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Comparative Analysis and Evaluation of Uncertainties in Probabilistic Site Response Assessment

E. Faccioli[1], R. Paolucci[2], M. Vanini[3]

ABSTRACT

Paper addresses Probabilistic Seismic Hazard Assessment (PSHA) by a single-station sigma approach, with the following main objectives: 1. To compare at soil sites with instrumental recordings ground motion hazard estimates obtained with: (a) a data-based, one-step method using estimates of site factors ($\delta S2S$) and single-site sigma ($\sigma_{ss,s}$), and (b) a standard two-step method including exposed bedrock hazard estimation and 1D site response calculations. 2. To account for the main epistemic uncertainties involved through: on one hand, a logic tree (approach (a)) and, on the other hand, the quantification of the variability generated by *V*s profile, non linear response calculations, and input selection (approach (b)). 3. To show with applications at instrumented sites (in the Po Plain, Northern Italy) how the two approaches perform in site specific PSHA, for two different return periods (475 and 2475 yr).

Introduction

Paths for possible reduction of uncertainties in ground motion predictions by empirical attenuation models have been recently opened by segregating the prediction residuals (difference between the observed and the predicted ground motion parameter) into different types, see Rodríguez-Marek et al. (2014). Ground Motion Prediction Equations (GMPEs) for estimating response spectral ordinates, derived by regressing data from many sites and many earthquakes, produce an "ergodic" prediction when applied to a single site, because they replace the ground motion variability generated by different events at the site by the variability across many sites. On the other hand, for an individual site with strong motion records in sufficient number, the error of prediction from the GMPE is likely overestimated; however, it can be made site-dependent by the so-called "single-site sigma" approach, which introduces (non-ergodic) measures of variability derived from residual analysis. We refer to Rodriguez-Marek et al. (2011) for details, and recall that the total prediction residual can be partitioned into a between-event residual (average offset between predictions and observations for all stations recording a single earthquake), independent of the recording station, and a station dependent within-event residual. This can in turn be seen as the sum of a site factor, $\delta S2S$, and of a term, δWS_{es}, left after correcting the prediction for site and event, denoted site- and event-corrected residual. $\delta S2S$ is of special significance for the quantification of the local site effect, as it measures the systematic deviation of the observed site amplification from the median amplification predicted by the GMPE. On the other hand, δWS_{es} describes the record-to-record variability of the response at site

[1]Ezio Faccioli, retired Full Professor at Politecnico di Milano, Italy, ezio.faccioli@polimi.it
[2]Roberto Paolucci, Professor of Earthquake Engineering, Politecnico di Milano, Italy, roberto.paolucci@polimi.it
[3]Manuela Vanini, Engineering Consultant, Bergamo, Italy, mm.vanini@gmail.com

s for earthquake *e*.
The standard deviations of the $\delta S2S$ and δWS_{es} residuals are denoted as ϕ_{S2S} and ϕ_{SS}, respectively, while that of the between-event residual is denoted as τ. The standard deviation ϕ_{SS}, known as “single-station sigma”, is remarkably stable across different datasets and generally smaller than the within-event prediction error of a GMPE. A “partially non-ergodic” approach explicitly considers the site factor $\delta S2S$, which can be independently calculated, its epistemic uncertainty ϕ_{S2S}, and the epistemic uncertainty ϕ_{SS}. Such an approach combines ϕ_{SS} and τ into a “total single-station sigma” (σ_{ss}) (Rodriguez-Marek et al. 2014).

We illustrate first how the single-station sigma concept was applied in the PSHA of instrumented soil sites on the deep sediments of the Po Plain, Northern Italy, a moderate seismicity region shaken by strong earthquakes in 2012. Secondly, to introduce site effects in the PSHA, we apply both a two-step hybrid approach (*HyS*) and a site-specific fully probabilistic approach (*FpS*). *HyS* modifies the results of PSHA on exposed bedrock using 1D wave propagation analyses. On the other hand, *FpS* is a one-step (partially ergodic) approach, which introduces the site term $\delta S2S$ and the single-station sigma directly into the PSHA. We discuss the uncertainties affecting the two methods, and quantify for applications the different epistemic contributions, in particular- in *HyS* - those related to the V_s profile, to the linear vs. non-linear soil models, and to the seismic input of 1D propagation analyses.

Region, sites, source model and GMPE of analysis

The densely populated, sedimentary Po river Plain of Northern Italy was chosen as a study area. Figure 1 shows as salient features the fault rupture areas of the May 20 (M_w 6.1) and May 29 (M_w 6.0) 2012, Emilia mainshocks (Pezzo et al. 2013), the accelerograph stations of the

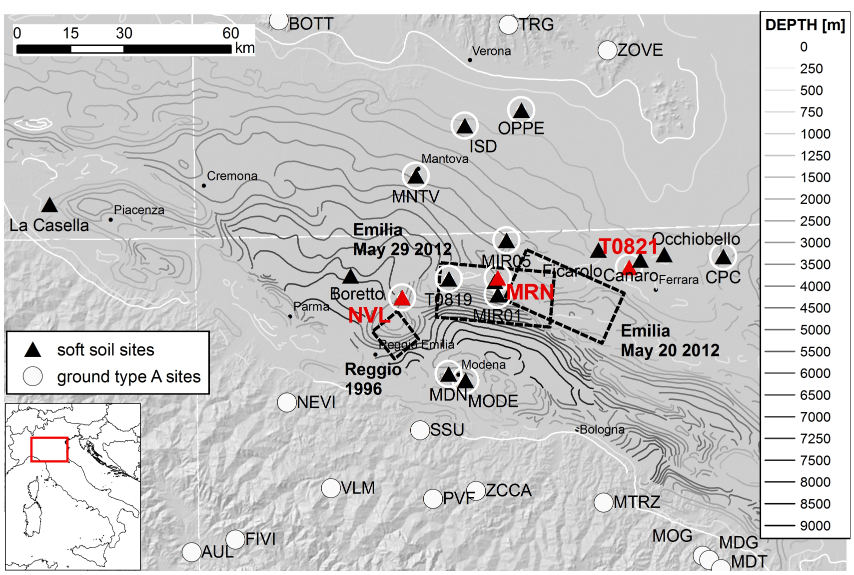

Figure 1. DEM of Po Plain area with sites of interest, showing also depth contours of the base of Pliocene (from Bigi et al., 1992). Rupture area projections of the Reggio 1996 and the two Emilia 2012 mainshocks are also displayed as black rectangles. S

permanent and temporary RAN (http://itaca.mi.ingv.it/ItacaNet) and INGV (http://ismd.mi.ingv.it/ismd.php)
Italian networks, and the depth contours of bedrock proper. Some stations, like T0821, lie above the top of buried ridges. Stations MRN (Mirandola), T0821 (Casaglia) and NVL (Novellara), main representative sites for our analyses, display in the upper 200 m by the types of *Vs* profiles shown in Figure 2.

Earthquake source models for the PSHA are found in Faccioli (2013); both area source and gridded seismicity representations were used. The point sources for the latter were taken from the poissonian HAZGRID model (Akinci, 2010), in a version including the 2012 events.
For attenuation of response spectral accelerations we used the regional models of Bindi et al. (2011), herein ITA10, and its updated version ITA13 (based on a Northern Italy dataset, including the 2012 Emilia events), by Pacor et al. (2013).

SH assessment via a one-step approach (*FpS approach*)

To apply the one-step PSHA approach to a site *s*, the median (logarithmic) spectral acceleration $S_a(T)$ predicted via GMPE, denoted as $\mu_{GMPE\ Sa(T)}$, is modified by the site term $\delta S2S$ (if $\neq 0$). Moreover, to express the aleatory variability of the prediction the event- and site-corrected single-station sigma $\phi_{ss,s}$ and the interevent variability τ, are combined into the total single-station sigma $\sigma_{ss,s} = \sqrt{\phi_{ss,s}^2 + \tau^2}$. The standard deviation of $\delta S2S$, ϕ_{S2S}, was not introduced in the $\sigma_{ss,s}$ computation, to avoid double counting; the epistemic variability of $\delta S2S$ is reckoned with independently, as explained in the sequel. Thus, the median $S_a(T)$ prediction takes the form

$$\mu_{corr\ Sa(T)} = \mu_{GMPE\ Sa(T)} \cdot 10^{\ \delta S2S(T)}\ . \qquad (1)$$

Next, data from a regional subset of 12 accelerometer stations recording at least 10 events, representative for deep sediments (see Figure 2), are used to estimate ϕ_{S2S} and $\phi_{ss,s}$ at the MRN, NVL, and T0821 study sites; the regional subset was shown to be representative of the whole Po

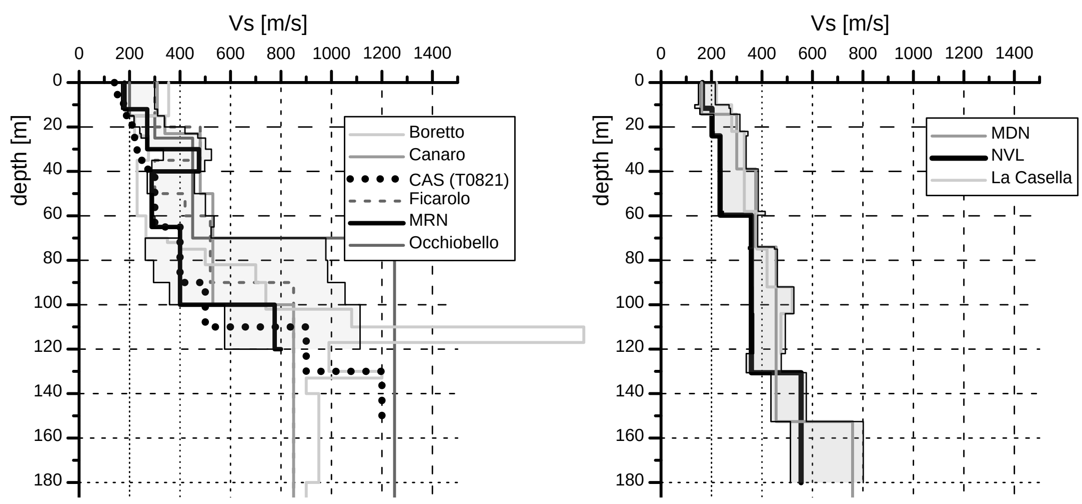

Figure 2 – Representative types of *Vs* profiles in Po Plain: (*left*) with strong impedance contrast at 80-to-120 m depth, (*right*) without strong contrast in the upper 200 m. (Faccioli et al. 2015).

Plain dataset (Faccioli 2013). $\phi_{ss,s}$ for this subset ranges between 0.1 and 0.45 (in $\log_{10}$ scale), while $\delta S2S$ ranges between about - 0.4 and 0.3 (with the lower bound for the T0821 site).
The variability of the mean $\delta S2S$ was computed as $\sigma_{S2S\ epistemic} = \phi_{S2S} / \sqrt{N}$, where $\boldsymbol{\phi_{S2S}}$ is the std. dev. of the 12-site sample, and N is the number of records available at the site considered; this variability is significantly less than that carried by $\phi_{ss,s}$ and quite limited, as shown by the $\delta S2S$ $\pm 1\sigma$ bands for MRN, NVL and T0821 in Figure 3 (left). Thus, the (epistemic) variability of $\delta S2S$ was neglected in the sequel.

Figure 3, on the right, shows the total single-site sigma, $\sigma_{ss,s}$, for the same sites, with upper ($\sigma^{u}_{ss,s}$) and lower ($\sigma^{l}_{ss,s}$) variability limits estimated through the Equations shown in Figure 4.

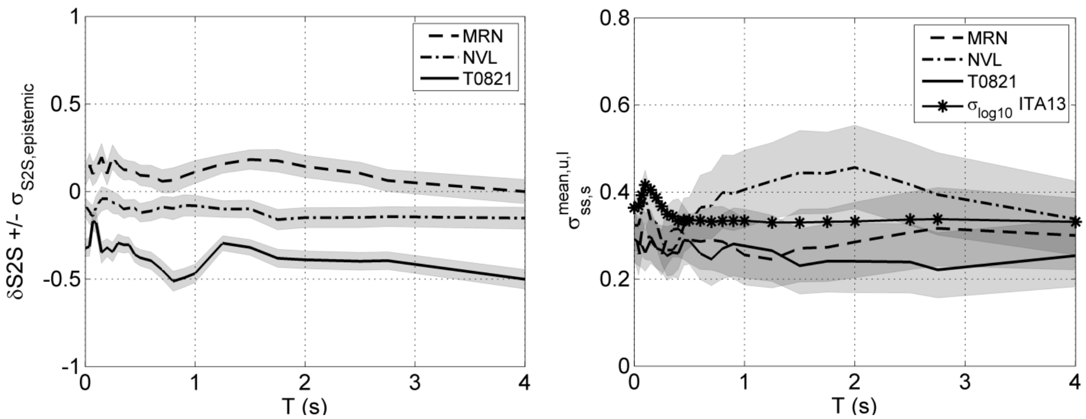

Figure 3 – (*left*) Site terms $\delta S2S$ for the three study sites with $\pm$ 1 $\sigma_{S2S\ epistemic}$ bands. (*right*) Total single-site sigma, $\sigma_{ss,s}$, for the same sites (solid lines), with shaded variability bands; the ITA13 GMPE standard deviation (σ_{log10} ITA13) is also shown.

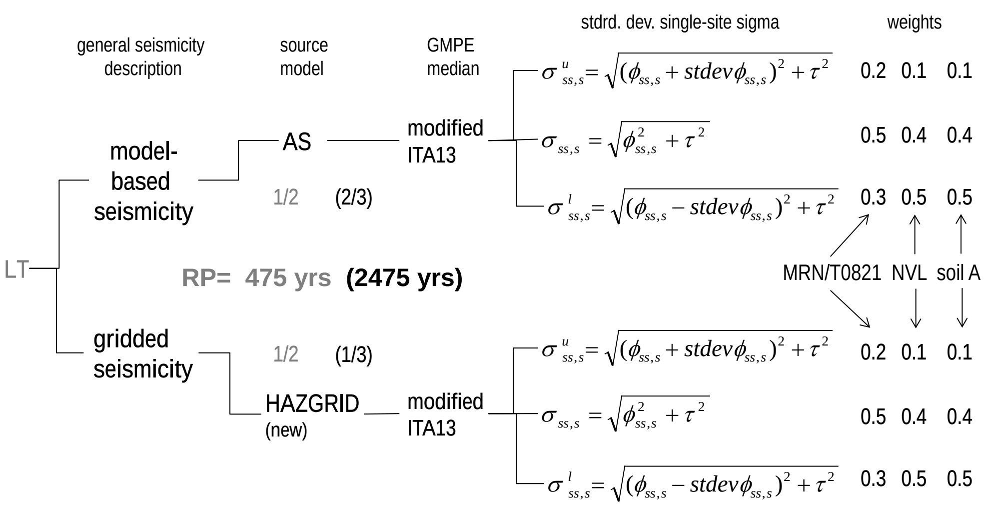

Figure 4 – Logic Tree for SH computations. “Modified ITA13” refers to Equation (1). Weights assigned to sigma level branches are shown on the right. Weights of the source model were changed from 475 to 2475 yrs, because the gridded seismicity model reflects the earthquake catalogue completeness period, not exceeding 500-1000 yrs for the higher magnitudes.

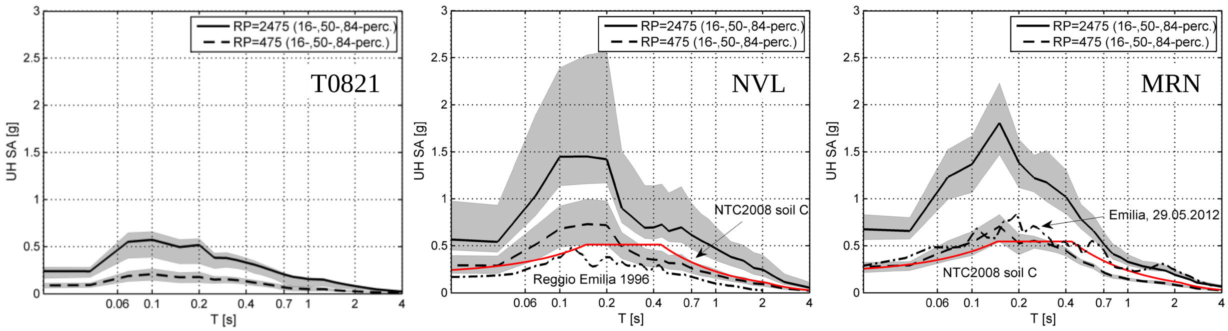

Figure 5 – Percentile Uniform Hazard Spectra calculated for the study sites with Logic Tree of Figure 4. Low UHS at T0821 depend on corresponding low $\delta S2S$ values (see Figure 3). Dash-dot curves for MRN and NVL are spectra from actual records (1996 and 2012), while red curves are Italian code spectra (NTC2008) for Eurocode 8 class C subsoil, 475 years return period.

Here, stdev($\phi_{ss,s}$) is the standard deviation of the event and site corrected single-station sigma across the 12-station subset (varying between 0.07 and 0.10), $\phi_{ss,s}$ the corresponding strd.dev. for the three study sites and τ is the inter-event variability component of ITA13.

The previous median and sigma estimations are combined in the simple Logic Tree for SH analysis

shown in Figure 4, where three branches handle the median and the variability of $\sigma_{ss,s}$. Assigned weights differ among stations, reflecting in part considerations on the $\phi_{ss,s}$ density distributions for the 12-station dataset made in Faccioli et al. (2015). PSHA calculations were performed with the CRISIS2008 code, in its latest version, 2014 (Ordaz 2013). The results are displayed in Figure 5, where spectra from records of significant recent earthquakes are also shown; at MRN these are mostly within the spread spanned by the Logic Tree branches for 475 yr return period, and the spectral shapes are reasonably similar. The percentile spread at NVL (caused by conservative hazard results of the gridded model) is larger compared to T0821 and MRN, consistent also with the high $\sigma_{ss,s}$ value shown in Figure 3 (right).
Hazard estimation on exposed bedrock, required in a two-stage PSHA, followed the same general logic previously described, with the essential difference that bedrock records were not available (as in most cases) for direct evaluation of $\phi_{ss,s}$ and $\delta S2S$. These parameters were assessed from data of accelerometer sites (with at least 5 records) on ground type A from the ITA13 dataset, lying within 120 km from the main 2012 Emilia events. The mean regional value of $\delta S2S$ on rock is close to zero, suggesting lack of bias from the dataset used, and the average σ_{ss} range resulted to be significantly lower than the GMPE standard deviation.
The resulting ground type A Uniform Hazard Spectra (not shown) exhibit lower amplitudes with respect to ground type C spectra of Figure 5, except for T0821, where the spectra for the two ground types are similar, due to the site specific features regarding $\delta S2S$ and σ_{ss} (Figure 3).

Site-specific probabilistic response spectra and associated uncertainty (*HyS*, two-step approach)

The *HyS* approach was applied only to the Mirandola (MRN) study site, in the following steps:

1. A) the computed mean UHS on exposed bedrock is taken as target spectrum for input motion selection at a specific return period.
   B) recorded accelerograms are selected, with response spectra approaching the target in a broadband sense, i.e., from 0 to 5 s period;
   C) the unscaled accelerograms are iteratively scaled in the frequency domain, with no phase change (preserving source-related features), until matching with target spectrum is achieved;
2. the input motions from previous steps are propagated in 1D site-specific analyses (from bedrock to surface), to explore epistemic uncertainties related to:
   - linear-elastic models of *Vs* profile;
   - non-linear soil models in terms of curves of normalized shear moduli and damping ratio versus cyclic shear strain amplitude (G/G_{max} - γ and ξ - γ);
   - non-linear modelling method: linear visco-elastic (LIN), equivalent-linear (EQL) and fully non-linear (NL).

The 1D propagation analyses were conducted using code DEEPSOIL, as discussed in detail in Faccioli et al. (2015). Note that the broadband compatibility with the target UHS ensures that any “double counting” problem of uncertainties is avoided.

We considered seven *Vs* profiles, measured with different techniques in the MRN urban area, and assumed that their differences represent the epistemic uncertainty in the model for 1D analyses (covariance of *Vs*, down to the engineering bedrock, being 10-15%). When broadband spectral matching is ensured the *Vs* profile uncertainty dominates, while the contribution of input motion variability is minor (there remains only a residual contribution caused by the intrinsic aleatory variability of different time histories, having the same spectral ordinates).
Four types of soil models curves representing G/G_{max} and damping ratio ξ vs γ were investigated: Darendeli; Ishibashi and Zhang; the mean standard curves of Seed and Idriss (Upper Limit) independent of confining pressure, and Resonant Column (RC) test results obtained on undisturbed samples of clay and sand extracted from different depths at a few Po

Table 1. Synthesis of results, with values of σ_{log10} as a function of period range and return period.

	$\sigma_{epistemic\_1D} = \sqrt{\sigma^2_{Vs} + \sigma^2_{\text{soil\_model}}}$	**T < 0.5 s**		**0.5 < T< 2 s**		**T > 2 s**	
	$\sigma_{TOT} = \max_T\left(\sqrt{\sigma^2_{epistemic\_1D} + \sigma^2_{PSHA\_rock}}; \sigma_{Kik-net}\right)$	475	2475	475	2475	475	2475
	$\sigma_{Kik\text{-}net}$	0.10		0.08		0.08	
	σ_{PSHA_rock} *(*)*	0.12	0.08	0.08	0.05	0.03	0.06
	σ_{input_1D}	Minor contribution to σ, provided that input motions are spectrally matched to the rock PSHA spectrum.					
LIN	$\sigma_{Vs} \equiv \sigma_{epistemic\_1D}$ *(all profiles and all input THs = 49 analyses)*	0.05	0.07	0.05	0.06	0.03	0.02
	$\sigma_{TOT\ LIN}$	0.13	0.11	0.09	0.08	0.08	0.08
NL	σ_{Vs} *(all profiles, 7x7 analyses)*	0.06	0.05	0.08	0.06	0.04	0.04
	σ_{soil_model} *(1 profile, 7x4 analyses)*	0.08	0.13	0.07	0.10	0.04	0.04
	$\sigma_{TOT\ NL}$	0.16	0.17	0.13	0.12	0.08	0.09

Results of EQL analyses are not shown, being comparable to NL ones
(*) computed as: $(\log_{10}(UHS_{84\text{-perc}})-\log_{10}(UHS_{16\text{-perc}}))/2$

Plain sites, several km from MRN (see Faccioli et al., 2015).

Results, computed in terms of response spectra at ground surface, show that differences in average spectral values of EQL vs NL approaches are limited (not shown). The variability due to the soil modelling assumptions, denoted as σ_{soil_model}, was found to exceed that due to the *Vs* profile (σ_{Vs}), and, as expected, to increase with increasing RP and to tend to vanish at long periods.

The different epistemic contributions to σ from all 1D analyses are summarized in Table 1, which includes as well the rules adopted to combine the different epistemic uncertainties into a single value ($\sigma_{epistemic\_1D}$) and both these uncertainties and the total (aleatory + epistemic) one carried by the PSHA on exposed bedrock (σ_{PSHA_rock}) into a single σ_{TOT} value, associated to the average site-specific response spectra for a given return period.

As pointed out previously, all contributions include the combined effect of variability of input motion, found to be negligible. The same Table shows the $\sigma_{Kik\text{-}net}$ values which were considered by Faccioli et al. (2015), to constrain results of numerical simulations, based on the observations of spectral amplification functions from several deep soil sites in the Kik-net.
As a summary, Figure 6 compares results from all the analyses performed in this study for the MRN site: PSHA one-step analyses (red lines), and two-step hybrid analyses (grey lines). The latter involve LIN 1D wave propagation calculations, performed with the 7 corrected acceleration records and the 7 available profiles, shown in dark grey lines, and the corresponding NL calculations, with the soil models discussed previously (light grey lines). The sigma values are the σ_{TOT} (LIN and NL) listed in Table 1, while the σ_{TOT} values for the one-step analysis range from about 0.09 at short periods to about 0.06 at long periods.

As previously discussed, the agreement between the one-step and the two-step approach is satisfactory only if the LIN assumption holds for soil response at MRN. As expected, this

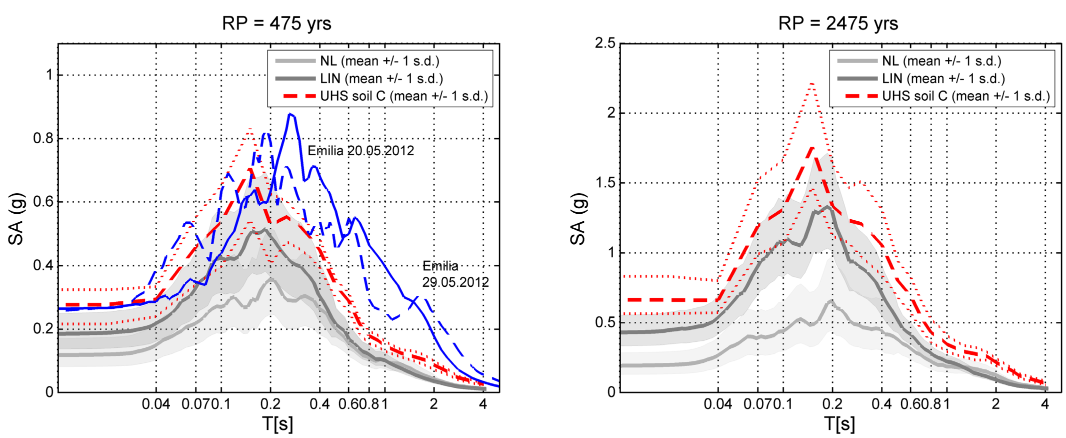

Figure 6 – Response spectra from linear (dark grey, shaded) and fully non-linear (light grey, shaded) analyses and UHS for class C soil (red lines) yielded by the one-step fully probabilistic approach (see Figure 5). Stdrd. dev. values of NL and LIN curves are the σ_{TOT} of Table 1. Response Spectra from MRN records are also shown.

assumption plays a growing role with increasing return period and, for RP = 2475 yrs, a sharp disagreement exists between the NL predicted spectrum and that obtained both by the LIN approach and the one-step UHS. The better agreement with the LIN two-step results may be related to the fact that in the one-step approach $\delta S2S$ is assumed to be a constant, which is the same as saying that it is linear. To remove the constant $\delta S2S$ assumption implies making this term dependent on a measure of the shaking intensity so that the correction factor $10^{\delta S2S}$ in (1) would account for such non-linearity; this is a task beyond the scope of our work.

Conclusions

A single-site sigma, PSHA (one-step, *FpS* approach) was first considered at three accelerometer sites lying on the deep sedimentary deposits of the Po Plain, using residual measure uncertainties estimated from an appropriate subset of the regional strong motion dataset. Although the study sites all belong to the same subsoil profile category, their site terms were found to sharply differ both at short and long periods, and significant differences were also observed in the site- and event-corrected residual variability leading to markedly different single-site sigmas in two cases out of three. The results suggest associations between response spectrum prediction residuals and local geological setting that may be difficult to interpret, due to likely 3D propagation effects at specific sites and, possibly, also to rupturing earthquake faults at close range.

The records from the damaging 2012 Emilia earthquake sequence ($4.0 \le M_w \le 6.0$) predominate in the regional dataset presently used and, moreover, many data of that sequence were recorded by temporary stations whose location was dictated by the epicenter locations, so that variability due to multi-pathing is underrepresented in our hazard estimates. However, the data and the residual parameters we used reflect well the influence of the potentially most hazardous sources for the analyzed sites. The (84-16) percentile spreads of the UHS spectra differ by up to nearly a factor of five at the three study sites, a warning on how sensitive the uncertainty estimates can be to the local geology and to the source factors.

A similar approach was followed to estimate single-site sigma UHS on exposed bedrock at the same locations, using regionally based estimates of site-term and site-and-event-corrected variability. The site term computed over a sizable regional subset of 21 rock sites exhibits a nearly vanishing mean of such term at all periods. The mean single-site sigma on rock is significantly lower than that of individual soil sites and to the ergodic sigma of the regional GMPE.

Based on the UHS at bedrock for two 475yrs and 2475yrs return periods, we computed the corresponding site-specific response spectra at one site (MRN) to quantify the effect of different sources of epistemic uncertainty. A thorough procedure was devised for this purpose (two-step *HyS* approach), segregating from the analysis the sources of aleatory uncertainty, already accounted for in the PSHA on rock. The epistemic contributions of the 1D modelling steps were evaluated separately, finding that the assumptions on the soil models accounted for (G-γ and ξ-γ curves) dominate the variability of results, especially for large return periods.

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