INVESTIGATIONS ON PSHA IN NORTHERN ITALY, WITHIN AND AFTER PROJECT SIGMA

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ABSTRACT

The large concentration of inhabitants, economic output and important infrastructure, as well as the peculiar geologic setting, motivated from the outset the Italian research team in SIGMA to investigate in depth the probabilistic ground motion (GM) hazard at selected locations in the Po Plain. The site-specific GM hazard assessed in SIGMA final phase by a PSHA one-step approach, modified to include a single-station sigma, is first discussed vis-à-vis a successive analysis that uses a simpler logic tree but accounts also for uncertainty in $\sigma_{ss,s}$. Both are here updated with new residual measures from post-2012 (Emilia earthquakes) records leading to an increase of probabilistic spectra at intermediate vibration periods, as a result both of changing the GMPE and of decreasing the source-to-station single-path influence of the 2012 records. Then, a two-step approach is presented (consisting of bedrock motion evaluation plus wave propagation through a local soil profile) considering the main epistemic uncertainties. Uniform hazard spectra on soil and exposed bedrock are discussed for the deep-soil MRN (Mirandola) accelerometer site, and compared with those from the one-step method. It is shown that the agreement between the one-step and the two-step approach is satisfactory only if the soil response at MRN is assumed to be linear.

Keywords: probabilistic seismic hazard analysis; single-station sigma; uncertainties quantification; Po Plain

1. INTRODUCTION

The results presented herein were obtained in the framework of the SIGMA project (2011-2015), with some recent updating, and illustrate the contributions of the Italian research team which focused on the Po Plain basin. This is a densely populated, highly industrialized region of Northern Italy, sitting on a large basin of deep Quaternary sediments with strongly variable total thickness. Earthquakes originate both from blind faults in the basement rock, and at greater depths (up to 100 km). The basin is exposed to moderate seismic activity, significantly less intense than the Central and Southern Apennines, but far from negligible. The Northern Italy seismicity is characterized by small energy events and by infrequent moderate earthquakes, such as those in the $M_W$ 5-to-6 magnitude range occurring in the last decade, notably the damaging 2012 Emilia sequence. This made it possible to collect a vast amount of geological, seismological, geophysical and geotechnical information through instrumental records, and field surveys and measurements, which now constitutes a case study apt to facilitate a refinement and possible reduction of uncertainties in seismic hazard (SH) assessment.

Defining the site-specific seismic hazard in the Po Plain poses a significant challenge, especially for low occurrence probabilities, partly due to the lack of surface evidence on earthquake sources, i.e. blind faulting. The variability of site effects on deep recent sediments also tends to make a realistic estimation of the seismic hazard more difficult. Emphasis of the work by the Italian team was placed on key modelling issues influencing the SH analysis, such as the characterization of blind faults, the scarcity of earthquake data and the estimation of site effects induced by deep sedimentary deposits. Three representative locations were chosen for the analysis (denominated MRN, NVL and T0821,

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shown in Figure 1), because they hosted accelerometer stations that recorded different earthquakes. Among the approaches available to account for seismic site effects within a PSHA, applications of a site specific fully probabilistic (one-step) and hybrid (two-steps) method are illustrated here. Both use a single-station sigma and an empirically based site-specific amplification factor \( \delta S^2 \) to reduce the uncertainties in the estimation of response spectrum ordinates, but these residual measures were used in a different way for soil or rock site characterization. Use of these approaches is thoroughly discussed in Faccioli et al. 2015 and Vanini et al. 2017. We show results relative to the Casaglia (CAS) site (identified with the temporary station T0821) for the one-step method, and to the Mirandola (MRN) site for the two-step method.

In addition to providing a synthesis of some salient PSHA results for the Po Plain, we revisited the analysis using single-station residuals measures updated with data recorded after 2012, including the sequence of June 2013, near Fivizzano (max \( M_w \) 5.1), shown in Figure 1. Therein, the selected sites on soft and hard soil used in the following are also indicated.

![Figure 1. DEM of Po Plain portion with accelerometer sites of interest, showing also depth contours of the base of early Pliocene from Bigi et al. 1992. Rupture area projections of the Reggio Emilia 1996 and the two Emilia 2012 mainshocks are shown as red rectangles, while the Fivizzano mainshock of June 2013 is shown by a red star. Sites NVL, MRN, and T0821 (or CAS) used in subsequent analyses are marked with a blue triangle.]

1.1 **Single station sigma approach**

Residual analysis of the ground-motion prediction equations (GMPEs) has shown that, when individual sites with recorded data and the associated (non-ergodic) statistical measures of variability are considered, the range of uncertainties at play may decrease with respect to the case when records from many sites are used, as is the case with GMPEs (ergodic case).

Relying for the definitions on Rodríguez-Marek et al. 2011, 2013, residual measures of ground motion predictions may be identified with a site factor \( \delta S^2 \) and a site- and event- corrected residual \( \delta W_{SE} \), the combination of which gives the within-event single-station residual. \( \delta S^2 \) represents the systematic deviation of the observed amplification at the site from the median amplification predicted by the GMPE, with simple site classification (Al Atik et al. 2010). In PSHA, the median prediction of the GMPE may then be corrected by adding the \( \delta S^2 \) term.

The standard deviation of the \( \delta W_{SE} \) residual is denoted as \( \phi_{\delta W} \); when this is combined with the standard deviation of the between-event component, \( \tau \), of the same residual, an estimate of the total
single-station sigma may be evaluated as:

\[ \sigma_{ss,s} = \sqrt{\phi_{ss,s}^2 + \tau^2} \]  

(1)

In a partially non-ergodic approach to PSHA, \( \sigma_{ss,s} \) replaces the sigma of the GMPE.

A detailed evaluation of the (epistemic) variability of the site factor \( \delta S2S \), denoted \( \phi_{S2S} \), mostly based on the 2012 Emilia records (Faccioli et al. 2015), showed that this tends to be significantly lower than the variability carried by \( \phi_{ss,s} \). Hence, \( \phi_{S2S} \) was assumed to be negligible, especially if the site term is afterwards calculated independently through a seismic-response analysis. An independent estimate of the epistemic uncertainty in the mean value of \( \delta S2S \), denoted as \( \sigma_{S2S, epistemic} \) was assumed as:

\[ \sigma_{S2S, epistemic} = \frac{\phi_{S2S}}{\sqrt{N}} \]  

(2)

Moreover, Faccioli et al. took into account the variability of \( \phi_{ss,s} \) by introducing in the logic tree an upper and lower bound of the single station sigma, as follows:

\[ \sigma_{ss,s}^{u} = \sqrt{\left(\phi_{ss,s} + \text{stdev}\phi_{ss,s}\right)^2 + \tau^2} \] (upper)  
\[ \sigma_{ss,s}^{l} = \sqrt{\left(\phi_{ss,s} - \text{stdev}\phi_{ss,s}\right)^2 + \tau^2} \] (lower)  

(3)

As to the present use of single-site sigma, none of the GMPEs adopted includes non-linearity in the site term, so that the assumption of a site factor \( \delta S2S \) independent of return period appears justified.

2. PSHA EVALUATION THROUGH A ONE-STEP APPROACH

A one-step partially ergodic approach may be seen as a site specific fully probabilistic method, in which the site response is introduced in the PSHA through the site-correction factors of the GMPEs and, in addition, the single-station sigma residuals are applied to account for the specificity of the site response with respect to the GMPE prediction.

Herein, we first summarize and compare results of one-step PSHA performed for the CAS (Casaglia) site, using a detailed logic tree and a simplified one. We then revisit results using the new residual measures of Lanzano et al. 2017, who revised the residual analysis of Pacor et al. 2013 with an updated database, enriched in recording stations and events.

2.1 Detailed logic tree analysis

In SIGMA, the SH assessment was performed in two phases: in Phase I, the influence of the epistemic uncertainties associated to the model of areal source (AS) zones, GMPEs, and other input elements was explored, and its results constituted the baseline for evaluating the uncertainty reduction achieved through the improvements introduced in Phase II. The latter revised on one hand key input data and tools of Phase I (magnitude scale conversion, updating of earthquake catalogue, GMPEs) and, on the other hand, introduced a more ambitious treatment of uncertainties, through a partially non-ergodic (single-site sigma) approach to the ground motion prediction.

Both a model-based seismicity and a gridded seismicity representation were used in the PSHA. In the former, an AS model modified with respect to the standard Italian model (Meletti et al. 2008) was introduced, as well as fault sources with background (FSBG) activity models. For the gridded seismicity representation, used in separate branches of the analysis, a map of occurrence probabilities was associated to a regular grid of point sources through the poissonian HAZGRID model (Akinci, 2010), in a version updated with the 2012 events.

After selection and ranking, the GMPEs retained for the final analyses were: an updated version, referred to as ITA13, of the Bindi et al. 2010 (ITA10) relations, specifically derived from a Northern Italy dataset, the bulk of which came from the 2012 Emilia sequence; Atkinson & Boore 2011 (AB11), based on a global dataset; Faccioli et al. 2010 (Fea10), in its modified version published by Faccioli and Chen 2012. In the final logic tree, reproduced in Figure 2, the site specific residuals were
introduced by adding the factor $\delta S^2 S$ to the median prediction of the GMPE and by replacing its sigma with that of Equation 1.

Figure 2. SIGMA Phase II logic tree, with weights of each branch shown in red (for return periods of 2475 and 10000 yrs). Only GMPEs in their partially non-ergodic mode were used.

The residual parameters adopted in this analysis for CAS (an Eurocode 8 C-type site with $V_{S30} = 190$-to-200 m/s) are shown in Figure 3, where the negative $\delta S^2 S$ indicate that the site amplifies ground motions less than predicted by the GMPE for a C-class site. Moreover, the total single-station sigma is significantly smaller than the sigma of most of the GMPEs. These differences, introduced through the noted corrections to the GMPEs, had a strong influence on the PSHA results. The residual parameters shown by the blue curves in Figure 3 were computed using ITA13 as GMPE, specifically developed for the Po plain in SIGMA. No magnitude conversion (from $M_L$ to $M_W$) was introduced in the dataset underlying this GMPE, to avoid extra variability introduced by the conversion. This resulted, in particular, in a reduction of the inter-event standard deviation with respect to ITA10.

Figure 3. CAS site. (left) Total single-station sigma ($\sigma_{ss,s}$), blue curve, with standard deviations of the GMPEs used in Logic Tree also shown (i.e.: Bindi et al., 2011 ITA10, and its 2013 modified version ITA13; Atkinson & Boore 2011, AB11; and Faccioli et al. 2010 modified version, Fea10). (right) Ditto: site correction factor $\delta S^2 S_s$, showing the deviation from the generic ITA13 GMPE prediction for site type C.

Figure 4 shows the probabilistic spectra obtained at CAS. The comparison of the Phase II spectra with those of Phase I (generated by the standard ergodic approach) shows differences depending on the site considered; at CAS the non-ergodic use of GMPEs led to a strong decrease in the spectra, driven by the negative $\delta S^2 S$ and the low $\sigma_{ss,s}$ values.
Figure 4. CAS site: mean with 16- and 84-percentile Uniform Hazard (UH) acceleration spectra (SA) on ground type C at return periods (RP) of 475 and 2475 years, from Phase II logic tree calculations (in red). Spectra from Phase I (in green), and NTC 2008 Italian code spectra are also shown for comparison (thick dashed curves).

2.2 An alternative logic tree analysis

A refinement of the former analysis has been published in Faccioli et al. 2015, proposing a different formulation of the PSHA logic tree (Figure 5) in which only area sources and gridded seismicity models were retained for simplicity and just the single, regional, GMPE used (ITA13), regarded as the most representative for the region at study. The uncertainty in the $\phi_{ss,s}$ single-station term was explicitly considered and Equations (3) used to define lower and upper levels of the single site sigma, beside the mean value of Equation (1). The CAS spectra obtained in this way are lower still than those of SIGMA Phase II (red curves in Figure 4): in the range of peak spectral response there is a decrease of the order of 15% in mean 2475-yr values and almost 30% in the 475-yr values. The spread, measured by the difference between 84- and 16-percentile levels, also decreases, as would be expected from the use of a simpler logic tree. The salient finding here is that the introduction of the uncertainty in the single-station sigma values, amounting to a variability of about ± 35% about the mean does not suffice to balance the decreased variability due to a simpler seismicity description and to using the single ITA13 GMPE. Predictions by the latter tend to be lower than with AB11 and Fea10, notably for CAS and NVL (see Vanini et al. 2017), mostly due to a lower inter-event ($\tau$) variability component.

Figure 5. Alternative logic tree (Faccioli et al. 2015). Weights attached to different seismicity descriptions are shown for the two adopted return periods (RPs): note decrease in weight for gridded seismicity when RP rises to 2475 years. For sigma level branches different weights were used depending on site and ground type.
2.3 Influence of new residual measures

Relevant developments occurring near the end of SIGMA and after it have included publication of the European Strong Motion Database (ESMD) website (http://esm.mi.ingv.it) with additional waveforms in the dataset, new site characterization, and update of event information. These included the data recorded after 2012, notably from the NW Apennines sequence of June 2013 (with maximum $M_w$ 5.1 of June 21, 2013), see Figure 1. For the CAS station the number of records increased from 14 to 19, for NVL from 11 to 20, and for MRN from 9 to 25; on average, there was an increase in the number of records of about 50%. From such enlarged dataset, Lanzano et al. (2017) updated the evaluation of the residual measures for all the regional accelerometer stations using the cited ITA10 GMPE, regarded to be more suitable for handling attenuation in regions neighbouring the Po Plain. Figure 7 compares for stations CAS, MRN and for a generic site A (averaged as explained in section 3), the “old” residual measures, linked to ITA13, with the “new” measures, which include data posterior to 2012 and are linked to ITA10. Figure 1 suggests that addition of the more recent data with SW azimuth with respect to the stations should reduce the EW, single-path bias affecting the CAS residuals when only the 2012 (and 1996) epicentres are considered. This reduction may explain the (slight) increase in $\delta S_2S$, $\phi_{ss,s}$ and $\sigma_{ss,s}$ seen in the graphs of Figure 7. However, the change of GMPE contributes even more to the differences in $\sigma_{ss,s}$: its values, in fact, increase mostly due to the increase in the between-event variability $\tau$ of the respective GMPE, ITA10, for $T > 0.15$ s, than to the moderate increase in $\phi_{ss,s}$. While one must recognize the greater sensitivity to new data of the residuals derived from the regionally based ITA13, the justification for adopting this GMPE rests on a representative database of 2174 records from 136 earthquakes with many stations located on a deep basin configuration in the middle of the Po plain where 2D and 3D effects can strongly affect the site response.

The influence of these changes on the PSHA, is illustrated in Figure 8 and Figure 9, where the computations with the LTs of Figure 2 and 5, respectively, where revisited introducing the new residual measures. Both figures exhibit a noticeable increase of spectral ordinates in the 0.15– to–2.0 s period range, reflecting the higher values of the updated site factor and, mostly, the increased single-station sigma portrayed in Figure 7, for the same periods.

3. PSHA EVALUATION THROUGH A TWO-STEP APPROACH

Two step-methods, often referred to as hybrid approaches, rely on the results of a PSHA for exposed rock conditions, where site effects are then superimposed by multiplying the uniform hazard spectrum on rock by a suitable site amplification function (SAF). A site-specific SAF is typically calculated as
the mean amplification function from 1D linear-equivalent (or non-linear) wave-propagation analyses for the specific soil profile at hand. Time-history calculations are normally carried out for this purpose, by considering a suite of real accelerograms compatible with the rock spectrum.

Figure 7. Comparison of single-station residual measures computed from Pacor et al. 2013 with respect to ITA13 in panels a), b), c) (left), and Lanzano et al. 2017 with respect to ITA10 (right). Sites displayed are: MRN, CAS (both of type C) and a generic site A, computed as explained in Section 3 (from Faccioli et al. 2015).
Figure 8. CAS site: Uniform Hazard (UH) acceleration spectra (SA) on ground type C at 475 and 2475 years RP, from Phase II calculations (logic tree of Figure 2). Results using old and new residuals of Figure 7 are shown. Thick dashed curves are the NTC 2008 code spectra for ground type C.

Figure 9. CAS site. Percentile uniform hazard spectra (UHS, thin solid curves) and mean spectra (thick solid curves) calculated using the logic tree of Figure 5 with the ITA13 GMPE, for 475 and 2475 years RP. Results using old and new residuals of Figure 7 are shown. Thick dashed curves are the NTC 2008 code spectra for ground type C.

In order to identify and quantify the different sources of uncertainties in site-specific PSHA studies using 1D seismic-wave propagation, the hybrid approach used in Faccioli et al. 2015, involved:

1) selection of real accelerograms, with response spectra closely approaching the target bedrock spectrum in a broadband sense (i.e., from 0 to 5 s period);
2) matching of selected accelerograms with the target spectrum, by iterative amplitude scaling;
3) 1D site-specific propagation studies with the input motions of previous steps, exploring the following sources of variability:
   • linear-elastic soil models in terms of $V_s$ profile;
   • nonlinear shear modulus and damping ratio curves vs. cyclic shear strain amplitude;
   • nonlinear modeling method.

The 1D analyses were performed by means of linear viscoelastic (LIN), equivalent-linear (EQL), and fully nonlinear (NL) approaches, using the DEEPSOIL code (www.illinois.edu/~deepsoil).
3.1 Hazard estimation on exposed bedrock

Hazard estimation on exposed bedrock followed the general logic described in Section 2.2, using the simplified logic tree of Figure 5, with the essential difference that no bedrock records were available (as in most cases) for direct evaluation of \( \phi_{ss,s} \) and \( \delta S2S \). At the study sites, as in the Po Plain at large, the upper sediments are from about 100 m to many hundreds of meters thick and, until recently, there were no borehole records within hard, geologically older formations.

We disregarded the influence on bedrock motion of \( \kappa \), the near-site attenuation factor causing an \( \exp^{-\pi \kappa f} \)-type high-frequency decay in the Fourier spectrum amplitude, and the associated uncertainties, see Pecker et al. 2017 for a discussion. Actually, two out of three study sites considered in SIGMA, i.e. MRN and CAS (= T0821), exhibit in their subsoil profile hard formations with \( V_s \sim 800 \text{ m/s} \) at around 100 m depth, with a marked impedance contrast with the upper sediments. For ITA13, as well as for several other GMPEs, \( V_{s30} \geq 800 \text{ m/s} \) characterizes standard rock, that is, ground type A of Eurocode 8 (2003).

Regionally based \( \delta S2S \) values applicable on exposed rock and their dispersion were estimated starting originally from two different record subsets on ground type A, selected from the dataset underlying ITA13, i.e. the subsets within 120 km and 75 km distance from the main Emilia 2012 earthquakes. After testing the influence of the number of records on the estimated \( \delta S2S \), it was found that at short period the mean \( \delta S2S \) for the < 75 km group were biased toward negative values due to the data of the strong thrust-fault events of May 2012, which generated lower-amplitude motion at the southern stations (such as ZCCA, MTRZ, RNC and BSZ depicted in Figure 10) with respect to those to the N (e.g. MLC and TGG in same figure; see Luzi et al., 2013). Thus, only the < 120 km subset was retained. Figure 10 shows on the left panel the “old” values of the site factor \( \delta S2S \), calculated with ITA13 by Pacor et al. 2013, including 21 stations, and on the right panel the updated values of Lanzano et al 2017, calculated with ITA10, including 30 stations.

The \( \sigma_{SS} \) epistemic uncertainty on rock, from Equation (2) of Section 1.1, ranged between 0.10 at short period and 0.05 for \( T > 0.35 \text{ s} \) with the old residual measures, and decreased further with the new ones. Same as for soil sites, and for the same reasons, we neglected this uncertainty.

![Figure 10. Site factors for the < 120 km distance stations on ground type A, with at least five records (21 stations for panel on the left and 30 for the one on the right). Mean +- 1sd band (shaded). A selection of stations from the North (MLC and TGG) and from the South (ZCCA, RNC, BSZ and MTRZ) has been identified with different symbols.](image)

Figure 7 shows in the upper two panels the regional \( \delta S2S \pm \sigma_{SS} \) values on rock (“site A” in the figure), used as final values in subsequent analyses: in panel a) those computed with the residuals of Pacor et al. 2013, in panel d) those recalculated with the Lanzano et al. 2017 residuals.

The same figure shows with the same distinction, in panels c) and f), respectively, also the single-station values \( \sigma_{ss,s} \) for ground type A. The increase in \( \sigma_{ss,s} \) values on rock from panel c) to panel f) leads to considerably enhancing the amplitudes of uniform hazard spectra at all periods, as illustrated
in Figure 11 for the MRN site, derived from PSHA with the Figure 5 logic tree.

Figure 11. MRN site: Uniform Hazard (UH) acceleration spectra (SA) on rock (site class A) at 475 and 2475 years RP, calculated using the logic tree of Figure 5. Results using old and new residuals of Figure 7 are shown. Thick dashed curves are the NTC 2008 code spectra for ground type A.

At MRN the agreement of the present probabilistic spectra on rock with the Italian code spectra is better than at CAS for site class C conditions. The discrepancy points to complex 3D effects in the seismic response at CAS, if one assumes that possible nodal plane effects from the 2012 data are balanced by the contributions from different focal mechanisms (see Figure 1) and source-to-site azimuths in the updated residuals.

3.2 Results of two-step approach

1D Propagation analyses carried out for estimating ground motion at the soil surface in a two-step approach are extensively discussed in Faccioli et al. 2015, including a detailed quantification of the sources of associated epistemic uncertainties. We recall here some salient results for site MRN, and compare them with the one-step approach, using only the “old” rock spectra (in blue in Figure 11). Figure 12 illustrates the surface response spectra at MRN resulting from linear and non-linear propagation analyses, compared with the UHS from the one-step approach (via the logic tree of Figure 5). The uncertainties associated to surface spectra combine the standard deviations of the PSHA results on rock, with those related to 1D modelling procedure. While a discussion of such uncertainties is not a goal of this paper, we just remark here that there is gross agreement between the one-step and the two-step approach only if the assumption of linear soil response (LIN) holds at MRN. As expected, this plays a growing role with increasing RP; and for 2475 yrs the predicted NL spectrum is much lower than the spectrum obtained by the LIN approach and the one-step UHS. The good agreement of the latter with the LIN two-step result is likely related to the assumption that $\delta S2S$ is constant in the one-step approach, which is like saying that the site response is linear.

5. CONCLUSIONS

Rather than simply recalling the salient results of SIGMA on site-specific PSHA in the Po Plain of Northern Italy, already published, we made here the attempt at an update. This relied on work still under development at the end of the project (2015) and, especially, on data and elaborations that became available more recently, related to refinements in the (partially) non-ergodic approach adopted in Phase II of SIGMA. That phase had led to a large decrease in the site response spectra at representative sites (e.g. CAS) with respect to the Phase I spectra, derived by a standard (ergodic)
Figure 12. MRN site. Comparison of response spectra from linear (LIN, green curves and shading) and fully nonlinear (NL, purple curves and shading) two-step analyses, and from site class C one-step analysis (gray curves, UHS soil C, ‘old residuals’). Mean +/- 1 standard deviation bands are shaded. Standard deviation (s.d.) values have been computed as explained in text.

PSHA approach, as a result of using measures of the GMPE prediction residuals dominated by the records of the 2012 Emilia earthquakes. Although representative of strong ground shaking from earthquake sources near the sites, those measures suffered from source-to-site single-path (oriented E-W) effects, as one may infer from Figure 1. Additional records of the last few years were used to update the residuals and, thus, to mitigate the influence of single-path effects; through such update we have shown that the spectrum levels at the CAS site undergo a moderate increase at intermediate periods and tend to become more broadband. The change, however, depends even more on the GMPE actually used to evaluate the residuals, and notably on its inter-event ($\tau$) standard deviation, see $\tau_{IT13}$ vs. $\tau_{IT10}$ curves in panels b) and e) in Figure 7. The influence of the update with respect to the final SIGMA results is significant on the rock spectra required as an intermediate step in a two-step approach to site-specific PSHA, and manifests itself in an increase of the single-station sigma. This indicates that when working with regional GMPEs, even if well supported by data, the specificity of the dataset can affect the estimation of the residuals. Also, in order to reduce biasing from single-path effects and underestimate of the residuals, more than five recordings per site should be used, possibly from earthquakes generated by different seismogenic structures. Finally, in reporting results from the two-step approach applied at the Mirandola site, that recorded strong motions in 2012, we highlighted that agreement in surface spectra from the one-step and the two-step approach is reasonable only assuming linear soil response, while a nonlinear description leads to strong disagreement between the two approaches, growing with the return period.

7. REFERENCES


