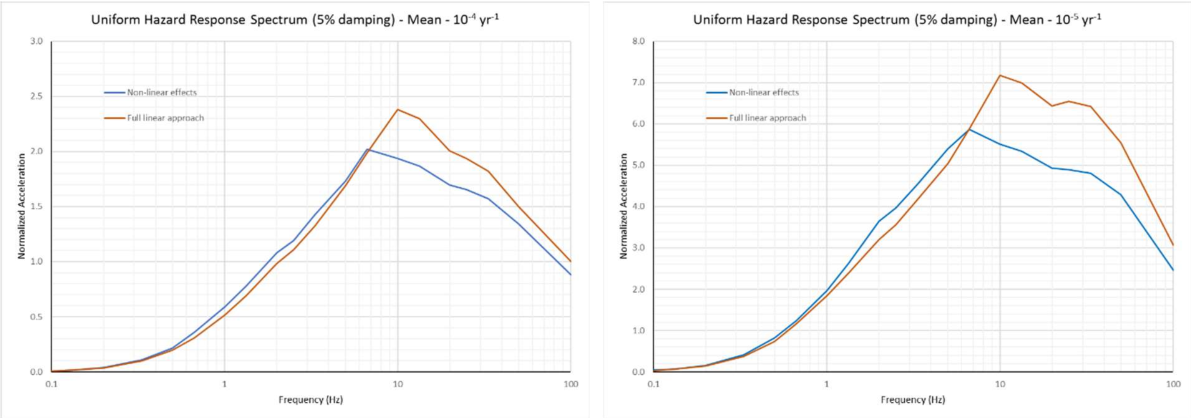

Figure 8. Comparison of mean UHS for 10^{-4} and 10^{-5} yr^{-1} annual frequency of exceedance in the sample site, with and without consideration of non-linear effects in the κ_0 parameter

were obtained for the levels of earthquake corresponding to annual frequencies of exceedance of 10^{-4} yr^{-1} and smaller (Fig. 8).

The effect of selecting too small a κ_0 parameter is illustrated by Fig. 7 (right), which shows the result of the same exercise described in the previous paragraphs, but with an initial κ_0 parameter derived from the lowest V_{s30}-κ_0 correlation (0.0061 s, Table 1). The lower κ_0 parameter results in significant differences in the spectral shape within the high frequency band, with the appearance of a peak in the response spectrum at about 25 Hz. This effect is considered to be counterintuitive by some seismologists (Nuclear Energy Agency, 2021; Bard et al, 2020). Even though the consideration of the non-linear response at the ground column reduces the magnitude of the high-frequency peak by about 20%, the peak does not disappear. The original hysteretic damping assigned to the ground column was very low.

CONCLUSION

When assessing site effects in current seismic hazard assessment practice, lack of site-specific data may result in selecting κ_0 parameters based on correlations with V_{s30} derived from records corresponding to earthquakes producing small amplitude motion at the recording stations. This is a conservative practice, which may result in overestimation of UHS spectra at spectral frequencies larger than about 10 Hz, for the annual frequencies of exceedance of interest in the definition of design basis earthquakes or seismic risk assessment (i.e. 10^{-4} to 10^{-6} yr^{-1}).

In this paper, a methodology has been presented to derive a correction to the κ_0 parameter selected from correlations, based on the idea that the κ_0 parameter to be assigned to a ground profile depends not only on the V_{s30}, but also on the severity of the shaking. Thus, stronger motions would lead to larger effective κ_0 parameters, since the shaking will result in more energy dissipation within the profile, especially in the more surficial layers. The proposed correction uses equivalent linear ground response analysis to derive a degraded shear wave velocity profile and a hysteretic damping profile, compatible with the different levels of shaking required to assess the seismic hazard. From these profiles, corrected κ_0 parameters are derived, to be used within the simpler framework in which only linear effects are considered in the ground (Boore, 2002). The effects of this correction may be significant at high spectral frequencies.

Generally, as in the sample site used in this paper, the uncertainty in the κ_0 parameter for a given site is very significant, especially if no site-specific motion records are available (Nuclear Energy Agency, 2021). In seismic hazard assessments, uncertainty in the κ_0 parameter is taken into account by means of logic trees. The weights assigned to each κ_0 branch by the hazard assessment team may result in final uniform hazard spectra (UHS) with a significant high frequency content. The discussion about if this high frequency content is realistic or not, for the levels of earthquake relevant for the assessment of seismic risk in a nuclear facility, is out of the scope of this paper. However, in the current practice, sensitivity of the computed site effects to the selection of the κ_0 parameter underscores the importance of reducing epistemic uncertainties to the maximum extent feasible. Installation of appropriate recording instruments would be a step in this direction (Nuclear Energy Agency, 2021).

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