APPROACHES TO ACCOUNT FOR SITE EFFECTS IN THE PSHA OF SELECTED SITES IN THE PO AREA

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Executive Summary

This report explores the approaches available to account for specific site effects in the framework of a Probabilistic Seismic Hazard Analysis (PSHA), with special emphasis on the application to selected sites in the Po plain. Specifically, it aims at providing the general framework in which the site-specific PSHA studies introduced in the Sigma Deliverable D4-94 "Probabilistic study for Po plain area (site specific)" were carried out.

With this objective, we have focused this study on the Hybrid and Fully probabilistic site-specific approaches, *HyS* and FpS respectively, introduced in Chapter 1. Specifically, Chapter 2 summarizes the basic features of the *FpS* approach and will provide some insight on the site amplification functions (SAFs), conditioned on the amplitude of motion at the rock site, observed on a set of Kik-net stations, resembling to the Po plain sites in terms of deep soil profile. In Chapter 3, the *Hys* approach selected for this research, which was applied in Deliverable D4-94 for specific sites in the Po plain, is illustrated, aiming at evaluating site-specific SAFs as a function of the reference return period (RP) and at applying them as a multiplication factor to the uniform hazard (UH) response spectrum from the PSHA at rock. For proper application of this approach, practical tools to select earthquake motions to be used as input for site-specific seismic response analyses must be available, with the objective to provide a compatibility with the UH spectrum in a period range as large as possible to cover site amplification effects in the long and short period range, as well as for linear and non-linear soil behaviour. The proposed tool for earthquake ground motion selection is illustrated in Chapter 4. In Chapter 5, considerations are made for the practical quantification of uncertainties in site response evaluations, with specific reference to the case studies in the Po plain.

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1. Introduction

1.1. Background

This report explores the approaches available to account for specific site effects in the framework of a Probabilistic Seismic Hazard Analysis (PSHA), with special emphasis on the application to selected sites in the Po plain. Specifically, it aims at providing the general framework in which the site-specific PSHA studies introduced in the Sigma Deliverable D4-94 "Probabilistic study for Po plain area (site specific)" were carried out.

Making reference to Fig. 1.1, where a cross-section of Po plain is illustrated in the vicinity of the epicentral area of the May 2012 earthquakes, the main geological feature affecting earthquake ground motion in this area is the presence of deep or very deep soil sites, with depth of the top of Miocene formations rapidly increasing from about one hundred m to some km. The main consequences of this geological context from the point of view of seismic soil response, coupled with a moderate seismicity with maximum earthquake magnitude around 6, can be summarized as follows:

- earthquake ground motion amplification at long periods;
- efficient generation of surface waves, also related to the sharp submerged topography irregularity, as sketched in Fig. 1.1;
- moderate non-linear effects in earthquake ground motion, with possible liquefaction phenomena in the presence of loose saturated soils, as observed during the May 2012 seismic sequence.

An introduction to the earthquake ground motion features observed during the Emilia earthquakes has already been presented in the Sigma Deliverable D3-54 "Evaluations of seismic ground motion variability at soft sites by 3D-1D propagation models, including Christchurch and selected sites in the Po plain", where records were compared with preliminary results of 3D numerical simulations. Such work was completed in the second year of the Sigma project and presented in Deliverable D2-93: "Ground shaking scenarios in the Po plain with special emphasis on the area affected by the earthquake sequence of May 2012".

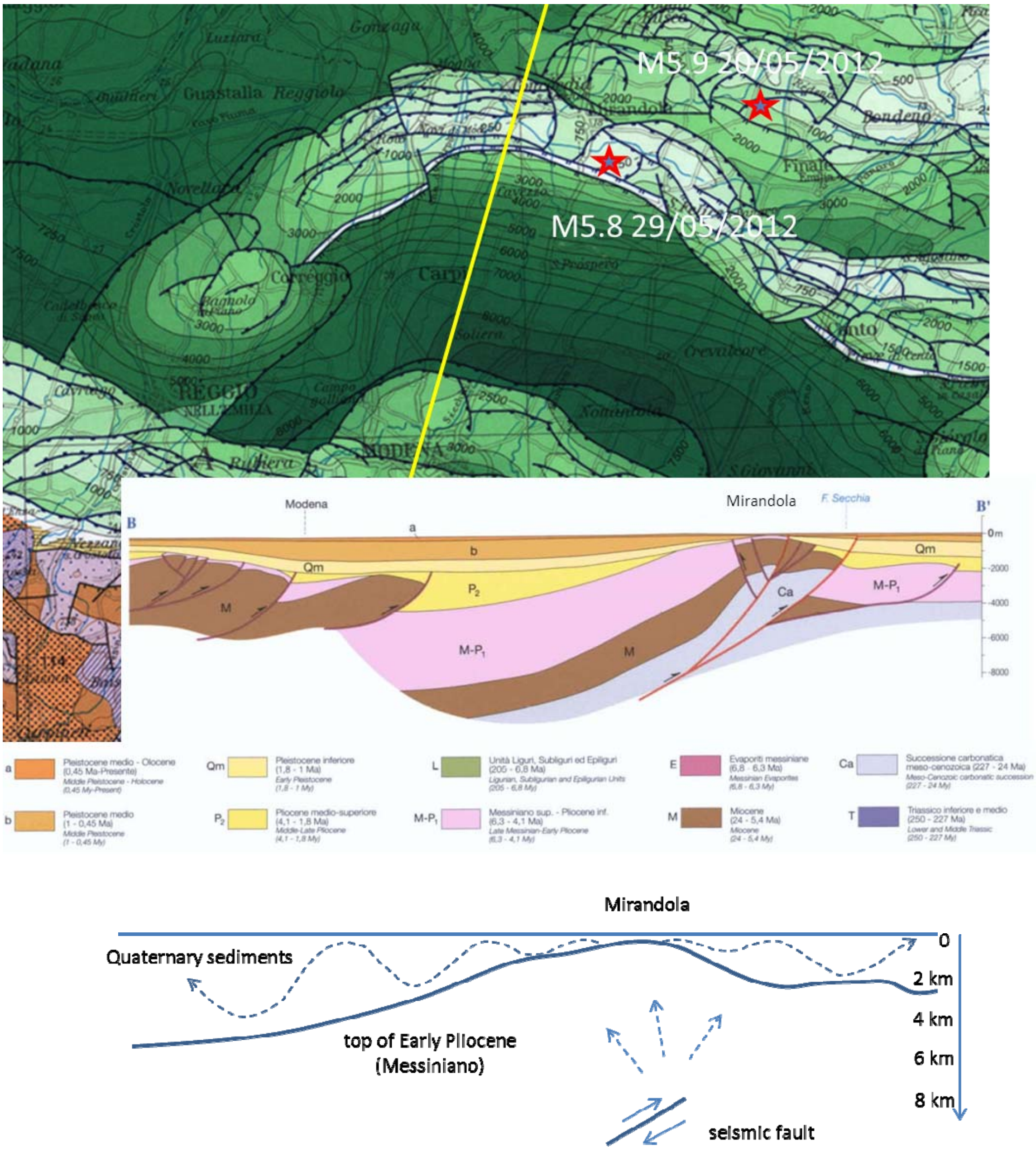


Figure 1.1 – Top: epicentres of the two main shocks of the Emilia-Romagna seismic sequence, plotted on the 3D structural geological map of Italy, with indication of the depth of the Miocene formations. Middle: geological cross-section along the yellow line drawn in the top part of the figure, based on the seismotectonic map of Emilia-Romagna. Bottom: sketch of the geological cross-section, illustrating the possible interaction of seismic waves with surface geology.

1.2. Approaches to account for site effects in the PSHA

It is well known that the seismic response features of a specific site may be quantified by site amplification curves, typically described as a function of frequency (or of the vibration period). In most cases, these site amplification functions (SAF) are defined either by the Fourier or by the response spectral ratio of the response at the site divided by the corresponding response at the ideal outcropping bedrock (reference station), where available. While in the numerical calculations the availability of a reference station is not generally of concern, since response at an ideal rock site can generally be determined and used as a reference for the corresponding response at soft sites, experimental evaluations of SAFs are in most cases limited by the lack of suitable reference stations in the vicinity of the site. This is an even more critical problem for sites in the Po plain, where outcropping bedrock may lie tens of km away.

For this reason, the experimental approaches for the evaluation of site-specific SAF have moved towards the use of single-station horizontal-to-vertical spectral ratios (HVSR). However, HVSRs may not be used within a PSHA which typically provides values of horizontal ground motion at rock sites[1]. Therefore, in the compilation of this report, we decided to present results by considering only those SAFs which could be directly introduced within a PSHA.

Following Cramer (2003), Bazzurro and Cornell (2004), Perez et al. (2009), the classes of approaches to account for seismic site effects within a PSHA can be broadly classified as summarized in Table 1.1. Hybrid approaches are typically based on the results of a PSHA at a rock site, where site effects are superimposed by multiplying the uniform hazard spectrum at rock by a suitable SAF. The latter one may be defined either by the spectral amplification factors for generic sites introduced typically by local norms or guidelines (approach *HyG*), or by a site-specific SAF, calculated in most cases by considering the mean amplification function from 1D linear-equivalent seismic wave propagation analyses for the specific soil-profile (approach *HyS*). In the latter case, time-history analyses are typically carried out by considering a suite of real accelerograms, satisfying the response spectrum compatibility with the target PSHA spectrum on rock. While *HyG* is the approach implicitly outlined by seismic norms,

[1] Incidentally, it can be suggested that PSHA based on the vertical component of motion coupled with experimental HVSR could be a rationale alternative for future studies on this subject.

approach *HyS* is frequently used for site-specific seismic hazard analyses of important facilities so that it may be considered as the reference approach for this study.
Although sound, and easy to be understood, from an engineering point of view, the limitation of the hybrid approach is that it may provide estimates of the exceedance rates at the site that may not be consistent with the corresponding ones on rock, as noted by Bazzurro and Cornell (2004).

Table 1.1. Classes of approaches to account for site effects in PSHA

Hybrid probabilistic/deterministic		**Fully probabilistic**	
Generic site (HyG)	*Site-specific (HyS)*	*Generic site (FpG)*	*Site-specific (FpS)*
PSHA at rock + SAF based on seismic norms	PSHA at rock + SAF based on site-specific soil response analyses (typically 1D)	PSHA based on GMPE with site correction factor	PSHA at rock + convolution with SAF conditioned to rock ground motion, typically based on 1D soil response analyses

The previous limitations may be overcome by following fully probabilistic approaches, that may be broadly subdivided in terms of their range of application, either for a generic site (*FpG*) or for a specific site (*FpS*). *FpG* approach is based on the standard application of PSHA, where the site response is summarized within a period-dependent site correction factor to modify the expression of the considered ground motion prediction equation (GMPE). Such correction factors are provided by practically all recent GMPEs (see e.g. the review by Douglas, 2011), either in terms of broad soil categories or in terms of soil classes related to seismic norms, or of other related engineering parameters such as $V_{s,30}$. The drawback of such approach is that it may not provide reliable results when dealing with site-specific response evaluations. In the latter case, a site-specific GMPE could be used (e.g., Ordaz et al., 1994; Atkinson, 2006), if a sufficient amount of strong-motion records are available at the site for a reliable GMPE to be constructed, but this is seldom the case.
Finally, a *FpS* approach may be followed, such as proposed by Bazzurro and Cornell (2004), involving the calibration of conditional SAFs, i.e., of the site-specific ground motion amplification values at a specific vibration period, conditioned to the exceedance of a given level of ground motion at rock.

1.3. Scope and Organization of work

Since our objective is to investigate methods to couple PSHA at rock with site-specific response analyses, with emphasis on the application to the Po plain, we will focus this study on the *HyS* and *FpS* approaches. Specifically, Chapter 2 will summarize the basic features of the *FpS* approach and will provide some insight on observed conditioned SAFs from several stations of the KikNet, resembling to the Po plain sites in terms of deep soil profile. In Chapter 3, the approach selected for this research, and applied in Deliverable D4-94 for specific sites in the Po plain, will be illustrated, aiming at evaluating site-specific SAFs as a function of the reference return period (RP) and at applying them as a multiplication factor to the uniform hazard (UH) response spectrum from the PSHA at rock. For proper application of this approach, practical tools to select earthquake motions to be used as input for site-specific seismic response analyses must be available, with the objective to provide a compatibility with the UH spectrum in a period range as large as possible to cover site amplification effects in the long and short period range, as well as for linear and non-linear soil behaviour. The proposed tool for earthquake ground motion selection will be illustrated in Chapter 4. In Chapter 5, considerations for the practical quantification of uncertainties in site response evaluations will be made, with specific reference to the case studies in the Po plain.

2. Observations on the conditioned site amplification functions

2.1. Scope

The objective of this section is to provide observational insight on the main object on which the *FpS* approach to carry out site-specific fully probabilistic PSHA is based, i.e., the conditioned SAF. As a matter of fact, the presentation of site amplification functions conditioned to the intensity of ground motion at rock, for a specific vibration period T, is a powerful way to highlight some specific features of site response, such as its dependence on magnitude or on non-linear effects.

2.2. Fully probabilistic approach based on conditioned SAFs

Borrowing, at least in part, the notation after Bazzurro and Cornell (2004), we denote by *X* a parameter of ground motion amplitude at rock (e.g., the spectral ordinate at period T), and by *Z* the corresponding parameter at the site. *Z* and *X* are related by the site amplification function *Y*, so that $Z = Y{\cdot}X$. Based on the total probability theorem, and denoting by $f_X(x)$ the probability density function of the random variable *X*, and by $F_X(x)$ the corresponding cumulative density function, it can be written

$$F_Z(z) = \int_0^{\infty} P\left[Y \leq y = \frac{z}{x}\middle| x\right] f_X(x)dx \quad , \qquad (2.1)$$

or, in discretized form

$$F_Z(z) = \sum_{all\ x_j} P\left[Y \leq y = \frac{z}{x}\middle| x_j\right] p_X(x = x_j) \quad . \qquad (2.2)$$

It should be noted that practically the same approach as proposed by Bazzurro and Cornell (2004) was introduced about 30 years earlier by Faccioli and Ramirez (1975), who used for *X* the root-mean-square (rms) ground acceleration at a given reference hard site, for which seismic hazard is known, and applied linear-equivalent 1D analyses to compute a probability function for the amplification function *Y*.

Similarly to Faccioli and Ramirez (1975), Bazzurro and Cornell (2004) used a wide set of finite element numerical simulations of 1D seismic wave propagation in non-linear soils to evaluate the moments of the conditional probability function

$$F_{(Y|X=x,y)} = P\left[Y \le y = \frac{Z}{X} \middle| x\right]. \qquad (2.3)$$

Therefore, the core of the method is the calculation of the conditioned amplification function *Y=SAF(X)*, providing for each period *T*, or frequency *f*, the median amplification at the site, and the corresponding σ, conditioned to the attainment of a given value *X* at the reference rock site. The typical outcome of the analysis can be illustrated as in Figure 2. 1, where a set of amplification values of the spectral ordinates at 1 Hz at the site (vertical axis) with respect to the corresponding value at the reference rock site (horizontal axis) are plotted, together with the median values.

According to Bazzurro and Cornell (2004) the conditioned amplification function *SAF(X)* is (i) log-normally distributed, (ii) is poorly dependent on Magnitude and Distance, (iii) can be deduced by 1D numerical simulations by using a relatively limited suite of rock records (around 10 should be sufficient to get the median) and by considering a randomly varying soil profile. Furthermore, typical values of $\sigma_{\ln Y}$ were found to range from around 0.25 (~0.10 in $\log_{10}$) at small frequencies to 0.7 (~0.30 in $\log_{10}$) at high frequencies, and a piecewise linear interpolation of the median *Y* allows one to obtain closed-form solutions.

Although this fully probabilistic site-specific approach allows a formally correct incorporation of seismic site effects into the PSHA, it suffers of several limitations that were already addressed in Deliverable D3-54 and will be further discussed in this deliverable in view of the completion of analysis of KikNet data, namely:

- the probability distribution of the conditioned amplification function is based on 1D numerical simulations of vertically propagating plane waves in nonlinear soil sites with uncertain properties: this assumption is expected to deeply affect not only the median amplification function, but also its deviation;
- observed amplification at the site may also be affected by source-to-site azimuth and directivity, especially in near-source conditions (e.g., because of different angles of incidence of waves, or because of larger/smaller onset of surface waves depending on the relative position of the source with respect to the basin). This is neglected by 1D approaches;

- no validation is available against a sufficiently wide set of strong motion records, especially to quantify the amplitude of the σ values.

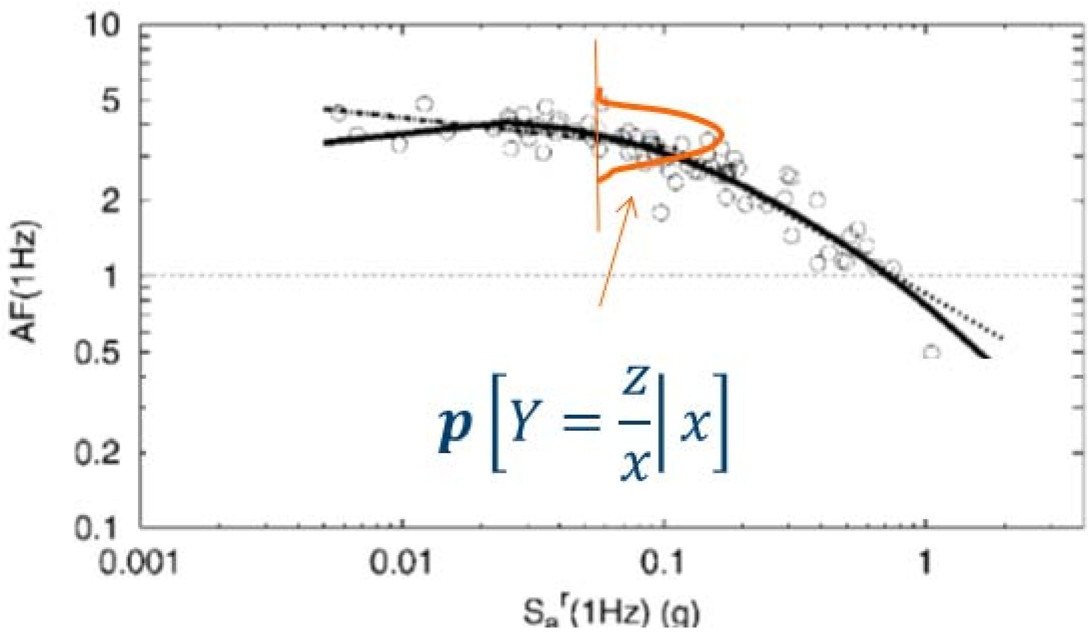


Figure 2.1. Example of conditioned amplification function based on the work of Bazzurro and Cornell (2004).

2.3. Conditioned SAFs based on Kik-net records

An introductory presentation of this topic was already provided in Deliverable D3-54 and will be finalized here, with illustration of a few representative cases.

Kik-net (http://www.kyoshin.bosai.go.jp/) is a part of the Japanese array of strong-motion stations, densely distributed throughout the whole territory. Its feature is that each station is equipped not only with the ground surface accelerograph, but with a borehole instrument as well, typically installed at 100 to 200 m depth, within the bedrock. The shear wave velocity profile down to the borehole instrument is available for each station.

Among the Kik-net stations, we have selected those exhibiting a V_s soil profile similar to those observed in the Po plain, i.e., deep soil sites with $V_{s,30}$ values in the range 200-400 m/s. The V_s profile of two representative stations are illustrated in Fig. 2.2, together with the "unconditioned" SAF, obtained by the spectral ratio of the 5% response spectrum at ground surface with respect to the corresponding spectrum of the borehole record. Such unconditioned SAF is the classical way to illustrate the effects of soil stratigraphy on earthquake ground motion, although in this case they are referred to a borehole instrument. The two cases portrayed in Fig. 2.2 show a remarkably low variability of the SAFs, in spite of the large set of records of both stations, including, especially in the NIGH11 case, a significant number of important earthquakes recorded at short distance.

The drawback of this representation is that it does not allow one to disaggregate the observed amplification values as a function of the amplitude of motion at rock. This is provided by the "conditioned" SAFs (CSAF), which may be obtained by plotting, as in Fig. 2.1, the amplification value at a selected period as a function of a measure of amplitude of ground motion at rock. As a representative parameter for this purpose, we have selected the pseudo-spectral velocity $PSV^R(T)=T \cdot PSA^R(T)/2\pi$, instead of the more commonly used pseudo-spectral acceleration $PSA^R(T)$. The reason for this choice is that the range of variability of PSV does not change with period as significantly as for PSA, so that the same horizontal scale for different vibration periods can be used. This is shown in Figures 2.3-2.4, presenting the CSAFs at the previous stations, for periods from 0.1 s to 3 s, and grouped by Magnitude and epicentral distance.

Similar results were obtained from a total of 21 stations of the Kik-net, selected considering deep soil sites with similar Vs as in the Po Plain. Only shallow events (depth < 15 km) were considered, with PGA > 10 gal. Within this rather representative set of results, some general conclusions are summarized as follows:

- observed variability of SAFs at Kik-net deep soil sites is generally limited (see Annex A for a complete presentation of spectral ratios of selected stations), in spite of the wide range of magnitude and distances encompassed by records;
- conditioned SAFs do not show a significant, if any, dependence on the intensity of motion at bedrock, suggesting, for the stations considered, no clear evidence of non-linear site effects, in spite of the relatively soft soil conditions;
- $\sigma_{\log10}$ computed from the conditioned SAFs ranges typically between 0.04-0.08 ($\sigma_{\ln}$ from 0.09 to 0.18);
- furthermore, no clear evidence is found of a dependency of $\sigma_{\log10}$ with period, while, if the classical 1D approach would be followed, a significant reduction of variability would be obtained for increasing values of period, as discussed later in Chapter 5.

It is worth to remark that in most cases where a significant dependency of conditional SAFs on the level of amplitude on rock was found, such as shown in Fig. 2.5, it was recognized that this was related to very low magnitude events, either due to a low signal-to-noise ratio at long periods, or to the fact that for low magnitude levels PGD is controlled by high-to-intermediate frequencies (see e.g, Figini and Paolucci, 2009), or by a combination of both.

2.4. Conclusions

The analyses of conditioned and unconditioned SAFs from a limited, albeit representative, set of Kik-net stations on deep soil conditions, similar to those encountered in the Po Plain, allowed us to draw some interesting insight on the seismic response of deep soil sites based on observed records.

No clear evidence was found of significant NL effects in the response of Kik-net stations, which would have been made clear by the decrease of the conditioned SAFs with increasing amplitude of motion at the borehole station. This is at variance with results from Régnier et al. (2013) who found significant trends of the shift of the predominant peak frequency with increasing amplitude of motion at the borehole station. Reasons for such discrepancy should be understood by studying in detail selected stations with both approaches and by checking the dependency of results on the magnitude and distance ranges considered.

For the purpose of this study, it is interesting to point out that, in the ideal case of the NIGH11 station, where a wide range of records was obtained and a wide M-R range was covered, records of large magnitude earthquakes (M>6, R<40km) show SAFs smaller than the average for short periods (< 0.1s, see Fig. 2.6), possibly due to NL soil response. However, more interestingly, the site amplification values at periods longer than about 0.5 s (which is roughly the fundamental resonance frequency of NIGH11 site according to 1D models) are much larger than the average, showing that, in the vicinity of large earthquakes, the standard 1D approach may not provide an accurate evaluation of seismic site response (see also results from 3D numerical.

A similar hint of a limited aleatory variability of SAFs from low intensity records at deep soil sites is confirmed by the surface-to-borehole spectral ratios observed from a selected set of records in Casaglia, which will be illustrated in more detail in Chapter 5 (see e.g., Figure 5.5). The interesting remark on these records is that the observed SAF remains nearly unchanged, irrespective of earthquake magnitude and distance, both for local weak events and for distant stronger earthquakes. However, in none of the selected cases, the ground motion amplitude was high enough to predict any significant NL effect.

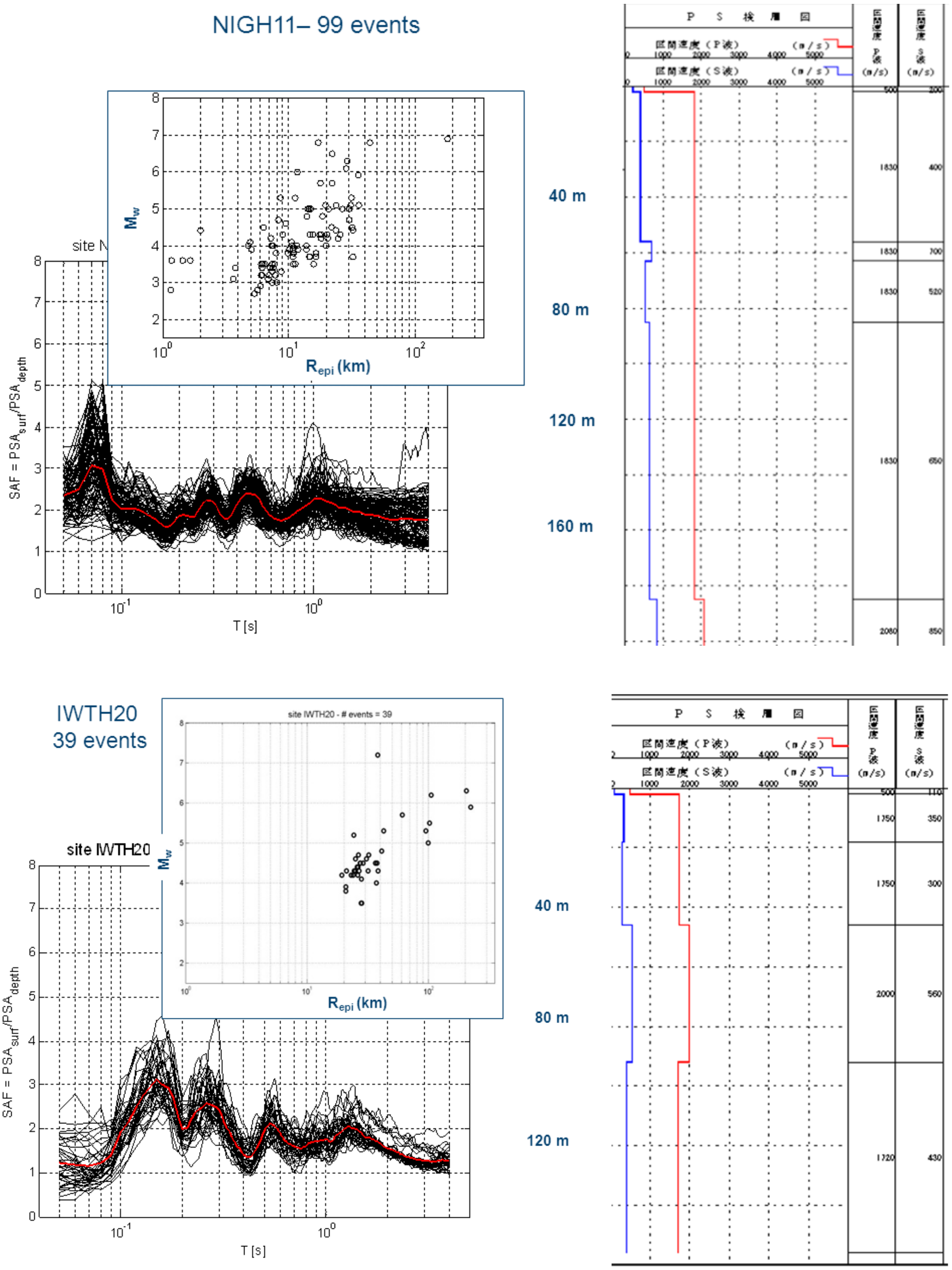


Figure 2.2. Unconditioned SAFs (left side) and V_s profiles (right side) for two deep soil sites stations in the Kik-net. The M_w-R_{epi} distribution for the considered records is also shown.

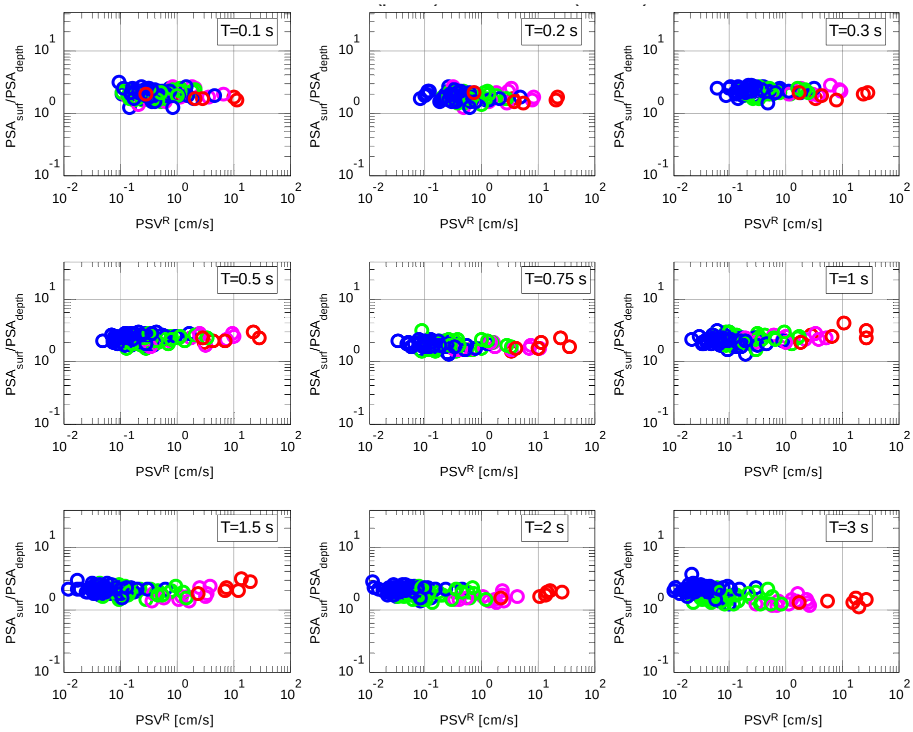


Figure 2.3 (a) Conditioned SAFs for different vibration periods for station NIGH11, with data grouped by Magnitude. Blue dots: M<4, green: 4<M<5; magenta: 5<M<6; red: M>6.

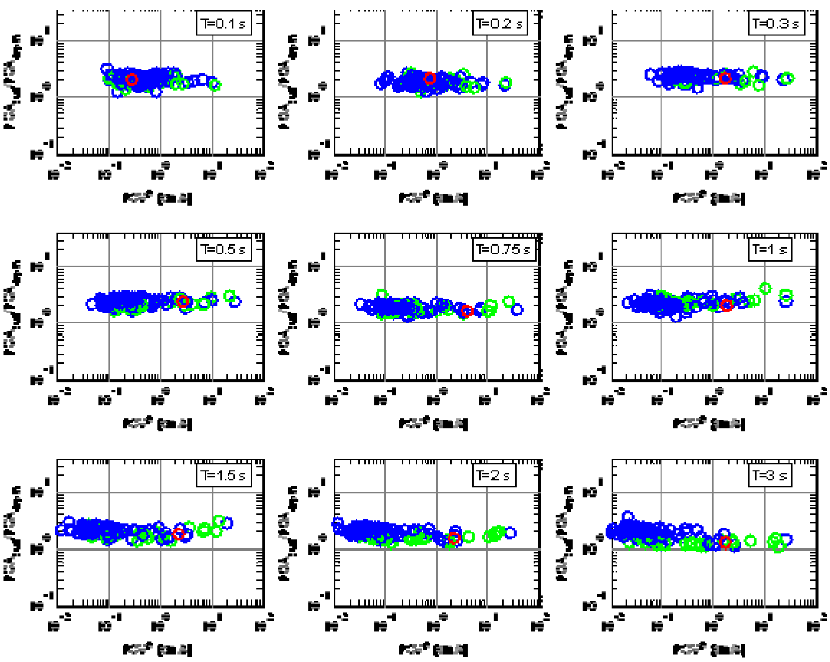


Figure 2.3 (b). Conditioned SAFs for different vibration periods for station NIGH11, with data grouped by Ep. distance. Blue dots: R<20km, green: 20<R<50; magenta: 50<R<100; red: R>100 km.

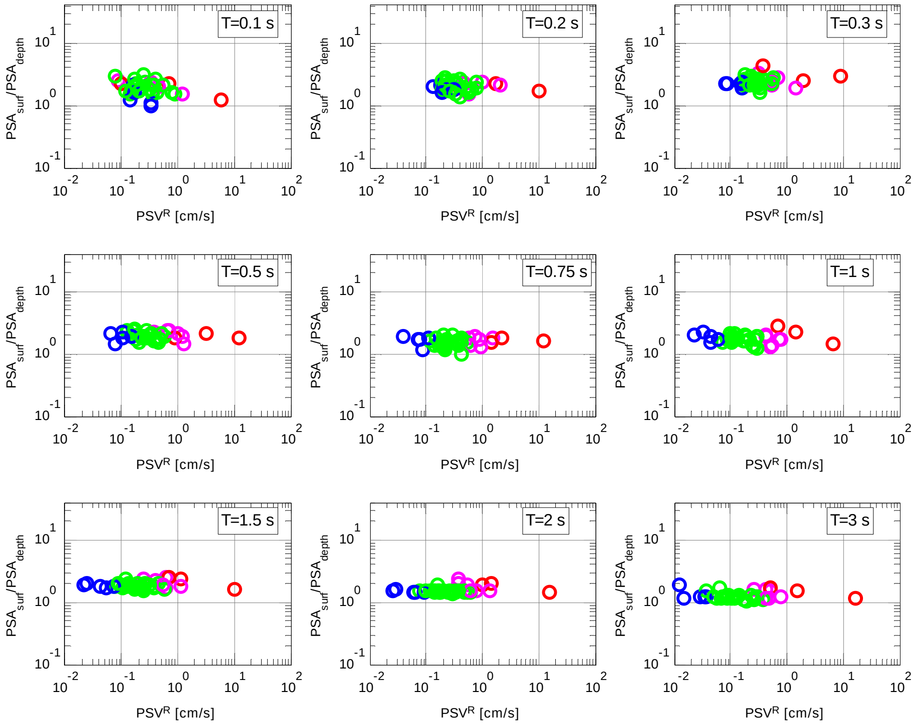


Figure 2.4 (a) Conditioned SAFs for different vibration periods for station IWTH20, with data grouped by Magnitude. Blue dots: M<4, green: 4<M<5; magenta: 5<M<6; red: M>6.

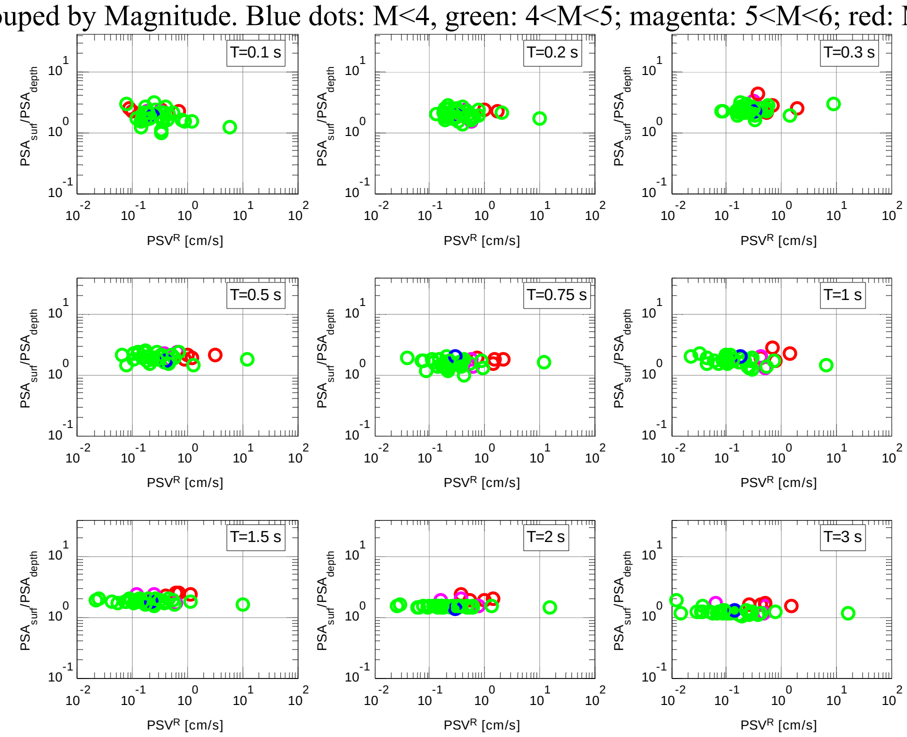


Figure 2.4 (b). Conditioned SAFs for different vibration periods for station IWTH20, with data grouped by Ep. distance. Blue dots: R<20km, green: 20<R<50; magenta: 50<R<100; red: R>100 km.

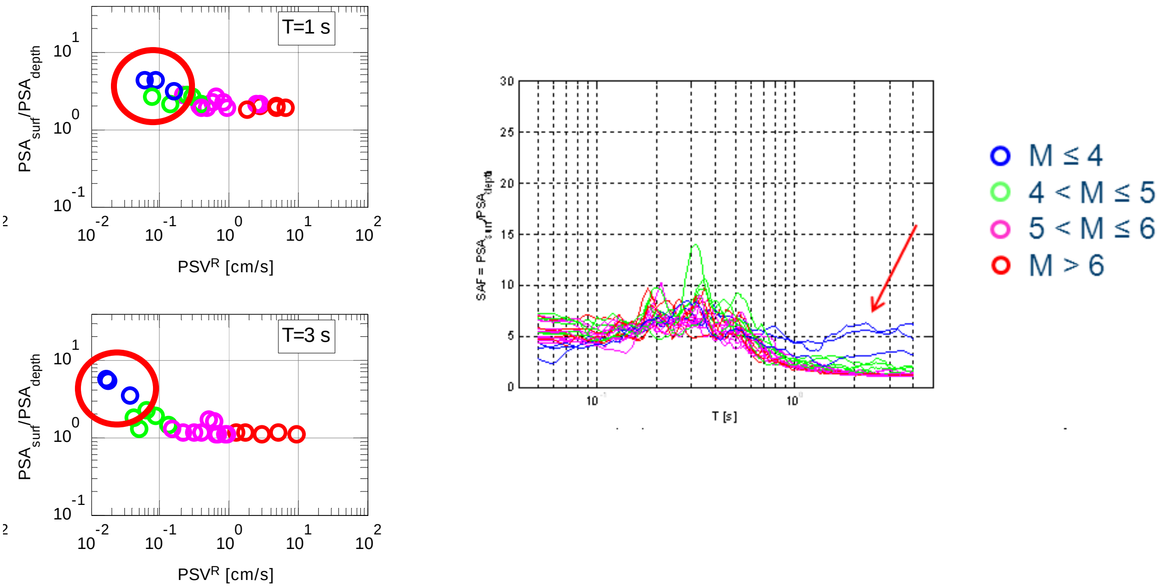


Figure 2.5 Left: Conditioned SAFs for two selected periods at NIGH08 stations. Right: anomalous spectral ratios for small magnitude events with low signal-to-noise ratios.

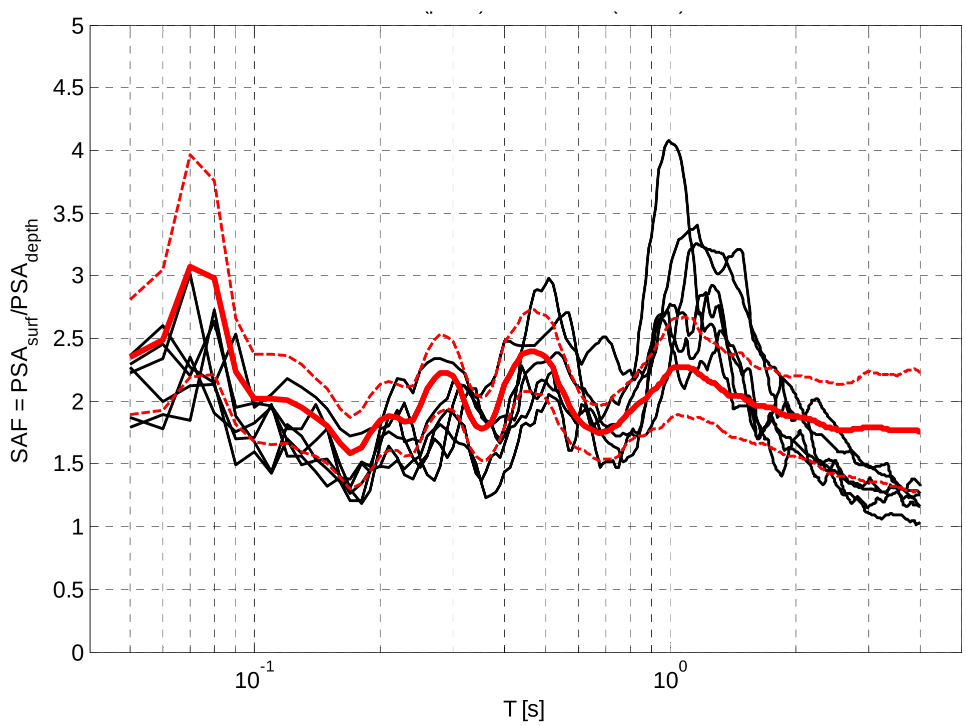


Figure 2.6 Red line: average SAF (±σ) from the 99 records at NIGH11. Black line: SAF obtained from the events with M>6 and R<40 km alone.

3. Selected approach to account for specific site effects in the PSHA

Following the investigations of the previous chapter, referring to the deep soil sites in Japan, but also supported by similar results at the Casaglia site in the Po Plain, as illustrated later in Chapter 5, we have concluded that the observed (aleatory) variability of SAFs at deep soil sites tends to be much smaller than usually predicted, especially when seismic events of low intensity occur. Furthermore, in case of high intensity events, only moderate NL effects on seismic response were found and limited to the very short period range (< 0.1 s), as noted in more detail in Figure 2.6 referring to the NIGH011 station, while, for long periods, the 1D models seems to be unfit to capture not only the variability but also the amplitude itself of observed SAFs.

To go through and quantify the different sources of uncertainty when accounting for specific site effects in the PSHA, we have followed the classical, and sound from an engineering viewpoint[2], hybrid approach, the basic steps of which are outlined in Fig. 3.1, and summarized as follows:

1) start from the median Uniform Hazard Response Spectrum (UHRS) at rock for the given return period (RP);
2) select a set of real unscaled, or moderately scaled, accelerograms (e.g., 7) the average response spectrum of which fits the median UHRS within a tolerable error (e.g., ± 10%), in a sufficiently large period range to encompass the peaks of the site-specific SAF;

[2] This is also the approach outlined in the US NRC (Nuclear Regulatory Commission) Regulatory Guide 1.208 (2007) "A performance-based approach to define the site-specific earthquake ground motion" : "To properly address amplification or deamplification effects of the soils between the generic rock horizon, the ground surface, and other interfaces in between, the following procedure should be used: (1) Develop the site-specific soil profile. (2) Develop appropriate modified earthquake time histories to be used in site response analyses. (3) Perform a suite of site response analyses to determine mean site amplification functions for a range of frequencies. (4) Develop the UHRS at the free ground surface based on the generic rock-based PSHA and the mean site amplification functions".

3) perform 1D numerical simulations, with nonlinear or linear equivalent soil models, using the set of accelerograms at point 2) as input motions and the best soil model based on an expert opinion[3];
4) compute the ratio of the response spectrum of output motions with respect to the input motions; the mean value of such ratio will be identified as the mean amplification function of the site associated to the specific RP considered;
5) the design response spectrum at ground surface will be obtained by multiplying the UHRS on rock by the site-specific SAF;
6) quantify uncertainties, either under a logic tree framework discriminating the different model selections at steps (2) and (3), or by considering expert opinion.

In the following two chapters, we will clarify how we have decided to deal with steps (2) and (5). We limit ourselves to note here that, as will be shown in the application example of Chapter 5, considering a proper selection of input motions "conditioned" to fit the target UHRS at rock, enables one to reduce significantly the scatter of results, so that the resulting SAF will be "conditioned" to the specific return period considered. This has the advantage to improve the control on the seismic response analyses, including non-linear effects, while keeping a reasonably low number of input motions, constrained to approach the UHRS.

[3] At this stage, selection of the best numerical code for the problem at hand, the more suitable nonlinear constitutive law for the soil layers, the best set of dynamic properties for the soil profile, cannot be made but on the base of an expert opinion

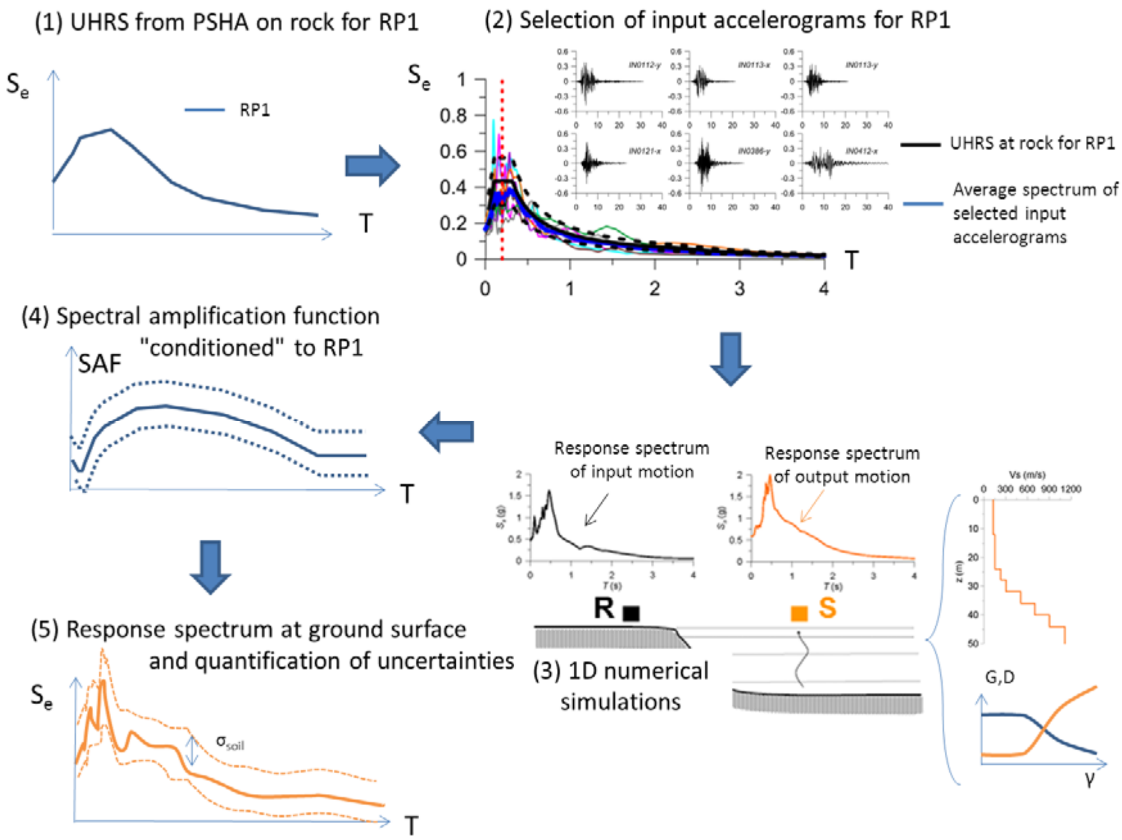


Figure 3.1. Flowchart for site effects evaluation starting from the PSHA on rock.

4. Selection of input motions compatible with PSHA at rock sites

4.1. Scope

Proper selection of input ground motions for linear and non-linear seismic analyses of structures and soil systems has become one of the leading topics in research in earthquake engineering. According to recent trends, as also recognized by the ASCE recommendations both for buildings and other structures (ASCE/SEI 7-10)[4] and for nuclear power plants (ASCE/SEI 43-05)[5], the suite of input accelerograms should have some basic properties that may be summarized as follows:

- they should come from records of real earthquake events approaching, in terms of magnitude, distance and site conditions, the conditions that mostly affects seismic hazard for the specific return period;
- the average value of response spectra of input accelerograms should closely approach the target UHRS (in a range that ASCE 43-05 recommends to be from -10% to +30%);
- a moderate scaling of accelerograms is generally accepted to improve the spectral matching with the UHRS;

[4] The ASCE/SEI 7-10 Standard (Minimum Design Loads for Buildings and Other Structures, ASCE, 2010), recommends that input ground motions shall be selected from actual recorded events "having magnitude, fault distance, and source mechanism that are consistent with those that control the maximum considered earthquake (..) The ground motions shall be scaled such that the average value of the 5 percent damped response spectra for the suite of motions is not less than the design response spectrum for the site for periods ranging from 0.2T to 1.5T where T is the fundamental period of the structure in the fundamental mode for the direction of response being analyzed".

[5] Quoting ASCE/SEI 43-05, Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities (ASCE, 2005), "The general objective is to generate a modified recorded or synthetic accelerogram that achieves approximately a mean-based fit to the target spectrum; that is, the average ratio of the spectral acceleration calculated from the accelerogram to the target, where the ratio is calculated frequency by frequency, is only slightly greater than one. (…) The computed 5%-damped response spectrum of the accelerogram (if one synthetic motion is used for analysis) or of the average of all accelerograms (if a suite of motions is used for analysis) shall not fall more than 10% below the target spectrum at any one frequency (…) The mean of the 5%-damped response spectra (if a suite of motions is used for analysis) shall not exceed the target spectrum at any frequency by more than 30% (a factor of 1.3) in the frequency range between 0.2Hz and 25Hz."

- such spectral matching in terms of average spectrum is recommended in a sufficiently wide period range to constrain not only the spectral ordinate at the fundamental period of the structure, but the spectral shape as well (e.g., Baker and Cornell, 2006; Haselton et al., 2009).

For structural systems (see e.g., ASCE/SEI 7-10) the latter requirement is typically introduced to account for the sensitivity of nonlinear structural response to spectral ordinates at periods larger than the fundamental one, and to the higher modes contribution at shorter periods, while, for systems possibly involving non-linear soil-structure interaction effects, the requirement may even be more stringent, because soil response is governed by a wide range of frequencies and not by a narrow band around the fundamental period of the structure. In the latter case the ASCE/SEI 43-05 recommend to consider the whole frequency range 0.2-25 Hz.

There are no standard methods to select acceleration time histories to fit a prescribed target spectrum, the ideal case being the selection of real accelerograms recorded in seismic conditions close to the target ones, e.g., based on the Magnitude, distance and epsilon coming from the disaggregation of the PSHA at rock. Different approaches have been proposed for such an optimum selection, although in practically all cases the accelerogram selection is more or less deeply modified by scaling procedures to improve the fit with the target spectrum. An effective tool for this purpose was introduced by Kottke and Rathje (2008), who published the software SigmaSpectra, enabling one to control in the selection not only the median spectrum but the sigma as well.
In the recent years, ground motion selection based on Conditional Spectra (Baker, 2011; Jayaram et al., 2011), has gained a growing relevance. However, this approach has been basically conceived for systems governed by their response at the fundamental vibration period, and its applicability is still disputed for cases where large non-linear effects and/or participation of higher modes in structural response may affect the choice of the conditioning period. For ground response analyses, this limitation of the Conditional Spectra is even more important.

In the following, an alternative approach is presented (Smerzini et al., 2013), based on the following ingredients:

- a high-quality strong motion database, made of digital records of earthquakes relevant for seismic hazard studies in Italy, obtained in stations with seismic site characterization, in most cases provided by the $V_{s,30}$;
- a software for automatic selection of strong motion records compatible on average with a target spectrum, within a prescribed period range and a prescribed tolerance.

Note that other approaches have been proposed recently with a similar objective (e.g., Corigliano et al., 2012). In our case, the key feature for the good performance of the approach is the *ad hoc* development of the strong motion database, which was developed specifically for this purpose, by giving priority to the quality and significance of records for seismic hazard analyses.

4.2. SIMBAD: a database of broadband earthquake ground motions

SIMBAD (Selected Input Motions for displacement-Based Assessment and Design) was initially conceived as a subset of the worldwide database assembled by Cauzzi and Faccioli (2008), with the main objective of providing records in the magnitude and distance ranges of engineering relevance for the most frequent design conditions in Italy. Selection of records in SIMBAD was based on the following criteria:

- records from shallow crustal earthquakes, at epicentral distance R_{epi} approximately less than 30 km, with moment magnitude M_W ranging from 5 to 7.3;
- accuracy of records at long periods, so that most records (about 90%) included in the database are from digital instruments, with a high-pass cut-off frequency of processed ground motions below 0.15 Hz;
- availability of V_{S30} at the recording station: only in few cases, we retained records where the ground classification according to the EC8 was available, without a direct V_{S30} measurements;
- approximately uniform distribution of records in the selected magnitude and distance ranges.

Table 4.1 provides a list of the worldwide ground motion networks used for assembling the SIMBAD database.

In general, raw acceleration time histories were processed with special care to ensure compatibility of corrected records according to the procedure introduced by Paolucci et al. (2010) to process records for the ITACA Italian strong motion database (http://itaca.mi.ingv.it). The latter requirement means that single and double integration of the corrected accelerograms produce velocity and displacement time series with zero initial conditions and without unphysical baseline trends, so that no further correction is needed. Only for the ground motions derived from ITACA or from USA providers (PEER, CESMD and NSMP databases, see Table 4.1), processed records were included in SIMBAD as disseminated by the data provider, without re-processing raw records.

The SIMBAD database presently consists of 467 three-component acceleration time histories, from 130 earthquakes worldwide. Most records come from Japan (47%), Italy (18%), New Zealand (17%), and USA (9%), with minor contributions from Greece, Turkey, Iran and other European countries (9%), as shown in Figure 4.1. Note that most records are representative of soil B (44%) and C (43%), while only a few of them are recorded on rock (8%), or soft soils D (4%) and E (1%), as depicted in Figure 4.1.

Table 4.1 Source of strong ground motion records included in the SIMBAD database.

Country	# records	Data provider
Japan	220	K-NET[a]
		KiK-net[b]
Italy	83	ITalian ACcelerometric Archive ITACA[c1] Department of Civil Protection[c2]
New Zealand	77	Institute of Geological and Nuclear Sciences: GNS[d]
USA	44	Center for Engineering Strong Ground Motion Data: CESMD[e]
		PEER Strong Motion Database[g]
		U.S.Geological Survey National Strong Motion Project: NSMP[f]
Europe	18	European Strong-Motion Data Base: ESMD[h]
Turkey	15	Turkish National Strong Motion Project: T-NSMP[i]
Greece	7	Institute of Engineering Seismology and Earthquake Engineering[l]
Iran	3	Iran Strong Motion Network ISMN[m]

[a]*http://www.k-net.bosai.go.jp/* - [b]*http://www.kik.bosai.go.jp/* - [c1]*http://itaca.mi.ingv.it/* - [c2]*http://www.protezionecivile.gov.it/*- [d]*http://www.geonet.org.nz-* [e]*http://strongmotioncenter.org/*- [f]*http://nsmp.wr.usgs.gov/* - [g]*http://peer.berkeley.edu/peer_ground_motion_database* - [h]*http://www.isesd.hi.is/* - [i]*http://daphne.deprem.gov.tr* - [l]*http://www.bhrc.ac.ir/* - [m]*http://www.itsak.gr/en/head*

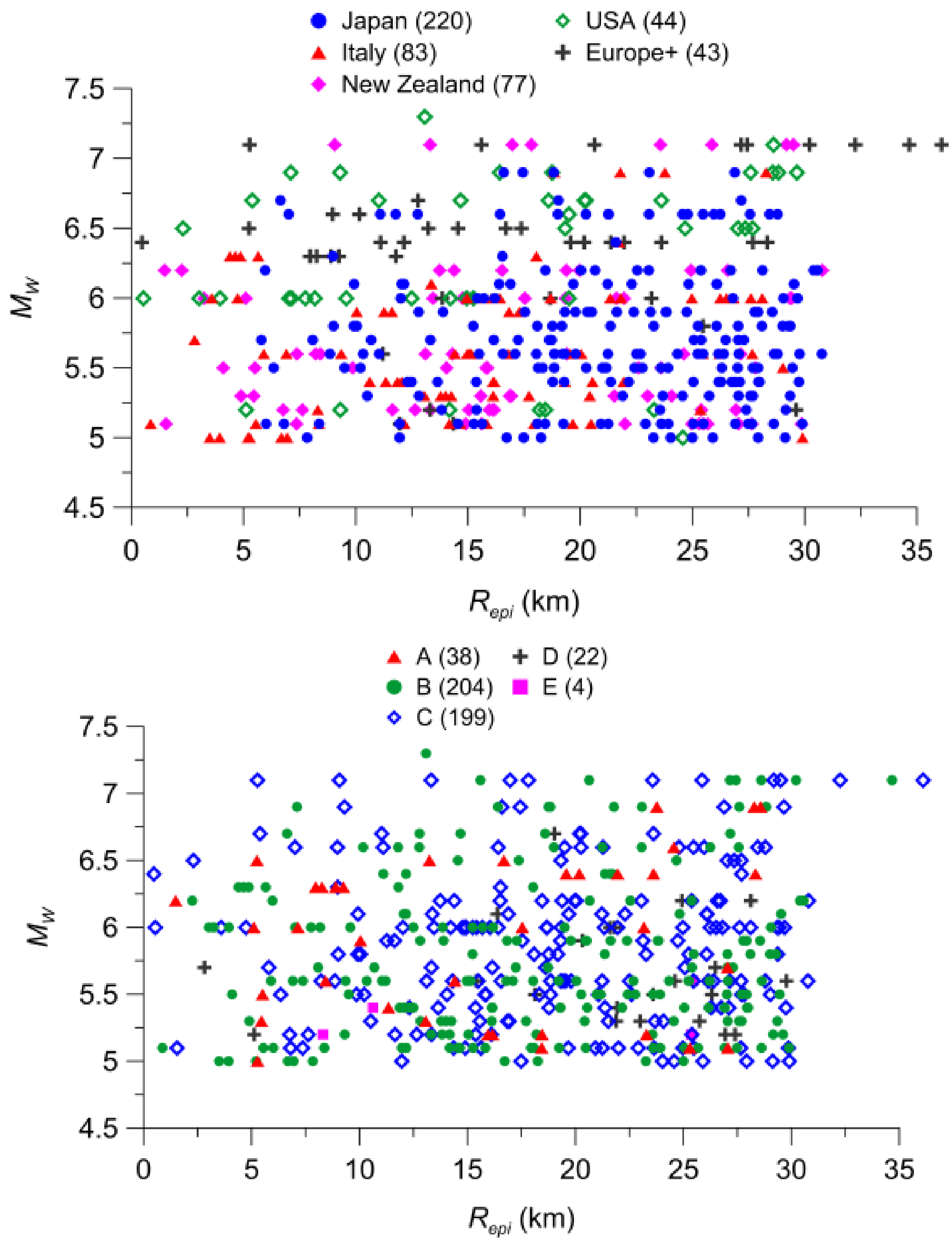


Figure 4.1 Distribution M_W, R_{epi} with indication of the geographical origin (*top*) and of the ground category according to the EC8 soil classification (*bottom*) of the records included in SIMBAD.

4.3. REXEL-DISP: software for the selection of displacement-spectrum-compatible ground motions

The availability of a high quality digital strong motions database, along with a target spectrum constrained both at short and long periods, may allow a more rational ground motion record selection for engineering applications. To this aim, a user-friendly software, REXEL-DISP (Figure 4.2), based on the same core algorithms of REXEL (Iervolino et al., 2010), was jointly developed at Politecnico di Milano and University Federico II, Napoli.

REXEL-DISP is freely available at www.reluis.it. The software enables one to select combinations of (multi-component) horizontal accelerograms whose average response spectrum is compatible with a target displacement spectrum in an arbitrary period range. The record search is carried out such that the response spectral shape of individual records is as similar as possible to the target one in the same period interval.

As regards the criteria for displacement-based ground motion selection, the search for combinations of real accelerograms within SIMBAD is based on the following target spectra:

- design displacement spectrum from the Eurocode 8;
- design displacement spectrum from the NTC08 (Italian norms for constructions);
- any user-defined spectrum, such as the one coming from the PSHA.

The sets of compatible records may consist either of single-component or of pairs of horizontal component accelerograms, either scaled or unscaled, to fit the target spectrum. For this application, the objective being the analysis of seismic site effects, we have preferred selecting only unscaled records.

4.4. Example of input selection for Casaglia site

Based on the PSHA results at rock obtained at Casaglia, Emilia-Romagna (see Deliverable D4-94), seven real unscaled accelerograms were extracted by REXEL-DISP from the SIMBAD database, to achieve an average broadband spectral compatibility from 0 to 8 s. For sake of brevity, We will consider here only the case of 2475 yrs return period. Table 4.2 summarizes the main features of the selected accelerograms.

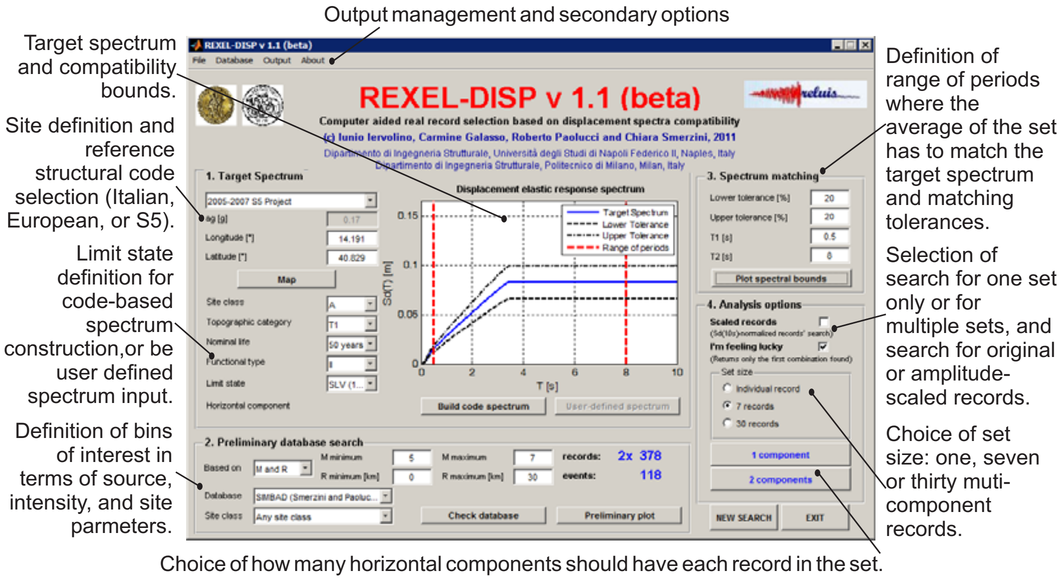


Figure 4.2 Graphic user interface of REXEL-DISP and main required information or record selection options.

Table 4.2 Selected records by REXEL-DISP, to fit the target rock UHRS at Casaglia for the 2475 yrs return period.

ID	*Station*	*Earthquake*	*Date*	*Mw*	*R_{epi} (km)*	*PGA (m/s^2)*	*PGV (m/s)*	*Soil class*
i112x	ST_105	South Iceland	Jun 17 2000	6.5	14.5	2.07	0.127	B
i436y	ST_36420	Parkfield	Sep 28 2004	6	3.9	4.09	0.157	B
i169x	GSA	L'Aquila	Apr 06 2009	6.3	18.0	1.47	0.098	B
i114y	ST_108	South Iceland	Jun 17 2000	6.5	13.2	1.56	0.113	A
i115x	ST_109	South Iceland	Jun 17 2000	6.5	17.4	3.75	0.152	B
i395x	HVSC	Christchurch	Jun 21 2011	5.2	15.0	2.72	0.102	B
i020y	TTR009	W Tottori	Oct 06 2000	6.6	11.8	3.01	0.366	B

As can be seen in Fig. 4.3, a satisfactory agreement is achieved in terms of average response spectra, both in the short and long period ranges, although the overall scatter of this selection is rather high, especially due to two outliers out of the seven records. Although a better selection could have been obtained by enabling control of the maximum error, we have preferred to keep this “dispersed” selection to check the differences in terms of 1D site amplification functions, when comparing such a set with a perfectly matched one. This will be illustrated in Chapter 5.

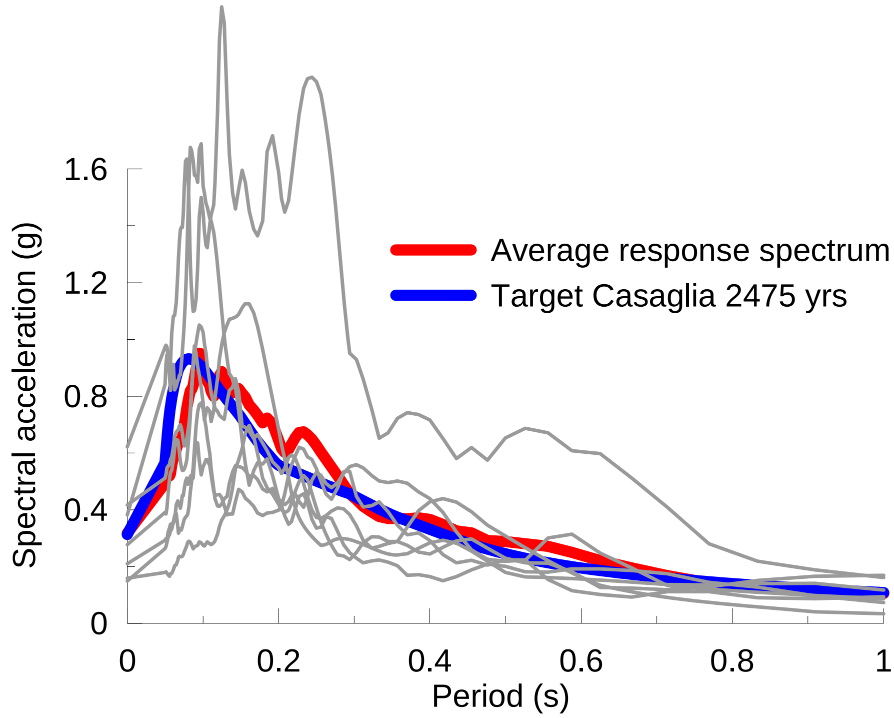
We finally note that the target spectrum is for ground class A, but, to increase the number of candidate records, these have been selected to lie within soil classes either A or B, with B sites characterized by relatively high V_{s30} values. As well known, strong motion records at class A sites are rather poorly represented in worldwide databases, so that it is reasonable that the soil class compatibility should be relaxed.

4.5. Spectrally matched selection from real records

As a second complementary step of the input motion selection procedure, we have also created a "spectrally matched" set of accelerograms. Starting from the previous selection, a scaling procedure in the frequency domain is applied. Namely, a correction factor for the Fourier spectrum of a prescribed accelerogram is calculated based on the ratio of the response spectrum (RS) of the accelerogram, with respect to the target one. Such correction factor is applied to scale iteratively the amplitude of the Fourier spectrum of the accelerogram, while keeping the same phase as the original one, until its RS fits the target one. The procedure is similar to that proposed by Shahbazian and Pezeshk (2010).

In this way, seven "perfectly matched" accelerograms were obtained (Fig.4.4). Contrary to other spectral matching approaches, since the seed real accelerograms have a broadband average spectral compatibility and are reliable also in the long period range, the frequency scaling does not usually imply a significant modification of the original record, neither in terms of acceleration, nor of velocity or displacement. This is shown in more detail in Fig. 4.5 for the case of record i69x, where, on the top, the comparison in terms of acceleration RS is shown, while, in the bottom side, velocity and displacement of the real and spectrally matched records are compared.

Starting from these results, we will explore in the next section the effect of different selection criteria on the median seismic site response at the Casaglia site, as well as on its variability.



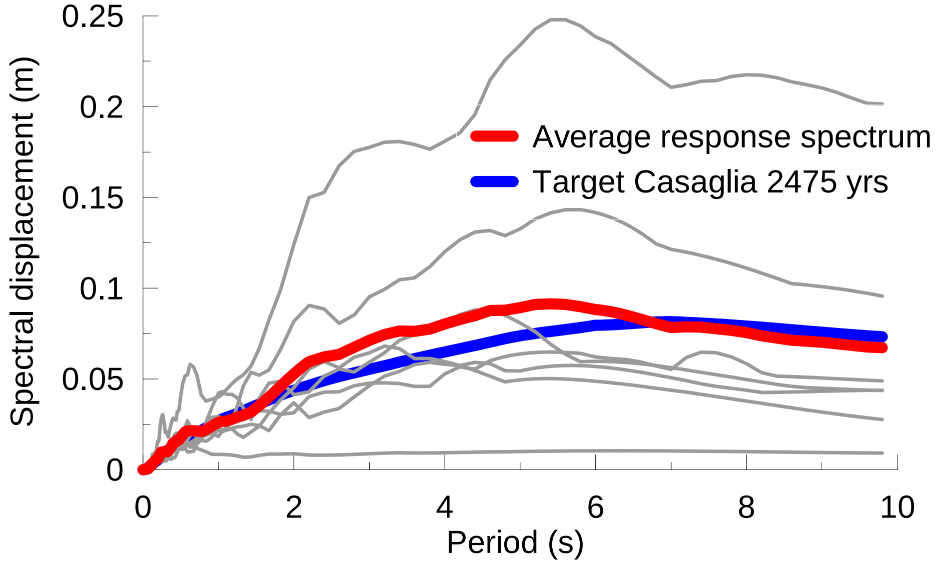


Figure 4.3. Response spectra in acceleration (top) and displacement (bottom) of the selected accelerograms for the Casaglia site reported in Tab. 4.2. Note the different horizontal scales in the plots, to highlight the short and long period range of the compatibility.

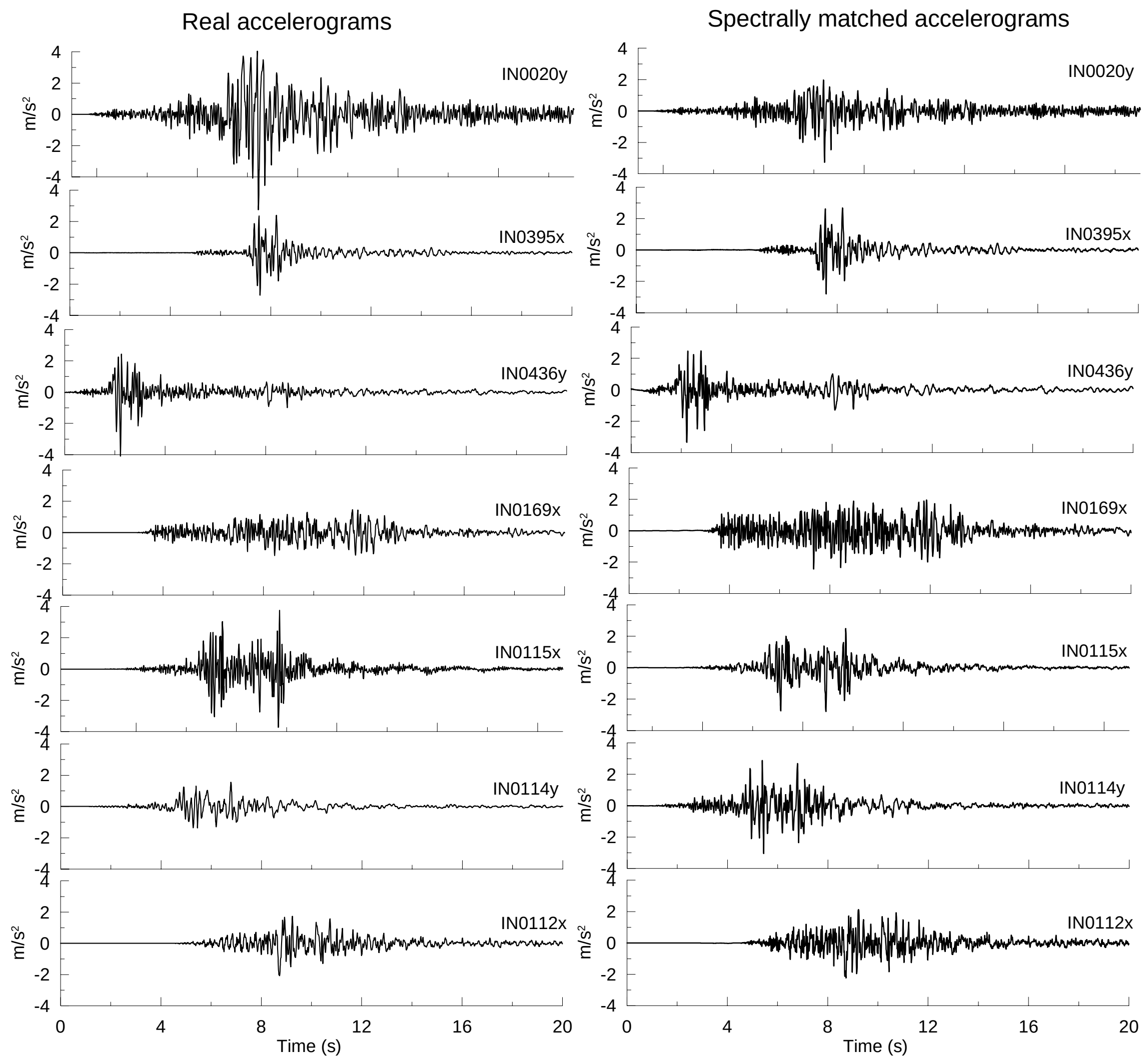


Figure 4.4 Left: time histories of the selected accelerograms in Tab.4.2. Right: time-histories of the corresponding spectrally matched accelerograms.

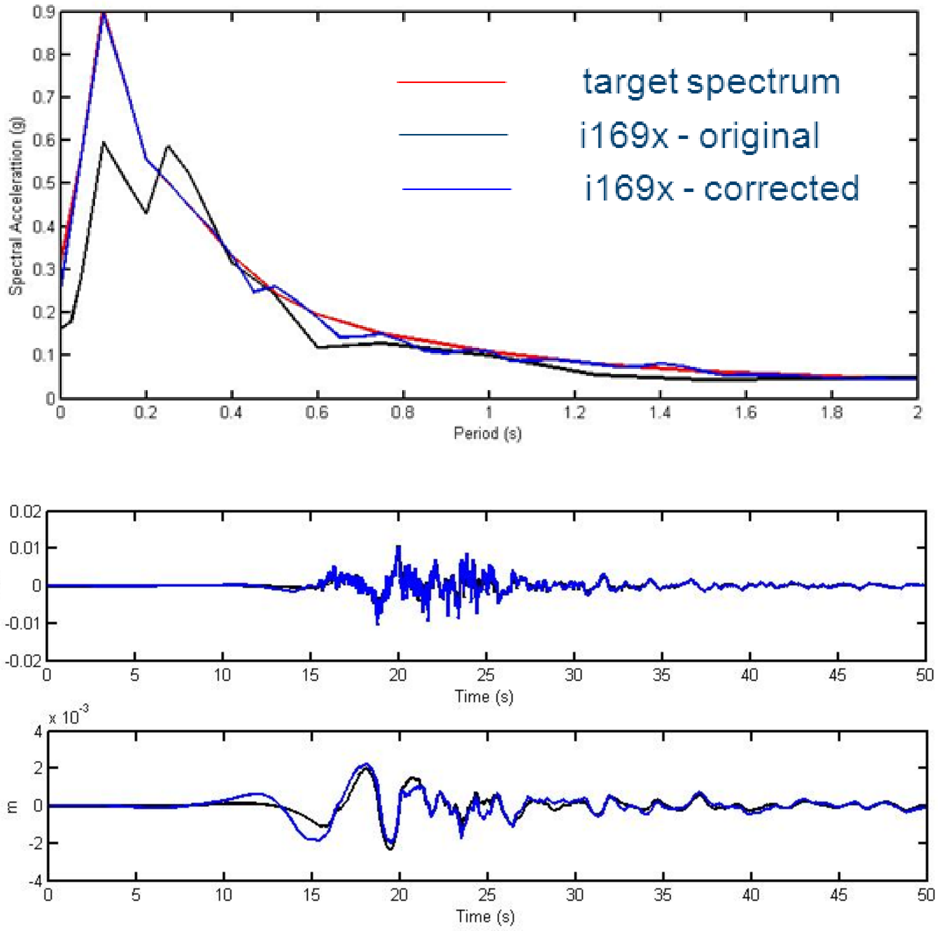


Figure 4.5 Results of spectral matching for record i169x. Top: Comparison in terms of acceleration response spectra (black: RS of the original record; red: target spectrum; blue: RS of the spectrally matched record). Bottom: comparison in terms of time-histories of velocity and displacement (black: original record; blue: corrected record).

5. Site-specific seismic response analyses and quantification of uncertainties

5.1. Introduction

Given a specific target spectrum on rock, either based on a PSHA or on a deterministic approach, sources of uncertainties in specific site effects evaluation can be identified as related to (see Fig. 5.1): (a) selection of input motions; (b) characterization of soil profile dynamic properties; (c) selection of the method of analysis and computer code; (d) modeling and quantification of non-linear soil behavior.

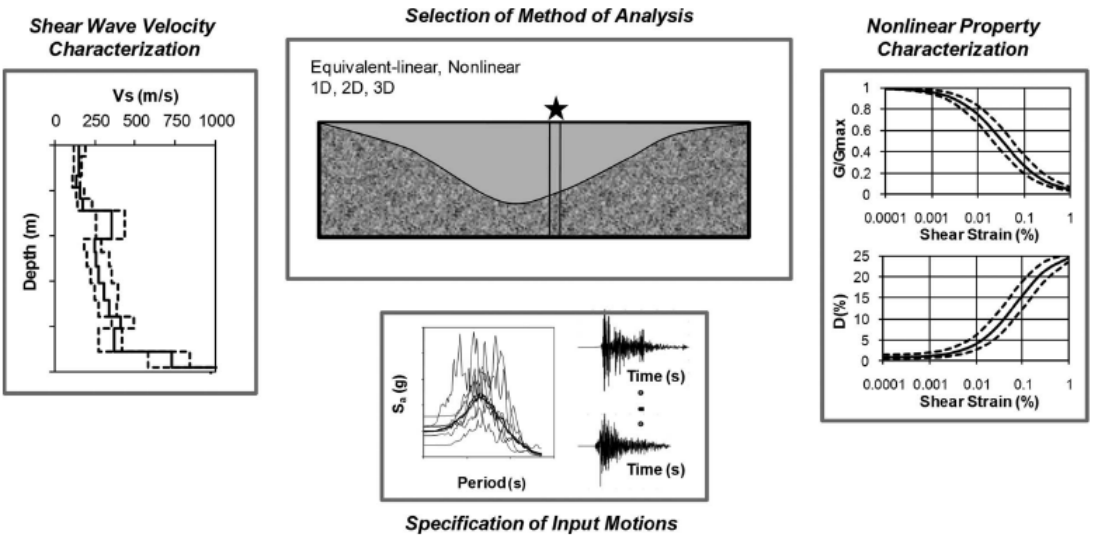


Figure 5.1 Sources of uncertainties in seismic site response analysis. After Rathje et al. (2010).

As a matter of fact, such sources of uncertainties are significantly interconnected and it may not be correct to treat them separately. If considered in the framework of a logic tree approach, such interconnection can be sketched as in Fig. 5.2, and the complexity of the problem may soon become huge and hardly manageable. Of course, this complexity increases as the amplitude of input ground motion becomes larger. For low levels of input, only the Vs profile and the method of analysis may play a role, while, for large levels, coupling of input motion selection and non-linear soil response will have the largest role. Besides, attributing weights to the different combinations within the tree appear to be rather arbitrary, at least at present.

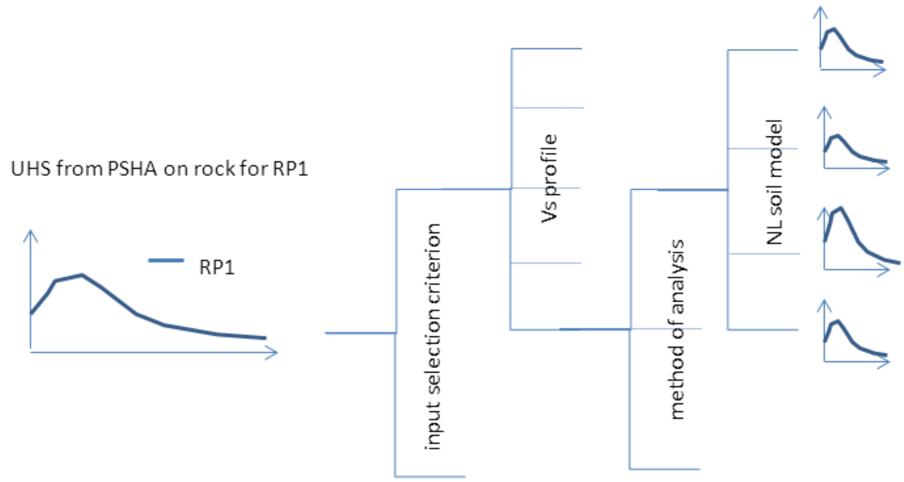


Figure 5.2. Sketch of a possible logic tree approach for site effects studies in the PSHA. The starting point is the Uniform Hazard Spectrum on rock for a given Return Period.

Therefore, quantification of uncertainties will be dealt with in this section in a simplified way, by treating them as independent contributions.
The results presented in this section will refer to the site-specific investigations for seismic hazard analyses in the Po Plain. In this case, the following conditions are met, namely:

- detailed investigations available at several sites regarding the deep and shallow soil profile characterization;
- availability of a large amount of records from the Emilia earthquake sequence, but no close-by outcropping rock sites to be considered as a reference for site effects analyses;
- availability of surface and borehole records at the Casaglia site, albeit only for relatively weak motions.

Under these premises, and considering as a target the Casaglia site, we will explore in this section, and quantify the epistemic uncertainty, related to the following assumptions:

- Vs soil profile model;
- Non-linear soil behavior and modelling approach;
- Criteria for selection of input motion;
- 3D modeling of site amplification functions.

5.2. The Casaglia site in the Po Plain

A borehole station was installed in Casaglia in the mid-90s by researchers of the Istituto Nazionale di Geofisica e Vulcanologia (Margheriti et al., 2000; Cocco et al., 2001) at the soil-bedrock interface at some 130 m depth, to exploit the detailed knowledge of the underground geology available from oil exploration in the Po Plain and the shallow depth of the limestone and marl bedrock underlying the Quaternary sediments of the Plain. As a matter of fact in the Casaglia area, as well as in that of Mirandola hit by the 2012 earthquakes, the seismic bedrock lies at a depth ranging from 130 to 150 m, providing a rather unique opportunity to investigate bedrock motions in the Po Plain.
After the M5.4 Reggio Emilia earthquake of Oct 15 1996, a second instrument was installed at the ground surface, and the pair of surface and borehole instruments recorded the aftershock sequence of Oct 1996. The instruments were subsequently removed but, after the Emilia mainshocks of May 20-29 2012, two new stations were installed at the same locations. These stations are now operated by the Osservatorio Geofisico Sperimentale (OGS), Trieste. More recently, a further instrument was installed in the vicinity of the OGS one, at few hundreds m distance.
For this reason, the Casaglia site was selected by the Italian partners of the Sigma Project as one of the benchmark sites on which to make investigations on seismic site response analyses.

5.2.1. Vs profiles

Figure 5.3 shows, on the left side, a sketch of the surface geology of the Casaglia area, while, on the right side, the stratigraphic log of the first 130 m above the sensor is shown. The main features of the stratigraphic profile are the water table at nearly 15 m, the continental–marine transgression at nearly 100 m, and the Quaternary basement that lies at a depth of 130 m, just above the sensor. There are other minor horizons between 15 and 100 m, named paleosoil in Figure 5.3.
Body-wave velocities of the shallow alluvial layers were estimated during the perforation of the borehole by means of cross-hole measurements in the upper 80 m. This information, complemented by surface wave dispersion analyses to calibrate

velocities in the shallow layers, allowed the INGV researchers to obtain the Vs profile plotted in Figure 5.4 (Margheriti et al., 2000).
Later on, further studies of seismic site characterization were carried out at the Casaglia site, especially after the 2012 earthquakes. A summary of the main results of such investigations is reported in Table 5.1 and in Figure 5.4.

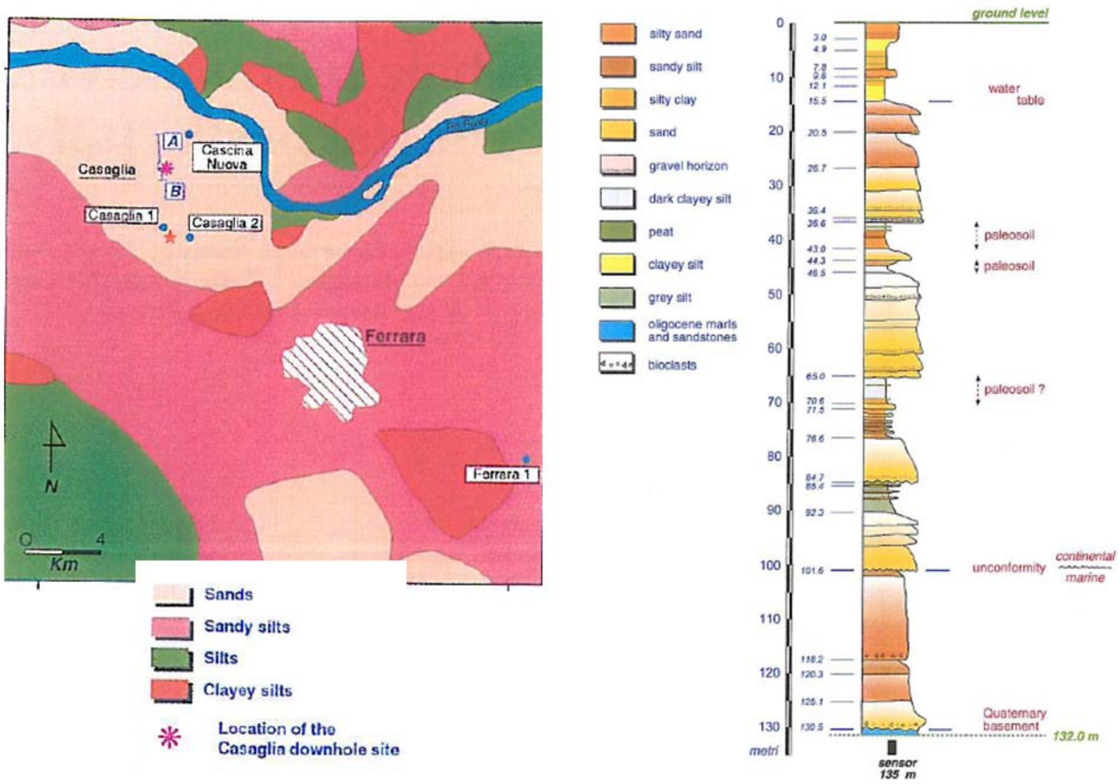


Figure 5.3. Left: Surface geology map of the Casaglia site. Right: Soil column down to the Quaternary basement at 130 m depth. Adapted after Cocco et al., 2001.

Table 5.1. Summary of techniques of Vs survey in Casaglia, and seismic site classification

Site	Source profile	V_{S30} [m/s]	Ground type
Fioravante et al., 2012	down hole + cross hole	201	C
Picozzi and Albarello, 2007	inversion of Rayleigh wave dispersion and H/V spectral ratio curves	164	D
Margheriti et al., 2000	cross hole + inversions	191	C
DPC-INGV-S2, 2013, D4.1	cross hole	188	C

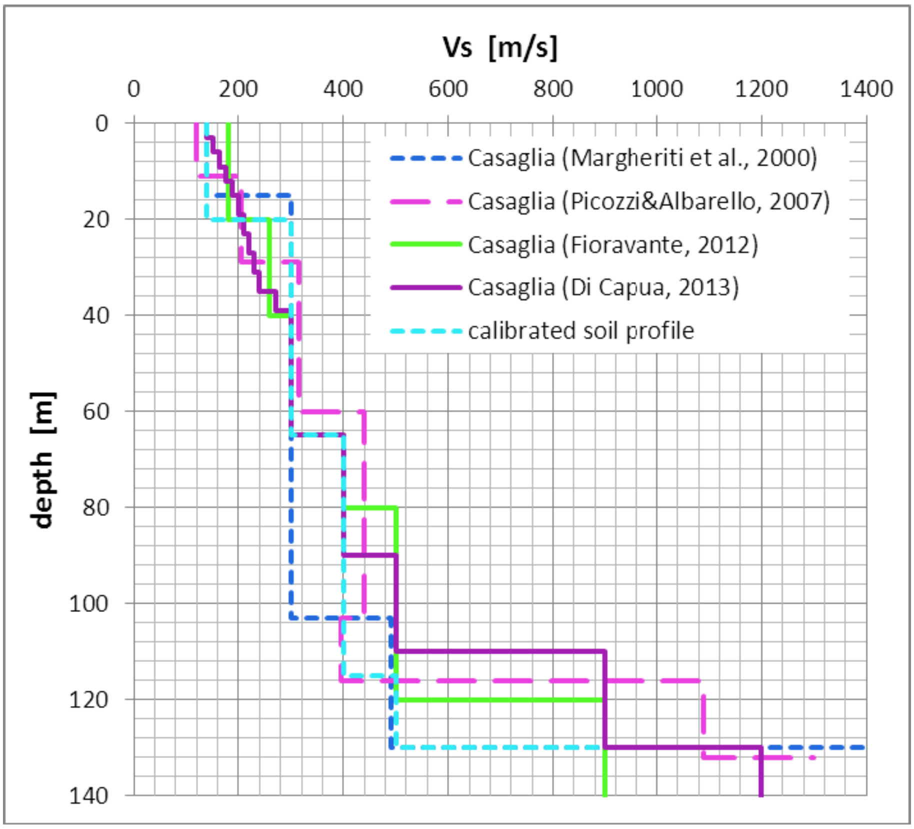


Figure 5.4. Different Vs profiles at the Casaglia site. The corresponding investigation techniques and the $V_{s,30}$ information + site classification are shown in Table 5.1. The Vs profile adjusted based on the surface-to-borehole spectral ratios (see section 5.2.3) is also shown.

Although there is an overall reasonable agreement among the various investigation results, it should be pointed out that, even in such a case where the available knowledge on the shallow soil profile is very detailed, there is still a substantial epistemic uncertainty on the Vs profile. Furthermore, none of the experimental profiles is capable to reproduce in detail the observed peaks of the experimental spectral ratios, as will be shown in sect. 5.2.3, so that an ad hoc Vs profile had to be adjusted. Finally, it is worth noting that in such a case the epistemic uncertainty of the Vs profile leads to different seismic site classification, in three cases C and one case D, with obvious consequences in terms of definition of seismic actions for design, in the case that the amplification factors from the norms were used.

5.2.2. **Available records**

3 sets of records were selected to investigate the seismic response in Casaglia (Table 5.2), namely:

Table 5.2. Records considered to study seismic response in Casaglia based on surface-to-borehole spectral ratios

INGV (1996)				
Data	**M_d**	**R_{epi} [km]**	**PGA [cm/s^2]**	**PGV [cm/s]**
1996-10-19/02:13	2.7	68.9	0.026	$4.12*10^{-4}$
1996-10-19/03:40	2.9	69.2	0.040	$8.98*10^{-4}$
1996-10-20/02:00	3.2	68	0.247	$4.63*10^{-3}$
1996-10-21/02:16	3.1	68.4	0.033	$8.36*10^{-4}$
1996-10-26/02:41	2.5	70	0.015	$4.52*10^{-4}$
1996-10-26/04:57	3.6	65.3	0.989	$4.83*10^{-3}$
1996-10-26/06:50	3.5	65.3	0.122	$3.42*10^{-3}$
OGS (2013)				
data	**M_L**	**R_{epi} [km]**	**PGA [cm/s^2]**	**PGV [cm/s]**
2013-02-12	3.8	175.8	0.228	$1.25*10^{-2}$
2013-04-22	3.6	116.0	0.268	$5.21*10^{-3}$
2013-06-21	5.2	139.3	4.183	$5.22*10^{-1}$
2013-06-23	4.4	132.0	0.293	$3.95*10^{-2}$
2013-06-30	4.4	133.6	0.271	$4.30*10^{-2}$
2013-07-11	3.9	126.7	0.210	$1.10*10^{-2}$
INGV (2013)				
Data	**M_L**	**R_{epi} [km]**	**PGA [cm/s^2]**	**PGV [cm/s]**
2013-03-24	3	20.6	0.184	$4.71*10^{-3}$
2013-05-04	3.8	8.5	1.920	$7.46*10^{-2}$
2013-09-04	3.3	20.2	0.147	$3.49*10^{-3}$
2013-09-06	3.4	19.9	0.202	$7.94*10^{-3}$

- INGV (1996): 7 records, surface + borehole, from the aftershock sequence of the M5.4 Reggio Emilia earthquake of Oct 15 1996[6];
- OGS (2013): 6 records, surface + borehole, from a series of large distance eartquakes[7];

[6] Courtesy of Lucia Margheriti, INGV, Roma.

[7] Courtesy of Carla Barnaba, OGS, Trieste.

- INGV (2013): 4 records, from a series of local earthquakes. Only one horizontal component available. In this case the surface records is located at few hundreds m from the borehole[8].

The mean (±σ) Fourier spectral ratios of the surface to borehole records are illustrated in Figure 5.5. It can be seen that there is an overall agreement among the different sets in terms of frequency peaks, while the amplitudes of the INGV (2013) peaks largely exceed those of the other two sets of records. This may be explained by the fact that in the INGV set the surface record is at some hundreds m distance from the borehole. As a matter of fact, for a single local event among the four listed within INGV (2013), a record from OGS at the top of the borehole was available. For this record, the surface-to-borehole spectral ratio was found to be in very good agreement with the mean OGS curve in Figure 5.5. Therefore, we can conclude that, in spite of the very different earthquake sequences included in the different sets, the seismic response seems in all cases to be governed by the 1D soil layering effects.

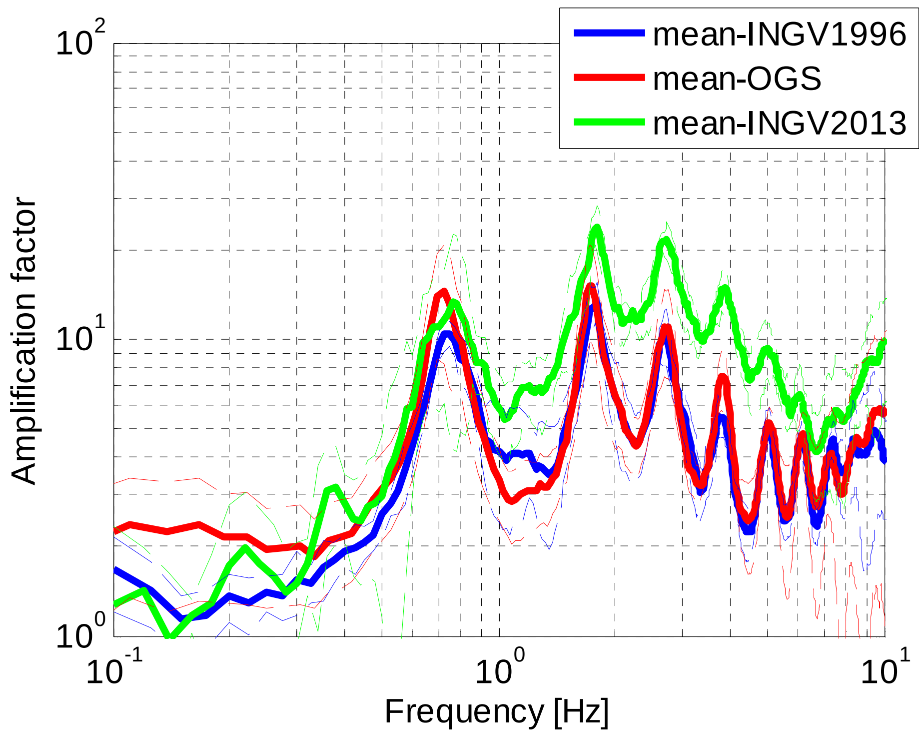


Figure 5.5. Average (±σ) Fourier spectral ratios, surface-to-borehole, from the three sets of records considered at Casaglia.

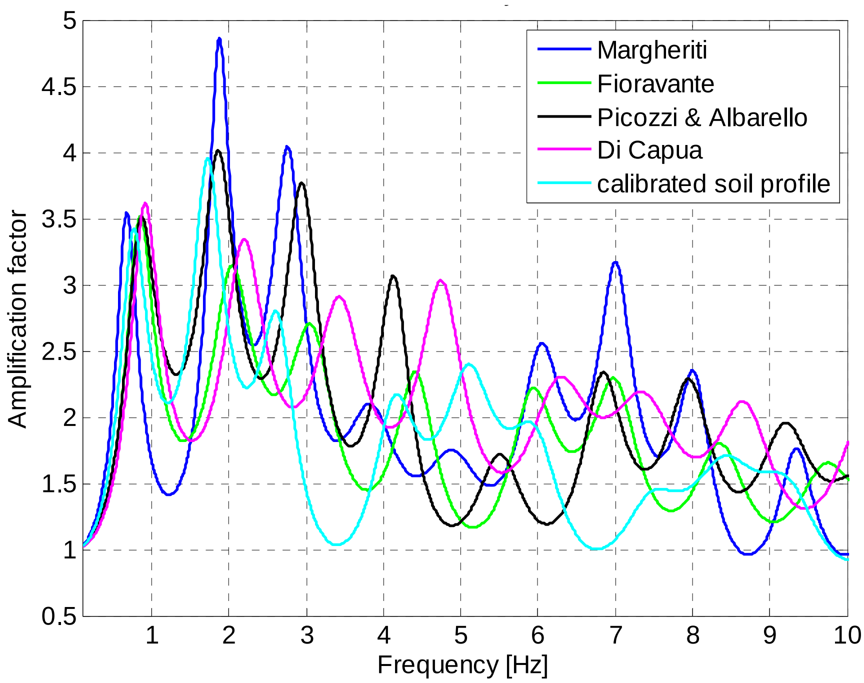
[8] Downloaded at the web site http://ismd.mi.ingv.it.

5.2.3. Adjustment of a best-fit Vs profile at Casaglia

For the reasons outlined previously, we excluded the INGV (2013) spectral ratios. Furthermore, although the OGS (2013) and INGV (1996) provide observed spectral amplification functions in very good agreement, we decided for sake of clarity to consider as the reference observed spectral ratio only that of OGS.
We considered the different Vs profiles available for Casaglia (see Figure 5.4) and we computed the linear transfer functions for the various profiles, estimating the quality factor according to the rule-of-thumb Qs=Vs/10 (Vs in m/s) for all cases, except for Margheriti et al., for which estimated values of Q were available. The surface-to-outcropping bedrock transfer functions are plotted in Figure 5.6a, and clearly show an increasing variability of response for increasing frequencies. The effect of such variability will be quantified in section 5.3.1.
Subsequently, in Figure 5.6b, we compare the surface-to-borehole average OGS spectral ratio with the corresponding function calculated based on the Margheriti et al (2000) Vs profile, which provides the best performance against observations among the various profiles available, and a best-fit Vs profile adjusted so to improve the agreement with observations, especially towards the high frequency peaks. The resulting best-fit profile is reported in Table 5.3 and it is illustrated in Figure 5.4.
Considering Figure 5.6b, it is clear that the overall agreement of 1D transfer functions with observed spectal ratios is good in terms both of peaks and amplitudes, except for the amplitude of the first fundamental mode. The amplitude of such peak depends on the quality factor Q alone, and, for a homogenous layer over bedrock, it can be proven (Faccioli and Paolucci, 2005) that the amplitude of the peak of the n-th natural frequency f_n is:

$$|A(f_n)| = \frac{4Q}{\pi}\frac{1}{2n+1} \quad (n = 0, 1, 2,..).$$

Therefore, to fit the observed peak $A(f_0=0.75\text{Hz}) \approx 10$, an average quality factor $Q \approx 8$ would be required throughout the soil layer, which looks unrealistically low.



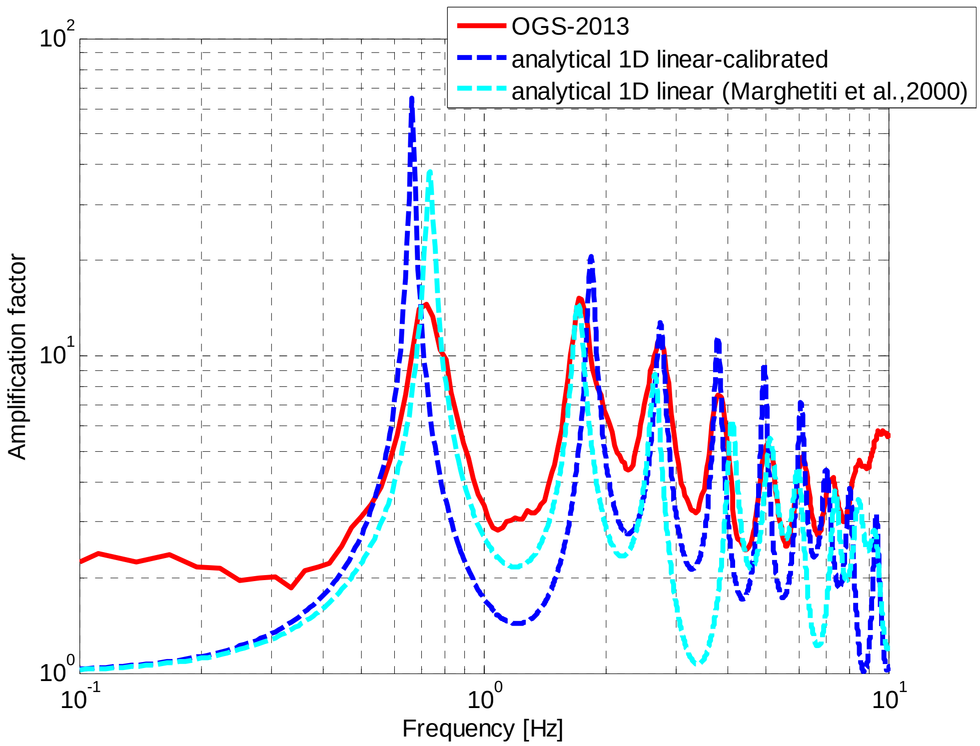


Figure 5.6. Top: comparison of surface-to-outcropping bedrock transfer functions obtained based on the different Vs prfiles of Figure 5.4. Bottom: surface-to-borehole spectral ratios observed based on OGS records and calculated according to the Margheriti et al (2000) Vs profile and the one adjusted to provide a best-fit with observations.

Table 5.3. Best-fit Vs profile, adjusted on the basis of OGS surface-to-borehole spectral ratio.

Thickness of layer [m]	Shear wave velocity [m/s]	Qs	Rho [t/m^3]
20	140	12	1.7
45	300	25	1.8
50	400	28	1.8
15	500	33	1.9

However, it was noted in several studies (e.g., De Martin et al , 2013) that the amplitude of the first natural peak of the surface-to-borehole spectral ratio may be affected by surface wave propagation and complex site effects, so that the estimation of *Q* based on such a peak and on the 1D theory may be biased and provide much lower values than reality.

For this reason, we did not care about the striking disagreement between the amplitude of the predicted peak in Figure 5.6 with respect to the observed one. Furthermore, the subsequent peaks are relatively well predicted.

5.3. Effect of the epistemic uncertainties in soil profile characterization and non-linear modelling

Uncertainty in determination of dynamic soil profile properties includes the aleatory contribution of small-scale random variability, the epistemic contribution related to the possible inaccuracy of the site investigation method, and the further epistemic contribution of the often uncomplete knowledge of site properties, especially when the bedrock depth is not well constrained.
Several studies have quantified such effects, such as Bazzurro and Cornell (2004) and Rathje et al. (2010). As a general numerical evidence, it was demonstrated that including aleatory soil property variability in seismic site response slightly decreased the median amplification factor and slightly increased its standard deviation; but it was also concluded that the variability introduced by the input motions is more important than the variability introduced by soil property uncertainties.
However, the previous works dealt only with the consequences of aleatory uncertainty in the soil profile. Such uncertainty may not be relevant for the purpose of this work,

because the aleatory component will not be double counted as it is already included in the PSHA at rock.

Therefore, in this section we will explore the consequences of the epistemic uncertainty alone, namely that associated to different approaches for Vs profile characterization (5.3.1), considering as a reference both Mirandola and Casaglia sites, and that associated to different non-linear approaches to model seismic soil response under large amplitude earthquake ground motions (5.3.2).

5.3.1. Effect of the epistemic uncertainty in the Vs soil model

Mirandola

After the Emilia seismic sequence, various site investigations were carried out for seismic site characterization in the area mostly affected by the earthquakes. One of the most interesting results is that the Vs profile spatial variability is rather limited, as shown by the plot in Figure 5.7, referring to sites in the Mirandola urban area, at minimum relative distance of few hundreds m. The values of the coefficient of variation, at least down to about 100-120 m where the engineering bedrock is found, are around 10-15%.

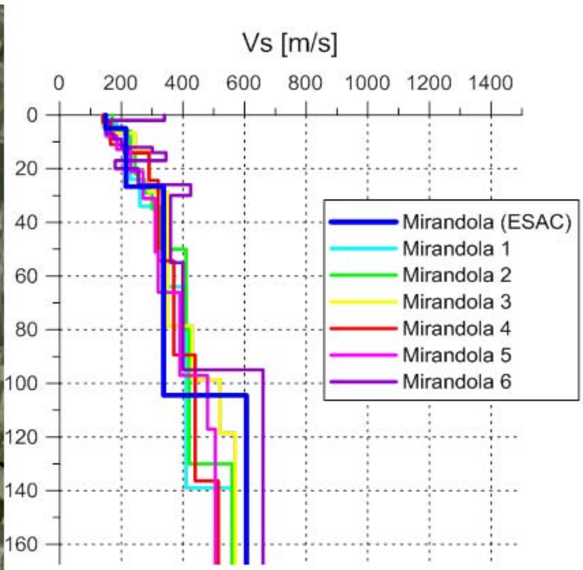


Figure 5.7. Vs profiles at several sites in the Mirandola urban area. Data from Project S2 (DPC-INGV 2012-13, Deliverable 4-1, https://sites.google.com/site/ingvdpc2012progettos2).

To quantify the effect of such variability on the spectral amplification function, we have carried out 1D linear equivalent numerical simulations, considering all the Vs profiles shown in Figure 5.7. To avoid superposition of input variability with Vs variability, we considered separately different input accelerograms from the set introduced in the previous section. A representative set of results is shown in Figure 5.8 for one of the input motions, but similar results were obtained also for the other input motions. It can be concluded that the small scale soil variability at the Mirandola site in the Po plain may only produce a moderate scatter in the surface response, for a given input, with σ_{log10} values in the range between about 0.05 and 0.12 ($0.11<\sigma_{ln}<0.28$) in the short period range (T<0.5s), while, in the long period range (T>1.5s), it falls to values smaller than 0.03 ($\sigma_{ln}<0.07$). Note that such range of values should be assessed for different return periods of interest, since the larger is the amplitude of motion, the larger should be the non-linear effects with corresponding larger hysteretic dissipation and possible reduction of the variability of results.

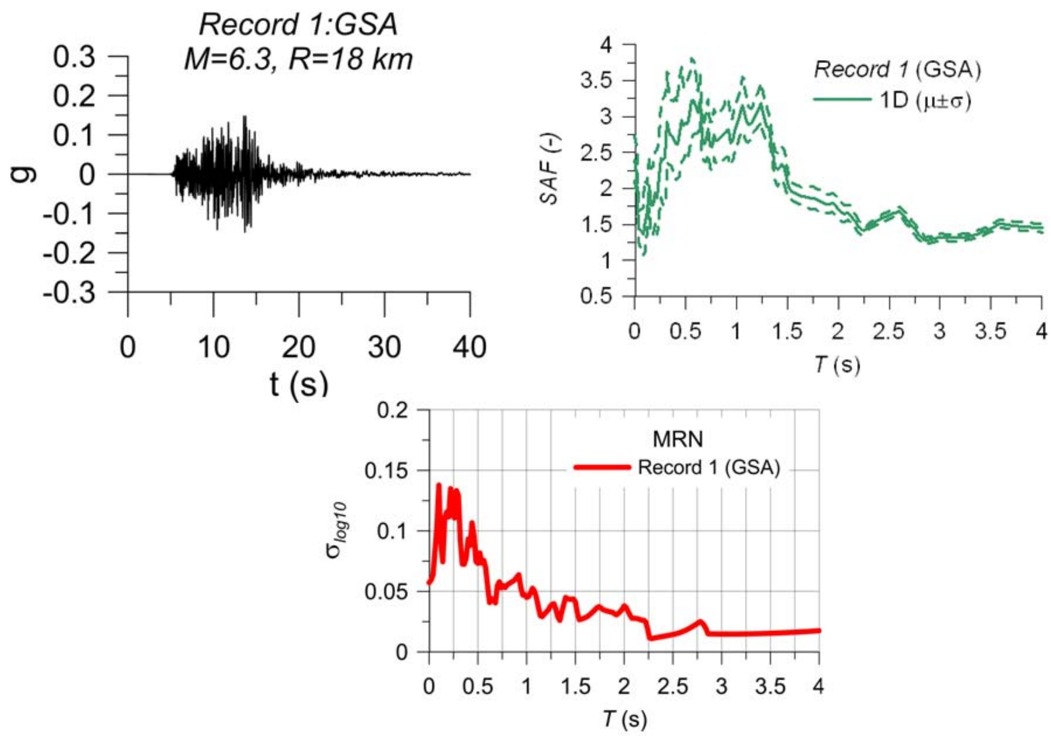


Figure 5.8. Top left: input accelerogram. Top right: SAFs computed on the response spectra by 1D linear equivalent analyses considering the Vs profiles in Fig. 5.7. Bottom: variability with period of σ_{log10}.

Casaglia

Similar results were obtained for the Casaglia site considering as the input motion one of the selected accelerograms introduced in Chapter 4 and with soil profiles those of Figure 5.4. Results are similar to those obtained in the Mirandola case, albeit with slightly lower σ_{log10} values (Figure 5.9). This may be explained by the fact that, whereas in Mirandola the selected Vs profiles were obtained by the same experimental technique but at close sites, at Casaglia the site is the same but techniques are different.

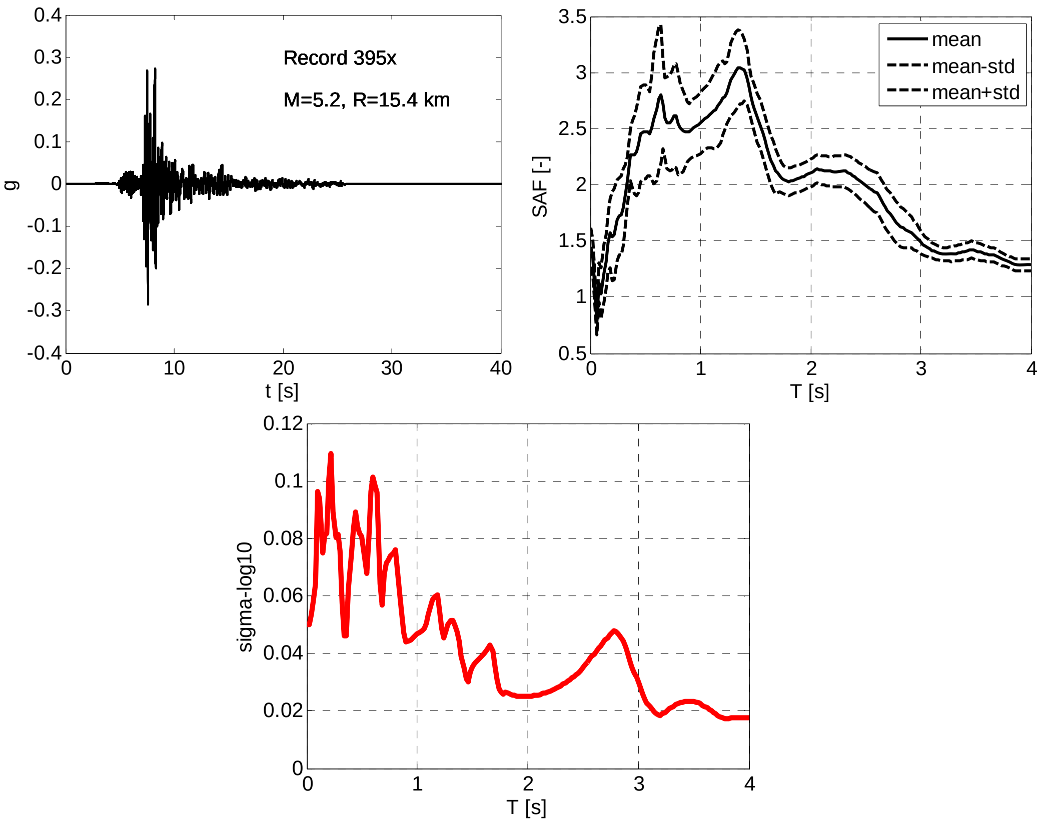


Figure 5.9. As for Figure 5.8, but for the Casaglia site and with Vs profiles in Figure 5.4.

5.3.2. **Effect of the modelling assumptions of the non-linear soil response**

The most critical soil property data used in seismic site response analysis are the profile of shear-wave velocity Vs, or, equivalently, of the small-strain shear modulus G_{max} =

ρVs^2, and the curves that describe the nonlinear dependence of the normalized modulus G/G_{max} and damping ratio ξ on the shear strain amplitude γ.

Many studies have been conducted to characterize the factors that affect G/G_{max} and ξ values for soils. The most important factors that affect G/G_{max} include, in addition to shear strain γ: the mean effective confining stress, σ'_m, the soil type and the plasticity index PI. Other factors that affect G/G_{max}, but appear to be less important, include (Darendeli, 2001): frequency of loading cycles, number of loading cycles, overconsolidation ratio (OCR), void ratio, degree of saturation, and grain size characteristics. In general, G/G_{max} curves decrease more slowly with γ, as σ'_m and PI increase. Likewise, the most important factors that affect ξ are, in addition to γ: σ'_m, soil type and PI, frequency of loading, and number of loading cycles. As σ'_m Increases, ξ tends to decrease for all strain amplitudes (Zhang et al., 2005).

Laboratory studies have highlighted the importance of σ'_m on nonlinear soil response (Darendeli et al. 2001), showing that soils are less nonlinear at higher confining pressures; this can significantly alter the expected site amplification at deep soil sites (Rathje and Stokoe, 2004).

Herein, the use of four types of degradation curves was investigated: the Darendeli (2001) curves and the Ishibashi and Zhang (1993) curves, both accounting for σ'_m; the mean standard curves of Seed and Idriss (Upper Limit) independent of confining pressure (Seed and Idriss 1970; Idriss 1990; Seed et al., 1986) and the available Resonant Column (RC) test results obtained on undisturbed samples at different depths in the nearby area of Casaglia (DPC-INGV-S2, 2013, D8.1).

In the Darendeli (2001) model, the shear modulus reduction curve is an hyperbola defined by:

$$\frac{G}{G_{max}} = \frac{1}{1+\left(\frac{\gamma}{\gamma_r}\right)^{a}}$$

where a is 0.9190, γ is the shear strain, and γ_{ref} is the reference shear strain. The reference shear strain (not in percent) is computed from:

$$\gamma_r = \left(\frac{\sigma'_o}{p_a}\right)^{0.3483} (0.0352 + 0.0010\, PI\, OCR^{0.3246})$$

where σ'_o is the mean effective stress and p_a is the atmospheric pressure in the same units as σ'_o.

In the model, the damping ratio is calculated from the minimum value at small strains (ξ_{min}) and from that associated to hysteretic Masing behavior (ξ_{Masing}). The minimum damping is calculated from:

$$\xi_{min}(\%) = (\sigma'_o)^{-0.2889}(0.8005 + 0.0129\ PI\ OCR^{-0.1069})(1 + 0.2919\ ln f)$$

where *f* is the excitation frequency (Hz). The computation of the Masing damping requires the calculation of the area within the stress-strain curve predicted by the shear modulus reduction curve. The integration can be approximated by:

$$\xi_{Masing}(\%) = c_1\xi_{Masing,a=1} + c_2\xi^2_{Masing,a=1} + c_3\xi^3_{Masing,a=1}$$

where:

$$\xi_{Masing,a=1}(\%) = \frac{100}{\pi}\left\{4\left[\frac{\gamma - \gamma_r ln\left(\frac{\gamma + \gamma_r}{\gamma_r}\right)}{\frac{\gamma^2}{\gamma + \gamma_r}}\right] - 2\right\}$$

with:

$$c_1 = -1.1143a^2 + 1.8618a + 0.2533$$
$$c_2 = 0.0805a^2 - 0.0710a - 0.0095$$
$$c_3 = -0.0005a^2 + 0.0002a + 0.0003$$

The minimum damping ratio ξ_{min} and the Masing damping ξ_{Masing} are combined to compute the total damping ratio (ξ) using:

$$\xi = b\left(\frac{G}{G_{max}}\right)^{0.1}\xi_{Masing} + \xi_{min}$$

with b = 0.6329 – 0.0057 ln *N*. where *N* is the number of cycles of loading.

In the Ishibashi and Zhang (1993) model, the shear modulus reduction curves are given by:

$$\frac{G}{G_{max}} = K(\gamma, PI)(\sigma'_m)^{m(\gamma,PI)-m_o}$$

where:

$$K(\gamma, PI) = 0.5\left\{1 + tanh\left[ln\left(\frac{0.000102 + n(PI)}{\gamma}\right)^{0.492}\right]\right\}$$

$$m(\gamma, PI) - m_0 = 0.272\left\{1 + tanh\left[ln\left(\frac{0.000556}{\gamma}\right)^{0.4}\right]\right\}exp(-0.0145PI^{1.3})$$

with:

$$n(PI) = \begin{cases} 0.0 & \text{for } PI = 0 \\ 3.37 \cdot 10^{-6}\ PI^{1.404} & \text{for } 0 < PI \leq 15 \\ 7.0 \cdot 10^{-7}\ PI^{1.976} & \text{for } 15 < PI \leq 70 \\ 2.7 \cdot 10^{-5}\ PI^{1.115} & \text{for } PI > 70 \end{cases}$$

Ishibashi and Zhang (1993) developed an empirical expression for the damping ratio of plastic and nonplastic soils:

$$\xi = 0.333\frac{1 + exp(-0.0145PI^{1.3})}{2}\left[0.586\left(\frac{G}{G_{max}}\right)^2 - 1.547\frac{G}{G_{max}} + 1\right]$$

As mentioned, we compared G/G_{max} and ξ curves from referenced authors, with available laboratory test results obtained on undisturbed samples of clay and sand at the site of San Carlo (at depths from 2 to 12 m), at about 15 km from Casaglia (DPC-INGV, S2 project, 2013, D8.1) and at the sites of Canale Boicelli and Po di Volano (at depths of about 40 m), at respectively 5 and 30 km from Casaglia (Fioravante et al, 2012). The curves from Fioravante (sand samples) perfectly agree with the ones from San Carlo, therefore, we used the G/G_{max} and ξ curves from the sand samples of Fioravante, for all sand layers, and the curves from the clay sample of San Carlo, for the uppermost layer of clay at Casaglia (down to a depth of 20 m).

Figure 5.10 and Figure 5.11 show the comparisons among the different nonlinear soil curves, at respectively 9.6 and 59 m depth, for clay and sand. In these figures two types of pressure dependent curves have been used: Ishibashi and Zhang (1993) and Darendeli (2001). For the two pressure dependent curves, values of σ'_m of 65.52 and 451.5 kPa were used, respectively, at indicated depths. (Note that OCR=1 and Ko=0.5, with number of cycles=10 and frequency of loading =10 Hz, were used to obtain the data supporting the Darendeli equations.). A value of PI=40 has been used for clay.

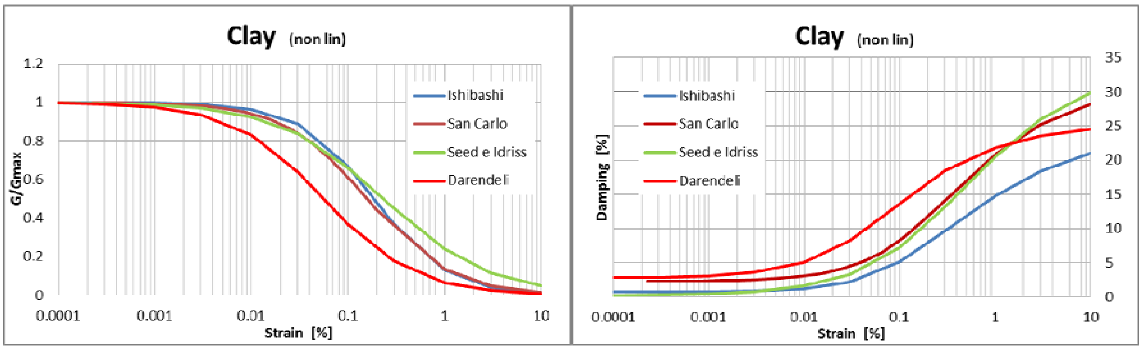


Figure 5.10. Modulus reduction and damping curves for clay soils compared with RC test data. Clay layer at 9.6 m depth.

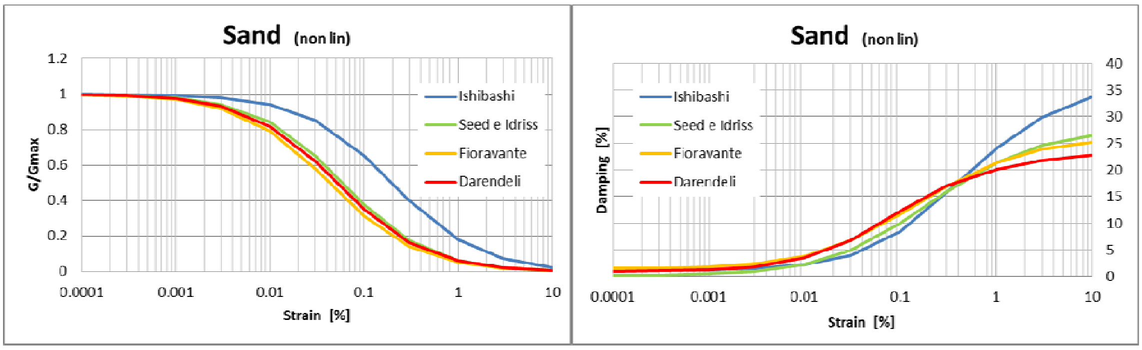


Figure 5.11 - Modulus reduction and damping curves for clay soils compared with RC test data. Clay layer at 59 m depth.

Relying on the calibrated soil profile of Sect. 5.2.3, and on the nonlinear soil curves shown herein, equivalent linear and non-linear analyses have been performed with the software code DEEPSOIL (Hashash, 2012, www.illinois.edu/~deepsoil). Table 5.4 summarizes the main features of the soil profile.

Table 5.4. Soil profile for parametric analyses on the effect of the non-linear soil modelling. Ish93 (Ishibashi and Zhang, 1993); S&I70 (Seed and Idriss, 1970); Dar01 (Darendeli, 2001).

Thickness [m]	**Soil material**	**γ[kN/m^3]**	**Vs [m/s]**	**Non-linear curves for G/G$_{max}$ and ζ**			
20	Clay	17	140	Ish93	S&I70	San Carlo (clay)	Dar01
45	Sand	18	300	Ish93	S&I70	Fioravante (sand)	Dar01
50	Sand	19	400	Ish93	S&I70	Fioravante (sand)	Dar01
15	Sand	19	500	Ish93	S&I70	Fioravante (sand)	Dar01
	rock	21	900				

The acceleration time history, shown in Figure 5.12, was used as input at the outcropping bedrock level.

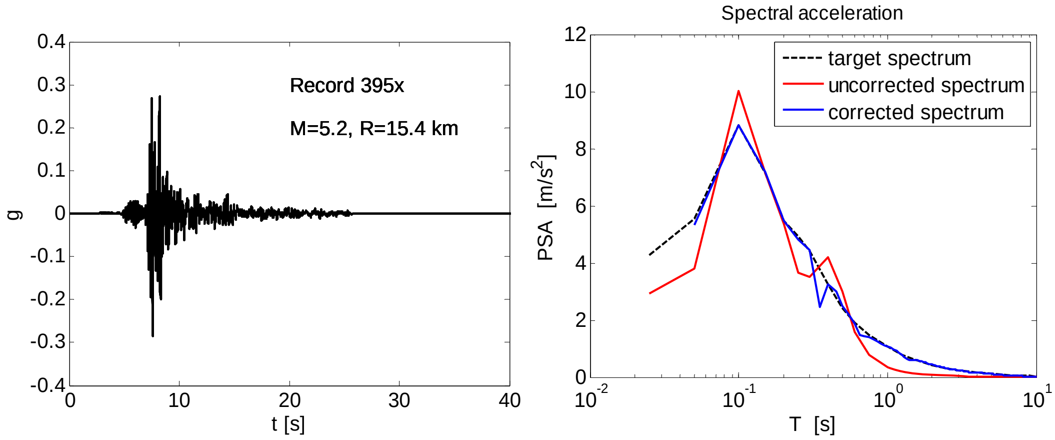


Figure 5.12. Acceleration time history used as input to 1D propagation analyses.

Figures 5.13 and 5.14 shows results of propagation analyses performed using all discussed nonlinear soil curves, for equivalent linear and nonlinear computations, while Figures 5.15, 5.16 and 5.17 show profiles with depth of Vs, damping ratio and maximum shear strain resulting from equivalent linear and nonlinear propagation analyses.

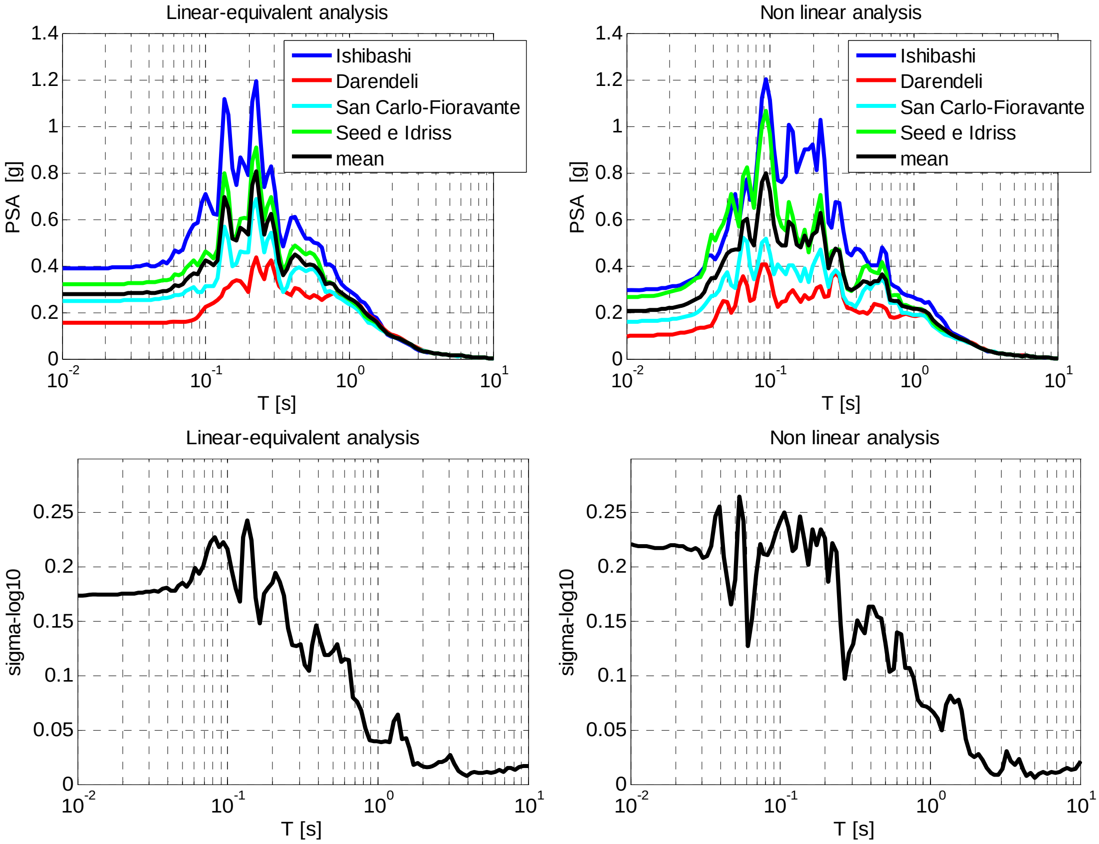


Figure 5.13. Top: Response spectra at 5% damping obtained by 1D propagation analyses performed with the selected TH of Figure 5.12, using the soil degradation curves summarized in Table 5.4. On the left side, results from Linear equivalent analyses; on the right side: results from fully nonlinear analyses using DeepSoil numerical code. Bottom: variability of response spectra illustrated at top, calculated in terms of σ_{log10}.

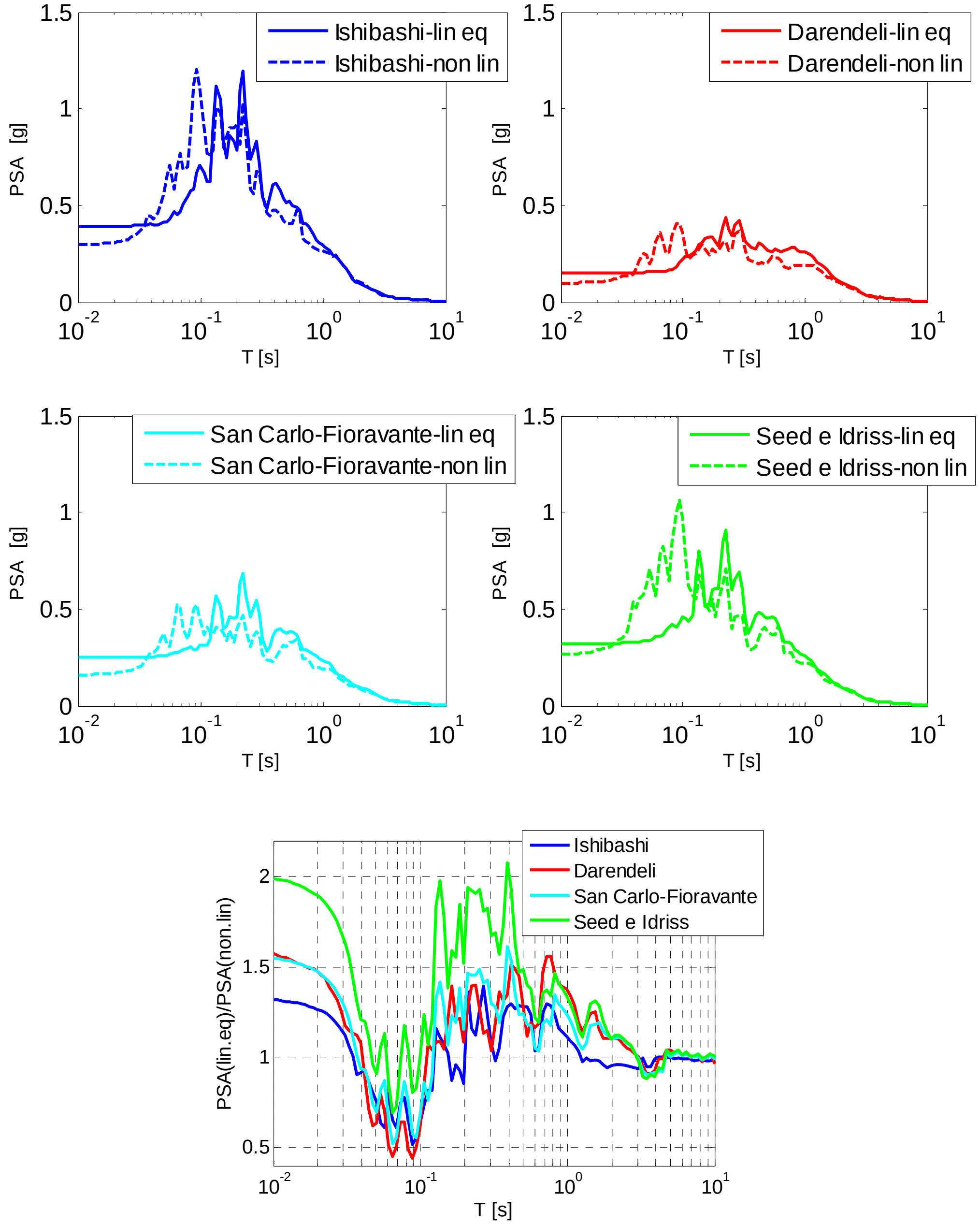


Figure 5.14. Top. Comparison of the same response spectra shown in Figure 5.13, to evaluate the effect of different approaches (linear-equivalent vs fully non-linear) in the 1D response analyses on the selected soil column. In each plot, the same degradation curves are selected. Bottom: Ratio of linear-equivalent vs fully non-linear response spectra.

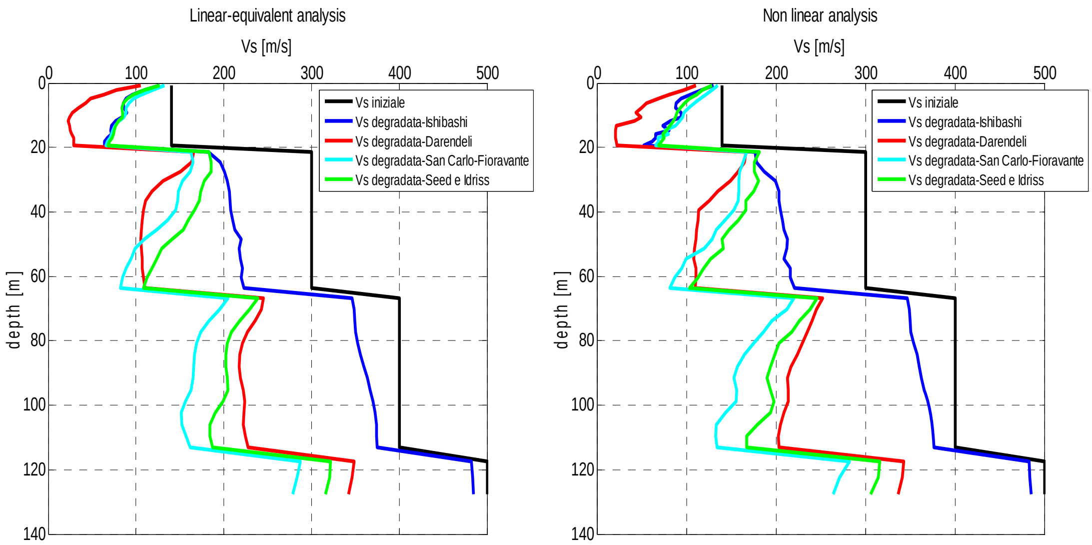


Figure 5.15. Vs profiles from equivalent linear and non-linear propagation analyses.

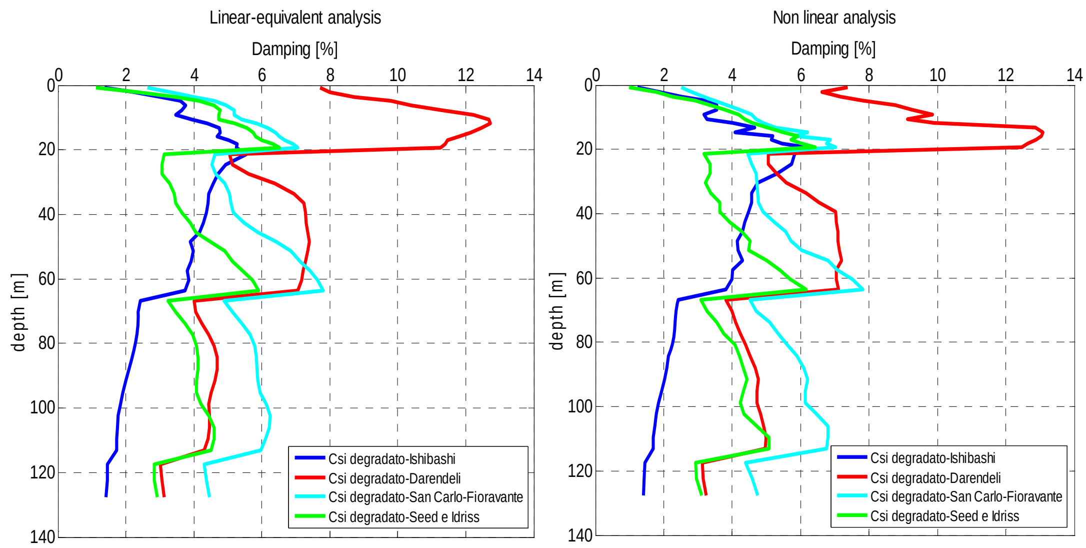


Figure 5.16. Damping ratio profiles from equivalent linear and non-linear propagation analyses.

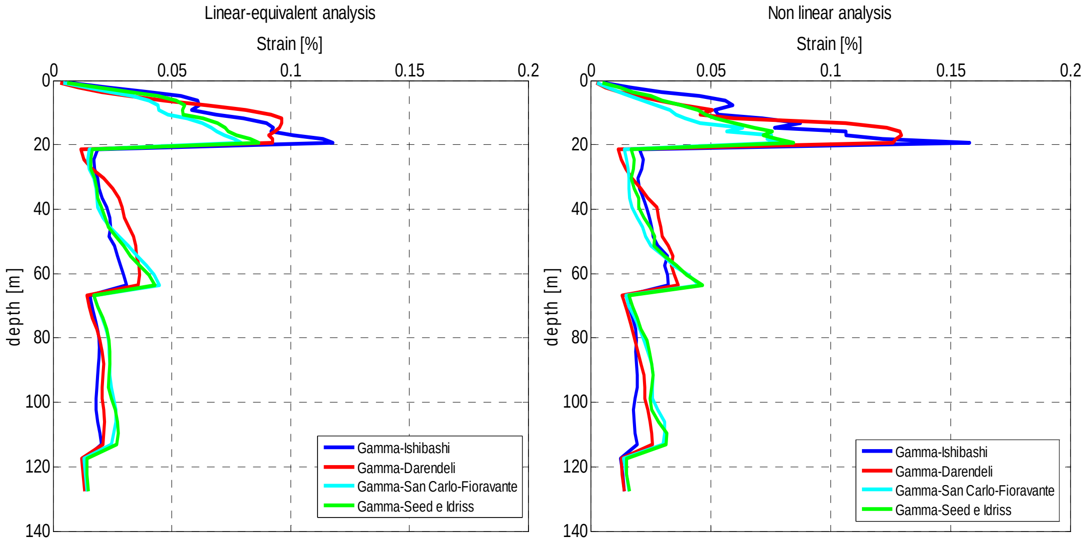


Figure 5.17 Maximum shear strain profiles from equivalent linear and non-linear propagation analyses.

Analysis of the previous results prompts some important considerations on the effect of non-linear modelling of soil response and its effects on uncertainty of PSHA results, namely:

(a) The influence of selection of *G-γ* and *ζ-γ* curves is dramatic (Figure 5.13) and by far dominates any other source of uncertainty in the site-specific PSHA for the Po Plain sites. This is due to the relatively large input motion amplitude considered and to the large thickness of sediments. Note that Ishibashi and Zhang (1993) and Darendeli (2001) provide the lower and upper bound results, with high amplifications for the former and very low for the latter, while the other curves, not depending on the confining pressure, lead to intermediate results. This is mainly related to the large damping increase with γ assumed in the Darendeli model, as shown in Figures 5.10 and 5.11. The consequences can be clearly appreciated by the high damping in the shallow layer (Figure 5.16) and corresponding low Vs values (Figure 5.15).

(b) The effect of the non-linear modelling approach, that is, linear-equivalent vs fully non-linear analyses, is less critical (Figure 5.14) than the selection of the soil degradation curves, provided that the non-linear soil model is calibrated so to provide the selected degradation curve. However, as noted from the ratio of response spectra of the linear-equivalent vs fully non-linear analyses, illustrated on the bottom side of Figure 5.14, the differences range over a factor of about 2 with systematic trends. As a matter of fact, the linear-equivalent overestimate the fully non-linear results below about 0.05 s, and in the whole range between 0.1 and 2 s. Between 0.05 s and 0.1 s the trend is opposite, while for periods larger than about 2 s the two solutions coincide.

5.4. Effect of the input motion selection on SAF variability

To explore the effect of different criteria to select spectrum compatible input motions for 1D wave propagation analyses, we present in this section the results of a parametric study involving different sets of accelerograms.

All sets were produced by the REXEL-DISP software illustrated in the previous section, using as the target spectrum provided by the PSHA at rock at Casaglia site, for 2475yrs return period. The sets are summarized as in Tab 5.5. Sets 1a and 1b are plotted in Fig. 4.4.

Table 5.5. Sets of accelerograms considered as input motions

1a	Real accelerograms with “large band” spectral compatibility between 0.1 and 8 s.
1b	The same as 1a, but scaled in frequency to exactly match the target spectrum.
2a	Real accelerograms with “narrow band” spectral compatibility between 0 and 1 s.
2b	The same as 2a, but scaled in frequency to exactly match the target spectrum

Just for chronological reasons, the selected Vs profile at Casaglia for this analysis was based on the Margheriti et al. (2000) investigations, rather than the one providing the best fit with borehole records, and is shown in Table 5.6. The linear equivalent approach was followed based on the G-γ and ζ-γ curves calibrated on soil samples of the Po plain (San Carlo + Fioravante, see Table 5.4).

In Figure 5.18 we show the median spectral amplification functions calculated based on the spectral ratio of the output vs input acceleration 5% damped response spectra. On the left side, the comparison is shown for the real records dataset (1a vs 2a), while on the right side the spectrally matched records are considered (1b vs 2b). From these figures, it can be seen that no relevant differences are found in terms of mean[9] SAFs, both for the real and for the corrected record sets.

[9] Mean and median values in those SAFs were found to be practically coincident in this case, thus suggesting a normal distribution

Table 5.6. Soil profile at Casaglia, for 1D linear equivalent analyses

	Layer Number	Soil Material Type	Thickness of layer (m)	Total unit weight (t/m^3)	Initial critical damping ratio (%)	Qs	Shear wave velocity (m/sec)	Location and type of earthquake input motion
Surface	1	clay	20	1,80	2,500	20	171	
	2	sand	20	1,80	2,500	20	234	↑
	3	sand	25	1,80	1,667	30	300	
	4	sand	25	1,80	1,250	40	400	
	5	sand	20	1,80	1,000	50	500	
	6	rock	240	2,00	0,556	90	900	Outcrop

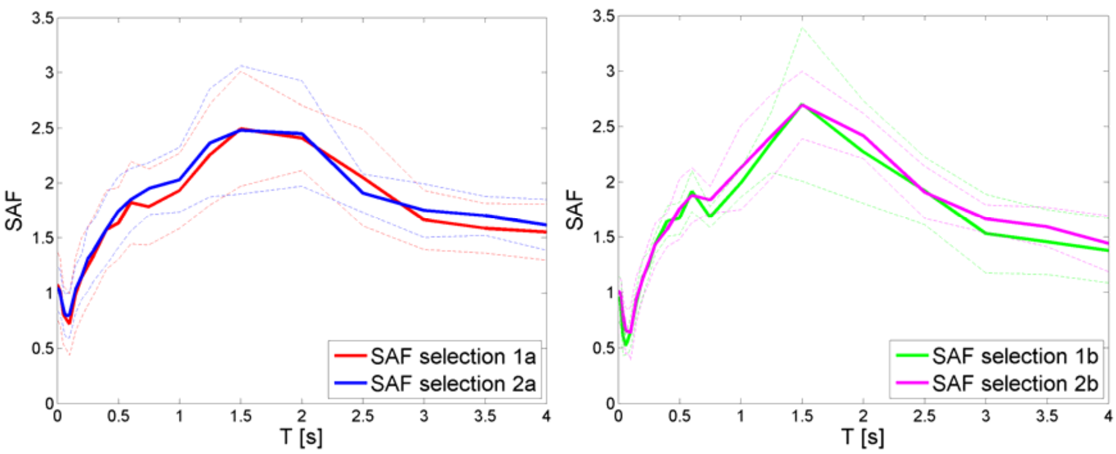


Figure 5.18. Spectral amplification functions at Casaglia site for the sets of records illustrated in Table 5.2. Left: real records. Right: corrected (spectrally matched) records.

As a matter of fact, the 1a and 2a real record sets are rather close to each other, in that the narrow band selection 2a was found to be in reasonable agreement not only with the short period, but with the long period target spectrum as well. This can be explained since the selection was based on the suitable magnitude and distance ranges, which “naturally” provide a reasonable fit with the target spectrum also in the long period range. The corrected records (2a and 2b) do not provide significant differences in terms of median amplification functions with respect to the real ones.

However, it is apparent from Figure 5.18 that, when using the corrected datasets, the variability is significantly reduced in the short period range, with $\sigma_{\log10}$ ranging from about 0.02 for periods shorter than 0.5 s up to about 0.08 for periods around 1.5 s, corresponding to the peak of the SAF. Such reduction of variability in the SAF at short periods, occurring for accelerograms matched to the target spectrum, can be explained if we consider that at high frequencies the dominant role in the equivalent linear model is played by damping, which tends to smoothen the peaks of the transfer function. On the other side, in the low frequency range, the prevailing effect comes from the shear modulus reduction, with the consequent change of the fundamental frequency of the system and of the shape of the transfer function.

As a conclusion from this section we can state that:
- the epistemic uncertainty related to the criterion for selection of input accelerograms is minor, in terms of real vs spectrally matched records, provided that the response spectra of all sets be close to the target UHS on rock and that the corrected records come from a seed set of real records approaching the rock UHS;
- the aleatory uncertainty due to the different records in the same set is also minor, especially when spectrally matched records are considered.

5.5. 3D modelling of ground motion and its effect on the SAFs: preliminary results

With the aim of evaluating the effect of variable source-to-site propagation paths on site amplification response, a suite of 3D numerical simulations was carried out by considering different seismic rupture scenarios occurring on selected portions of the Mirandola and Ferrara faults. These ideal scenarios are characterized by different magnitude, from 5.5 to 6.5, co-seismic slip distribution, focal mechanism, rupture velocity and rise time. Four rupture scenarios are produced along the Ferrara fault, which originated the May 20 2012 earthquake, and four are activated along the Mirandola fault (May 29 2012), for a total of eight scenarios.
The numerical procedure is based on the application of the 3D high performance spectral element code SPEED (mox.polimi.it/it/progetti/speed/SPEED/Home.html), developed at Politecnico di Milano, implemented to fully exploit large parallel computer architectures. Details of the numerical computations are presented in Deliverable D2-93 ("Ground shaking scenarios in the Po Plain with special emphasis on the area affected

by the earthquake sequence of May 2012), although studies for a more thorough understanding of the numerical results are still in progress.

In this section we will limit ourselves to illustrate the numerically computed Spectral Amplification Functions (SAFs), similar to those illustrated for the Kik-net records in Figs. 2.3 and 2.4. The spectral ratios at a generic site at the top of the deep soil sediments are calculated with respect to the ground motion calculated at the same site considered at the top of the outcropping bedrock. This means that, for each scenario, two 3D simulations were carried out, with and without the deep soil sediments.
As an example, Fig. 5.19 shows two numerical ground shaking scenarios in terms of PGV, for two hypothetical earthquakes of M6.0 (left) and M6.5 (right) along the same fault which caused the M6 May 29 2012 earthquake.

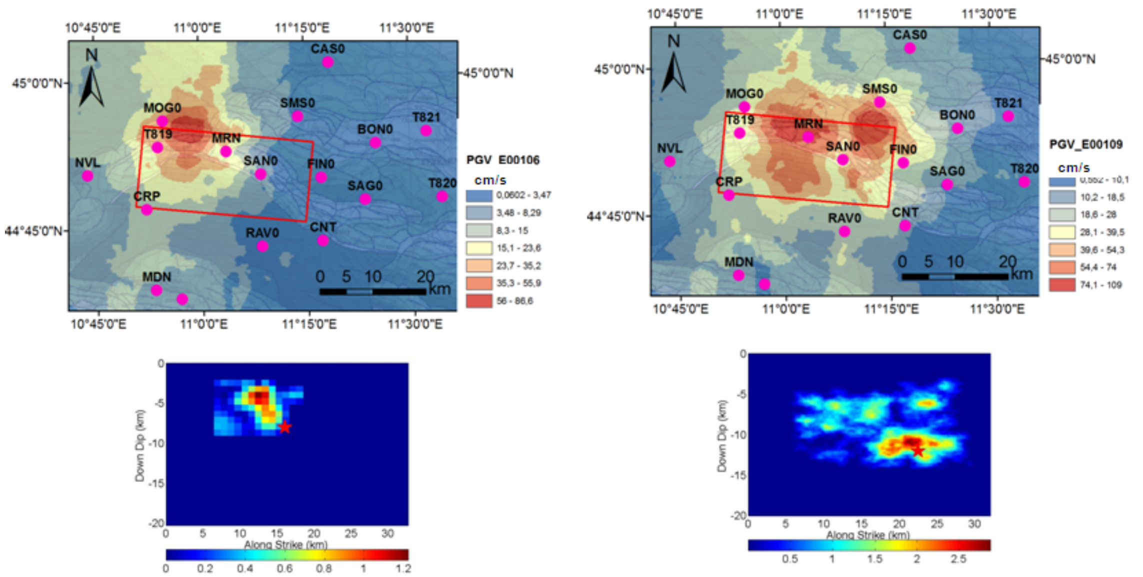


Figure 5.19. Ground shaking scenarios in terms of PGV for two hypothetical earthquakes along the Mirandola fault, M6.0 (left) and M6.5 (right). These scenarios are a sample of the 8 ideal ones illustrated in Deliverable D2-93.

Based on 8 of such hypothetical scenarios, the conditioned SAFs were computed for various vibration periods, in order to verify if the variability of such functions resembles the one observed in the Kik-net stations illustrated in Chapter 2. Some preliminary results are shown in Fig. 5.20, 21 and 22, for three sites in the epicentral area of such earthquakes.

It is interesting to note that, compared to the range of variability of such functions calculated from records of the Kik-net, with σ_{log10} ranging from 0.04 and 0.08, for the 3D simulations this variability is larger, with 0.04< σ_{log10} < 0.12 (0.1< σ_{ln} < 0.28), but it is smaller than the typical range 0.15-0.2 of single station sigmas calculated by statistical analysis of records at deep soil sites (Chen and Faccioli, 2013). Note that, as discussed in Deliverable D2-94, these simulations were carried out under a non-linear elastic assumption (i.e., at each time step, the elastic moduli and damping are updated based on the strain at the previous step). Furthermore, only periods of vibration larger than 0.75 s were considered, because of the frequency limitations of the numerical simulations.

It is difficult at this stage to understand whether such an increase of varibility may be due to some limits of the numerical modelling setup, or it reflects the intrinsic variability of site amplification functions in a realistic seismic environment. As a preliminary conclusion, strengthened by the reasonable agreement between these simulations and the Kik-net observations, it can be argued that, under the assumption of fully 3D numerical simulations accounting for the interaction of seismic source, propagation path and the shallow soil layers, the seismic amplification at deep soil sites in the Po plain may be characterized by a moderate variability with σ_{log10} < 0.13, i.e., σ_{ln} < 0.28.

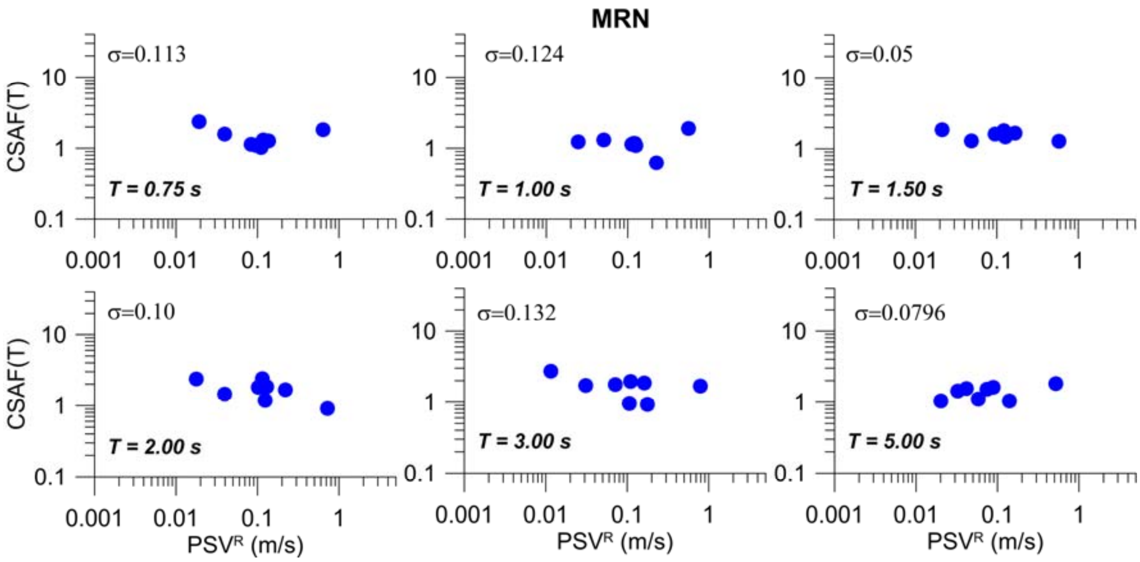


Figure 5.20 – Conditioned SAFs for MRN station computed as Response Spectral Ratio with respect to outcropping bedrock for different values of vibration period T (0.75, 1, 1.5, 2, 3, 5 s).

Furthermore, as in the Kik-net sites, there is no evidence of significant non-linear behaviour (smaller amplification levels for larger amplitude of motion at rock), although accounted for in the numerical simulations by a non-linear elastic model (see Deliverable D2-93). It should also be noted that this conclusion applies only for periods of vibration T > 0.75 s, because the accuracy of the numerical study was limited at high frequencies.

Further studies are presently in progress to understand under which conditions (e.g., source-to-site azimuth and/or distance, directivity, soil depth) the 3D SAFs approach the 1D SAFs and to quantify the scatter in such conditions.

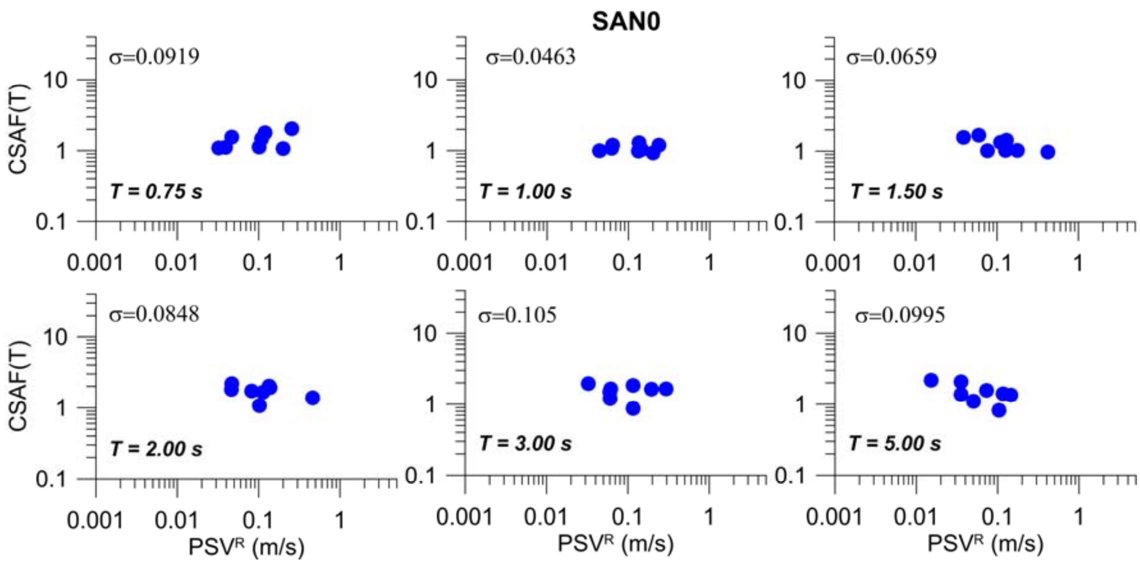


Figure 5.21 – Same as in Figure 5.20 but for SAN0 station.

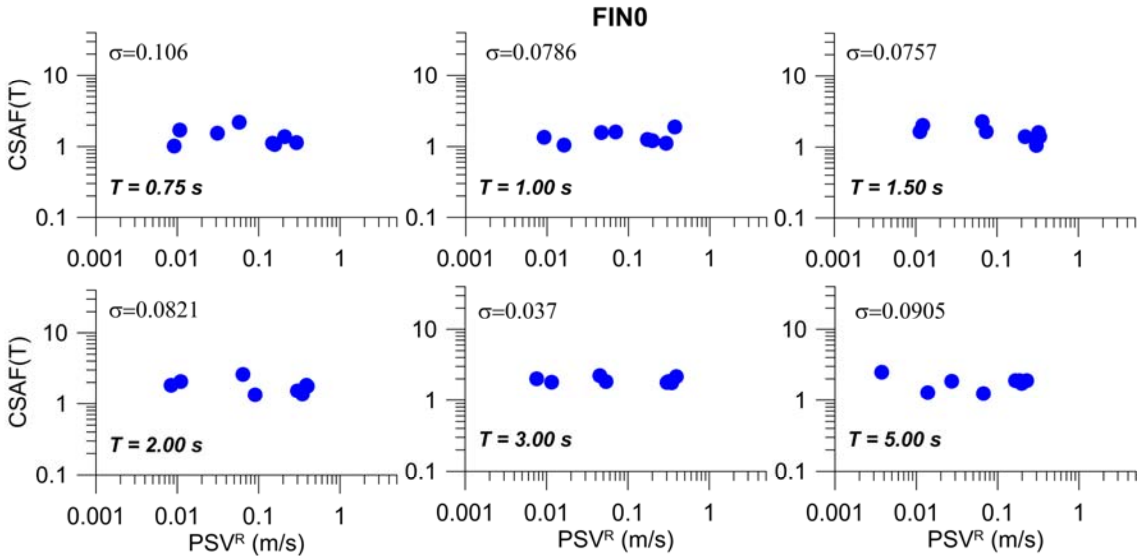


Figure 5.22 – Same as in Figure 5.20 but for FIN0 station.

6. Conclusions

In this report we have addressed different key issues related to the introduction of specific site effects in the PSHA.

First, based on the results presented in Chapter 2, we have argued that the fully probabilistic approach, based on the calibration of conditioned site-specific SAFs, should be considered with care since it tends to overemphasize the uncertainty in the amplification values conditioned to the occurrence of a given intensity of motion at rock. Supporting this remark are the conditioned SAFs derived from the Kik-net records obtained at deep soil stations, which show a significantly lower variability. Besides, no clear evidence was found of non-linear response, i.e., of amplification decrease for increasing intensity levels at rock, even for stations which provided records in the epicentral region of strong earthquakes, such as NIGH11. Based on the previous considerations, we have defined in Chapter 3 the approach adopted to carry out site-specific PSHA for the Po Plain sites, that is, a hybrid approach where the input motions for site-specific seismic response analyses are selected based on a broadband compatibility with the rock PSHA spectrum at a specific return period.

Alternative approaches have the following disadvantages. On one side, the Bazzurro and Cornell (2004) method tends to overemphasize aleatory site response variability, in the presence of strong non-linear soil response. As a matter of fact, since selection of of input motions should encompass an extremely wide range of spectral accelerations, typically 4 orders of magnitude, there is little control on the adequacy of the selected records, which are typically modified through large scale factors. In a recent application of the Bazzurro and Cornell approach (Papaspiliou et al., 2012), the selected acceleration time histories were multiplied by a factor ranging from 2 to 6. It is apparent, in the view of the authors of this report, that such a choice has the effect of artificially amplifying the aleatory variability of results by considering input motions that have no physical meaning[10].

[10] Just as one among many examples, the famous Tabas (Iran 1978, M7.3) earthquake record was amplified by a factor of 4 in the paper by Papaspiliou et al (2012), so that it was transformed from one of the most severe earthquake records in the history of strong

On the other side, the application of Random Vibration Theory (e.g., Rathje et al., 2010; Pehlivan et al., 2012) is confined to linear equivalent approaches, while for deep soil sites fully non-linear approaches are preferable.

For the previous reasons, we have introduced in Chapter 4 a rational criterion to select input ground motions, based on non-scaled real records fitting the target spectrum in a broad period range. To check the influence of such a choice on the resulting spectral amplification functions based on 1D linear equivalent numerical simulations, we have also considered different sets, either containing real accelerograms, selected by imposing compatibility over a short or over a large period range, or containing spectrally matched accelerograms. The latter were obtained by an iterative frequency scaling of the Fourier Spectra, until the response spectra of the corrected record approaches the target one.

In Chapter 5, we have explored at the Casaglia site within the Po Plain, the influence on the site-specific response of the epistemic uncertainties related to

a) Vs soil model;
b) Non-linear soil behavior and modelling approach;
c) Criteria for selection of input motion;
d) 3D modeling of site amplification functions.

Items from a) to c) refer to the standard 1D method to site response analysis, while item d) refer to a completely different approach involving physics based source-to-site numerical simulations. The 1D approach was applied to the Casaglia site, while the 3D simulations were carried out in the Po Plain region affected by the earthquake sequence of May-June 2012.
As mentioned earlier, all sources of uncertainty considered in the previous list refer to the epistemic class, whereas the aleatory component is supposed to be already included in the PSHA results at rock. For example, for the uncertainty related to the Vs profile for seismic site effects analyses, we did not consider the effects of random variability of soil properties, while the epistemic uncertainty was attributed to the availability of different Vs for the same site, obtained by different techniques and/or different

motion seismology into an apocalyptic input motion, with effects on the response of a real soil column that are meaningless and unpredictable by any NL soil model.

investigation teams. Furthermore, we neglected the sources of epistemic uncertainty that do not significantly apply to our case study, such as shallow 2D or 3D models that are not suitable for the seismic response in the Po Plain.

A summary of results of this report as regards the 1D approaches, is given in Table 6.1. The epistemic contribution regarding the selection of the Vs profile has been quantified in a simplified way, by attributing average values of σ, plotted in Figures 5.8 and 5.9, for different representative period ranges.

As regards the non-linear effect on the 1D seismic wave propagation analyses, we have explored two contributions to σ_{NL}. First, the selection of NL soil models in terms of cyclic degradation curves of shear modulus and damping, which turns out to provide by far the most important contribution to uncertainty. Second, the contribution of the NL modelling approach (linear equivalent vs fully NL) was also considered. However, since only two such approaches were considered and the fully NL approaches were restricted to the single model implemented in the DeepSoil code, we did not disaggregate the different contributions in the final evaluation of σ_{NL}, which is finally based on the 8 response spectral curves illustrated in Figure 5.13. As it can be seen by comparison of the values reported in Table 6.1 and the plots on the bottom side of Figure 5.13, the selection of the NL soil model dominates the overall uncertainty.

Finally, the epistemic uncertainty related to the criterion for selection of input accelerograms for 1D seismic response analysis was found to be negligible, but only provided that input motions, either real or spectrally matched, are compatible with rock PSHA spectrum at the selected return period. We consider that such approach is highly preferable to any other approach which selects the input accelerograms by scaling them to the target spectrum, with no consideration about magnitude, distance and more generally about the similarity of the "seed" real record to the target response spectrum.

Under these assumptions, the total epistemic uncertainty related to 1D modelling assumptions was quantified as in the last row of Table 6.1.

Table 6.1. Synthesis of results presented in this report to quantify the epistemic uncertainty related to 1D soil modelling, with representative values of σ_{log10} as a function of the period range.

	Short periods (<0.5 s)	Intermediate periods (0.5-2 s)	Long periods (> 2s)
$\sigma_{\text{Vs profile}}$	0.07	0.05	0.03
σ_{NL*}	0.19	0.08	0.02
σ_{input_1D}	Minor epistemic contribution to σ, provided input motions, either real or spectrally matched, are compatible with rock PSHA spectrum at the selected return period		
Total $\sigma_{epistemic\_1D} = (\sigma^2_{Vs}+ \sigma^2_{NL})^{0.5}$	0.20	0.09	0.04

* calculated considering the 8 response spectra in Figure 5.13, i.e., considering the combined effect of different NL soil models and different, linear-elastic and fully non-linear, approaches. The effect of NL soil model dominates results.

In the interpretation of such results, care should be paid to understand that the quantification of σ_{NL} presented in Table 6.1 is not absolute, since it refers to the specific soil profile considered and to the selected return period (2500 yrs in this example).

If we consider now the long period range in Table 6.1, it is clear that the level of uncertainty at long periods is much smaller than in the short and intermediate period ranges. An obvious reason for such low values comes from the 1D modelling assumption itself, which considers vertical propagation of plane S-waves in 1D horizontally layered media, with no consideration of complex site amplification effects related to source-to-site propagation path. Such limitation of 1D site response analysis in capturing the epistemic uncertainty related to site amplification was also noted by Rodriguez-Marek et al., (2014).

To quantify the relevance of such effects by filtering the input motion variability, Table 6.2 shows the σ_{log10} of the spectral amplification functions calculated (i) by the KikNet records at the selected Kik-net deep soil sites considered in Chapter 2 (see Figures 2.3 and 2.4), (ii) by the physics-based 3D numerical simulations in the Po Plain, illustrated in Section 5.5 and, in more detail, in the Sigma Deliverable D2-93.

Table 6.2. Period dependent variability (measured in terms of of σ_{log10}) of the site amplification functions observed on the Kik-net records (Chapter 2) and calculated based on the 3D numerical simulations (section 5.5).

	Short periods (<0.5 s)	Intermediate periods (0.5-2 s)	Long periods (> 2s)
$\sigma_{Kik\text{-}net}$	0.10	0.08	0.08
σ_{3D_sim}	Not available	0.08	0.10

It is clear that the SAF variability observed on the Kik-net records is hardly dependent on period, and that such variability is well reproduced by the numerical simulations. If we compare now with Table 6.1, it is clear that the epistemic variability at short periods, which, as already remarked, mainly comes from different NL soil models, is twice as large as that observed on the Kik-net records. However, it should be noticed that Kik-net records are biased towards relatively small amplitudes of ground motion, so that the NL soil behaviour does not affect significantly the variability of results.
Furthermore, while in the intermediate period range the observed variability based on the Kik-net records resembles the one calculated from 1D numerical simulations, it is clear that, in the long period range, 1D modelling assumptions do not capture the observed variability, that is approximated much better by 3D numerical simulations.

We can conclude that the following flow of operations be recommended when using the selected approach to account for specific site effects in the PSHA:

1. consider the mean uniform hazard spectrum (UHS) from the logic tree on rock for the selected return period, with the corresponding σ_{PSHA_rock} ;
2. select a set of real unscaled records compatible in a broad period range with the UHS on rock, and adjust those records, if necessary, by a spectral matching algorithm, as shown in Chapter 4; in this way the epistemic variability related to the input selection criterion will be minimized and can be neglected;
3. define the Vs profile, as well as the corresponding NL degradation curves, based on the best information available and possibly by in-situ evaluations of the G-γ and ζ-γ curves; quantify the related epistemic uncertainty $\sigma_{1D\_epistemic}$, based on the epistemic variability with depth both of Vs and of degradation curves, and on the evaluation of the corresponding effect on the seismic response, as illustrated in Chapter 5;

4. calculate the 1D response for the selected soil profile, by using the selected accelerograms as excitation, and calculate the average response spectrum at ground surface. This will provide the site-specific UHS for the selected return period;
5. consider $\sigma_{total\_epistemic} = \sigma_{1D\_epistemic}$, for $T < T_0$, where T_0 is the fundamental period of the soil profile, and $\sigma_{total\_epistemic} = 0.10$ (in log10), for $T > T_0$, the latter value assumed tentatively based on the Kik-net records and confirmed by 3D numerical simulations;
6. finally, calculate the total σ associated to the site-specific UHS by the following rule:

$$\sigma_{tot} = \sqrt{\sigma^2_{total\_epistemic} + \sigma^2_{PSHA\_rock}} \; .$$

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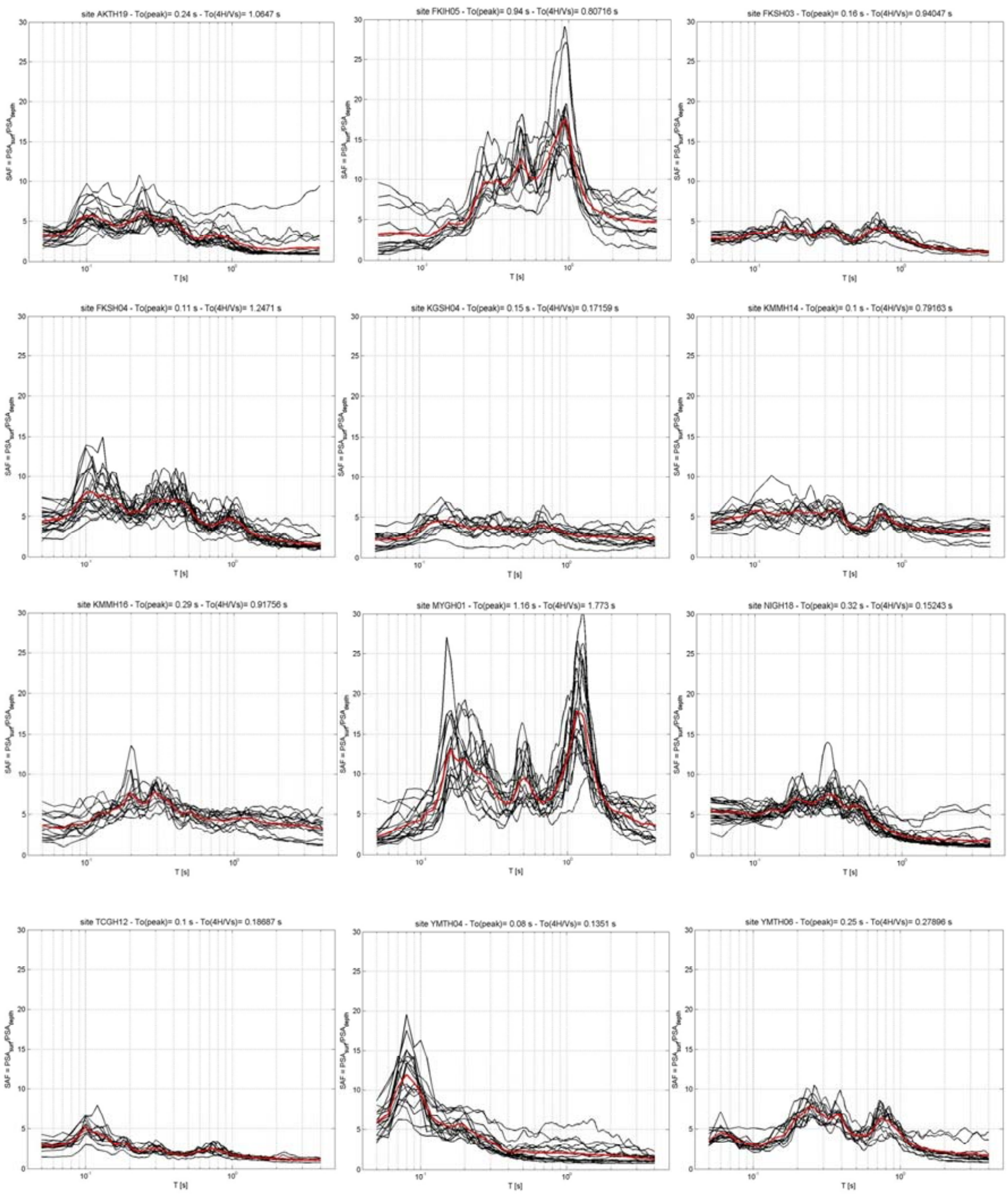
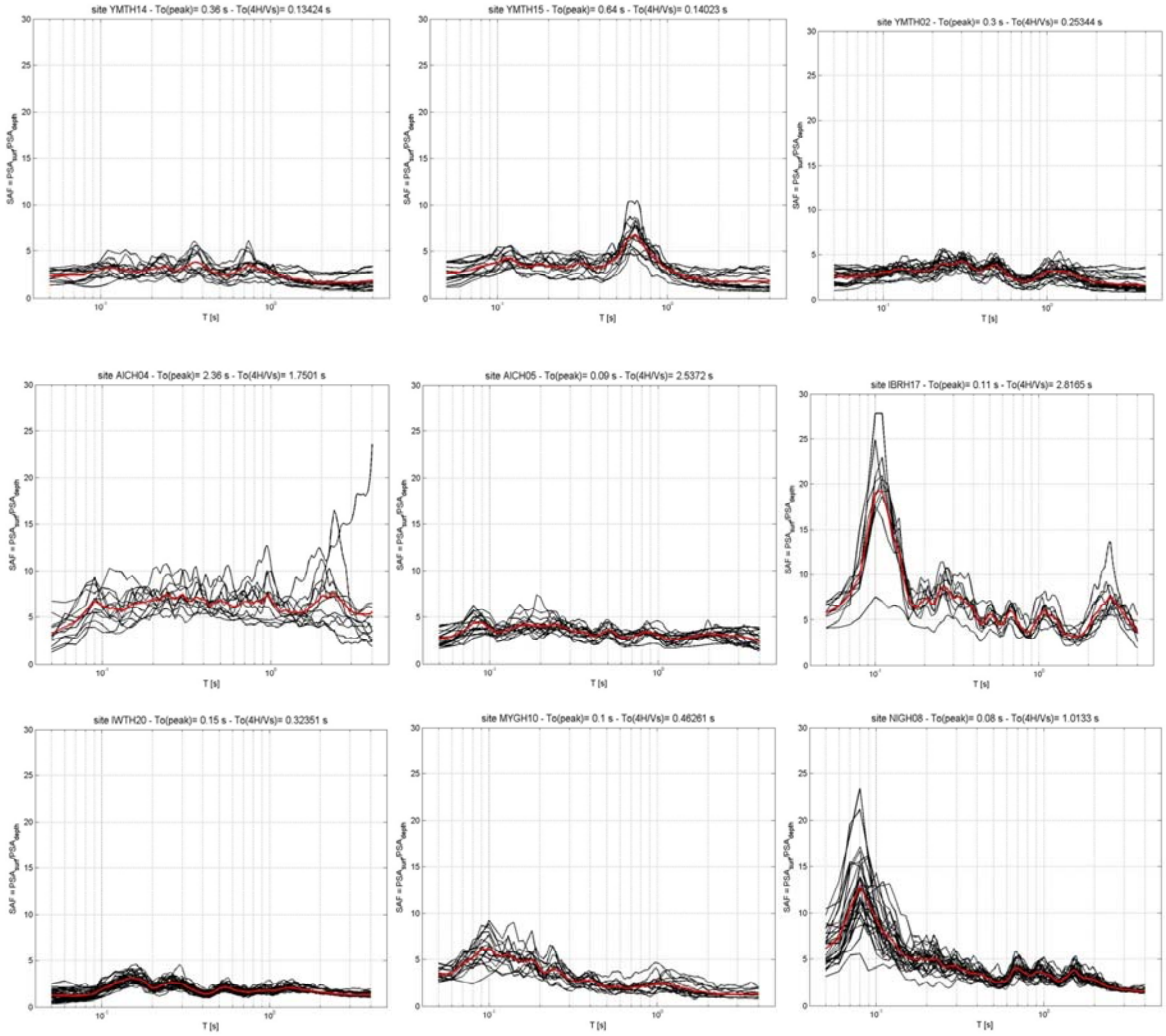
8. Annex A: Spectral ratios at deep soil sites from the Kik-net




site YMTH14 - To(peak)= 0.36 s - To(4H/Vs)= 0.13424 s
site YMTH15 - To(peak)= 0.64 s - To(4H/Vs)= 0.14023 s
site YMTH02 - To(peak)= 0.3 s - To(4H/Vs)= 0.25344 s
site AICH04 - To(peak)= 2.36 s - To(4H/Vs)= 1.7501 s
site AICH05 - To(peak)= 0.09 s - To(4H/Vs)= 2.5372 s
site IBRH17 - To(peak)= 0.11 s - To(4H/Vs)= 2.8165 s
site IWTH20 - To(peak)= 0.15 s - To(4H/Vs)= 0.32351 s
site MYGH10 - To(peak)= 0.1 s - To(4H/Vs)= 0.46261 s
site NIGH08 - To(peak)= 0.08 s - To(4H/Vs)= 1.0133 s
T [s]

D3-95
Review F.Scherbaum

Comments on deliverable D3-96

APPROACHES TO ACCOUNT FOR SITE EFFECTS IN THE PSHA OF SELECTED SITES IN THE PO AREA

Ref SIGMA-2012-D3-96 Version 01

Frank Scherbaum
University of Potsdam
Potsdam, Oct. 31, 2013

General remarks

The report aims at providing a general framework for the performance of site-specific PSHA studies for the Po plain. Following a short introduction, which introduces the study area as well as related studies previously done within the SIGMA project, the authors provide a brief overview of what they consider the general options for incorporating site effects in PSHA.

Based on a set of observed conditioned site amplification functions from Kik-net records obtained at deep soil stations, the authors then conclude that the fully probabilistic site specific aproach (described in chapter 2.2) is likely to overemphasize the dispersion of the results and the effect of non-linearities.

As a consequence of their conclusion the authors decide (in chapter 3) to subscribe to the US NRC approach outlined in RG 1.208 in which the calculation of the SAF is based response spectral ratios of Uniform Hazard Response Spectra on 1D numerical simulations using a small set of accelerograms representing the median rock UHRS (for a given return period).

In chapter 4, the authors discuss the selection of appropriate ground motion records, the criteria for which basically follow the ASCE/SEI 7-10 recommendations. A major portion of chapter 4 is devoted to the description of the REXEL-DISP software for the selection of displacement-spectrum compatible ground motions.

Chapter 5 finally is dedicated to some treatment of uncertainties. In this context, the authors consider soil profile uncertainty, 3D modeling of SAFs, selection of input motion, and close with a comparison with observed SAFs at Casaglia.

Overall, the report is very much in contrast to what I would expect to see in a study which starts out with „*This report explores the approaches available to account for specific site effects in the framework of a Probabilistic Seismic Hazard Analysis (PSHA)*".

Observed variability of SAFs at Kik-net deep soil sites

The second key aspect of this report is the small variability which is observed for the SAFs at the Kik-net deep soil sites. Based on this observation, together with the ergodic assumption, the authors conclude that the fully probabilistic approach tends to overemphasize the uncertainty in the amplification values, in other words, that the fully probabilistic approach is biasing the uncertainty in the amplification values towards high values.

However, while at first glance this seems a logical conclusion, I miss attempts to demonstrate that this is actually the best explanation. Could it be that some characteristics in the data set (e. g. the source locations or the selection process) are biasing the uncertainty in the observed amplification values towards low values? The question of **why** the variability is so small, is not addressed at all.

Concluding remarks

Overall, the report was a bit odd for me to review, since it is neither a scientific study, which could be judged according to the criteria for judging research, e. g. according to it being theoretically sound, its originality, significance, etc., nor a licence application (which needs to meet certain standards based on state-of-practice rather than state of the art) but a mixture of both.

I can´t say that I didn´t enjoy reading it, because it is (not surprisingly considering the authors) eloquently written and describes well **how** the authors did what they did, but I can ´t say that I have seen enough evidence to become convinced by **why** they did what they did.

The crucial question for a PSHA in my opinion is if the amount of ground motion variability represented by this approach is capturing the amount of variability relevant for the future (unseen) ground motion at any site of interest. In this context, I have problems to accept „the absence of evidence for larger variability" from the ground motion in Japan observed over a short time window as being equivalent to indicating „the evidence for absence for larger variability" in the Po plain in the long run.

I hope that the authors will present more evidence during the workshop to understand **why** the variability in the Kik-net deep soil sites is as small as it is and **why** one should believe that the observations obtained for the Kik-net deep soil sites are representative for the sites in the Po plain.

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Review of the SIGMA Deliverable D3.96

"Approaches to account for site effects in the PSHA of selected sites in the Po area"

(Authors : R. Paolucci, E. Faccioli, C. Smerzini and M. Vanini, PoliMi, 17/10/2013)

As indicated by the title, this report addresses the issue of the incorporation of site-specific amplification studies in the framework of probabilistic hazard analyses, for the specific case of the Pô plain characterized by deep soil deposits.
This report is well structured and clearly written. It starts with an overview of the classes of approaches proposed over the last decade to include site effects in PSHAs and the two ones considered a priori in this study to include "conditioned", site-specific amplification factors (i.e., "HyS" - Hybrid deterministic / probabilistic, Site specific -, and "FpS" - Fully Probabilistic Site specific -). The second section presents the results of a dedicated investigation of KiKnet data from deep soil sites to ground a critical analysis of some usual assumptions regarding the FpS approach, and disregard it in the following, keeping only the HyS approach. The next 3 sections present the way the "HyS" approach is implemented for studies on sites in the Pô plain, with an emphasis on the selection of input rock motion consistent with the rock hazard, and on the discussion of some aleatory and epistemic uncertainties associated with the site-specific analysis involving 1D or 3D simulations. The last conclusion section summarizes the main methodological findings. This report addresses mainly the methodological issues, much more than providing final results for the site-specific PSHA at some sites in the Po plain: this will probably the goal of other or future reports.

The way to better incorporate site-specific studies, which are often deterministic, in probabilistic hazard studies, is definitely a key issue in the whole SIGMA project. This report is an important milestone in that direction. However, taken alone, it leaves – in my opinion – some issues still pending without clear or convincing answers, as I detail hereafter in my comments. It might well be that some of these missing answers can be found in the two other deliverables that will be presented in the next SIGMA SC (one in WP2, D2-93, and another one in WP4, D4-94), but which were not available to me. Some of the following comments or questions may be completely irrelevant and I apologize in advance, asking the authors to consider that I do not have right now a complete picture of their whole work.

Comments

Approaches p. 6-7 / Table 1.1 :

- In the FpG approach, as I understand it, the site PSHA may be decoupled from the rock PSHA if the used GMPEs do not include any non-linearity in the site term. This decoupling would be possible also in the FpS approach if the authors are convinced the NL is not an issue for Po plain sites. The amount of non-linearity in the actual site response is therefore a key issue in the incorporation of site response in PSHA studies; for deep soil sites such as in the Po plain, it might be useful to distinguish the low and high frequency parts, with probably limited NL effects at low frequencies (except in the case of extensive liquefaction – as was experienced at some places during the main shocks of the 2012 sequence). "Po-specific" GMPEs or site specific amplification factors, derived from the available recordings, could then be used to obtain FpG or FpS estimates at least at LF.
- In the HyS approach, the deterministic numerical simulation of site response is not necessarily limited to 1D modeling.

Observations on the conditioned site amplification functions (p.9-17 + Appendix A)

The aim of the section is to take advantage of the large number of recordings at KiKnet sites "comparable" to the Po plain sites, to derive fully experimental "conditioned" site amplification factors, i.e., looking at the dependency of the SAF on the input motion level, and to compare them with the assumptions or propositions provided by Bazzurro and Cornell (2004) on the basis of 1D site response computations. This comparison mainly focuses on two issues : a) the amount of non-linearity and b) the variability of the conditioned SAF.

The authors select a subset of 21 KiKnet stations as "*deep soil sites with VS30 in the range 200-400 m/s*" (p. 11 bottom): this definition is not fully quantitative, and it would be useful to detail what is meant by "*deep soil sites*", and to display not only the Vs profiles of two "representative" stations (as in Fig 2.2), but also the velocity profiles from ALL the selected stations, and their comparison with the velocity profile in the Po plain. Of particular importance, in my opinion, is the velocity at depth: for IWTH20 for instance, the velocity at the downhole site seems to be still very low, much lower than in the Po plain where apparently the S-wave velocity reaches around 600 m/s at 150 m depth. This would also help to understand why the "theoretical" fundamental periods for each site, as indicated in Appendix A, vary so much from one site to another, with a number of sites with fundamental periods lower than 0.2 s (KGSH04, NIGH18, YMTH04, YMTH14, YMTH15), and also why the theoretical fundamental period 4H/Vs differs so much, in some cases, from the peak period T0(peak).

Considering the importance of the conclusion regarding the weakness on non-linear effects (if any), It would also be useful to display, for each considered KiKnet site, the distribution of pga (or PSV at a given period, a smart decision to keep the same scale for all periods), together for all the available recordings: this information is in principle available on Figures 2.3 to 2.5 for the three sites NIGH11, IWTH20 and NIGH08, but the horizontal scale is not precise enough to identify clearly the range of variabilty of input PSV^R: apparently, it does not exceed a few cm/s, which is not that big, and much lower than the values obtained from both the UHS^R and the 3D simulations in Chapter 5 (Figures 5.6 to 5.8). This would help to understand why the conclusions drawn here (very weak or no non-linearity) are not consistent with the results reported by Régnier et al (2013, BSSA) on a different – but sometimes overlapping – subset of KiKnet data, according whom there is a very significant nonlinearity. A discussion on this (at least apparent) inconsistency would be welcome, in order to better legitimate the subsequent dropping of FpS because of the weakness of non-linearities. The reconciliation between both conclusions might come from the fact that Régnier et al. indicate the significant non-linearities are located mainly at high frequency and shallow depth: it is not obvious however that such a situation cannot occur in the Po plain in places with very soft deposits at the surface.

Minor, more technical comments:

- P.10 middle (Bazzurro & Cornell, 2004) : their way to account for some amount of random profile variability requires in my opinion a careful discussion and might be misleading, although it is a very common approach in the US.
- P.10 second bullet from bottom : I do not understand why the site amplification factor could be affected by the source directivity ? Or is it only an indirect effect of directivity through the dependency on the amplitude of ground motion ?
- P. 17 Figure 2.5 : I am wondering whether the "anomalous" high long period SAF values correspond to a bad S/N (in principle, the selection with a minimum pga of 10 cm/s2 should ensure a satisfactory S/N ratio), or simply due to the frequency content of small magnitude events, which result in the fact the pgd (i.e., long period level of PSA/PSV/SD) is controlled by intermediate frequencies, where there is indeed a significant amplification ?

Selected approach to account for specific site effects in the PSHA (p.18-19)

This section presents a short outline of a 6-step approach, two of them being detailed in the next two sections. Some other steps would however deserve more details:

- The first one is the classical PSHA for "rock"; however, it lacks the definition of what is "rock", especially as it should correspond to the "deep" bedrock underneath the Po plain. Considering the huge amount of discussion and work associated to this question during the Pegasos /PRP project, I think the way this issue is addressed for the Po plain should be at least described (PSHA for which VS30 value, how does it match with the bedrock velocity in the Po plain, and whether some further "κ" adjustments are needed or not).

- The 1D numerical simulations (step 3) using either linear equivalent or non-linear soil models are said to be based on "expert opinion", which is certainly, at least partly, the only practical way, but raises the question of the associated epistemic uncertainties if there is only one expert or one branch on the logic tree – as mentioned later by the authors regarding step (6) about the quantification of uncertainties: this aspect is not fully addressed in the present report -. See further comments below about the section 5 "quantification of uncertainties"

Selection of input motions compatible with PSHA at rock sites (p.20-30)

I fully agree with the way the time histories are very carefully selected for a given target spectrum : starting with a dedicated data base with high quality, broad band accelerograms (SIMBAD), then with a selection of time histories with (magnitude / distance / site) conditions close to the expected ones for the considered return period, and broad band spectral constraints depending on the target spectrum, so that only limited scaling and spectral matching is required in the end, without any change to the phase.

My only question, for this section, concerns the choice of the target spectrum: the authors choose the Uniform Hazard Spectrum corresponding to the considered return period, while many other teams and studies, especially in the US, recommend the use of conditional spectra (mainly the CMS) to account for the poor correlation of ε values at very different periods. The authors do justify their choice by the fact that CS is conditioned on the spectra value at one period and its applicability to cases with large NL effects, large number of modes and/or site response analysis is disputed. I agree it deserves to be debated, but I would not be so critical with the CMS approach, especially at very long return periods (> 10 ky) for which ε is large. I personally think it would be worth to compare the UHS and CMS approaches, may be with consideration of not only one but two or more specific periods to anchor the CMS. The keynote lecture by N. Abrahamson will certainly help to clarify these issues. In any case, the UHS approach considered here is on the safe side, and is (much) simpler to apply than the CMS one, especially when the UHS has been derived with more than one GMPE, with a limited knowledge on the correlation between residuals at different periods.

Quantification of uncertainties (p.31-43)

As indicated in the deliverable, there are two kinds of uncertainties : epistemic and aleatory, the border between the two kinds being somewhat fuzzy and subject to evolution with time and improvement of the scientific knowledge. As I understand it, although it is not explicitly stated, this section is mainly addressing the issue of aleatory uncertainties, in view of comparing the "sigma" associated to site response, to what is usually considered.

This is indeed a big issue, not easy to answer, with a high risk of double counting some of them already accounted for in the rock PSHA !

This section starts with listing several sources of uncertainties affecting the site response (input tie histories, soil profile dynamic properties, analysis method and computer code, modeling of NL behavior – with some mixing between aleatory and epistemic), but only some of them are considered and quantified:

- Small-scale variability of the soil profile
- 3D modeling of site amplification functions
- variability of site response associated with the variability of input motion

The first one is answered by using velocity profiles obtained at various sites in the Mirandola area (a scale in Figure 5.3 would be useful), and the associated site response variability for a given input motion. The approach is right, but It should be a little more documented with some information on the way the different velocity profiles were derived (invasive or not, uncertainties on these individual profiles, and on bedrock depth): from the deliverable 4-1 of the DPC-INGV2012-2013 project mentioned in the caption of Figure 5.3, I suspect most of these profiles are derived from non-invasive

measurements, which result probably in a much larger uncertainty than what is depicted in this figure. As a consequence, I am not fully convinced of the reliability of the resulting σ values.
The second one addresses the variability related with the "3D modeling of ground motion". I feel uncomfortable to comment this section, as the "3D model" is not described in this report (it is probably in the deliverable D2-93, presently unavailable for me): I did not understand whether it includes a fully 3D model of the Po plain, or the "3Dimensionality" only concerns the incorporation of finite source scenarios with different kinematics. These computations are performed up to a frequency of 1.3 Hz, apparently with a non-linear component (middle of p. 36), and the variability of the SAF from one source scenario to the next are compared to the observed SAF variability in the KiKnet stations. The computed variability turns out to be slightly larger than the observed one in Japan : Could it be due to the absence, in the Japanese data, of several nearby M5.5-6.5 events, as considered in the 3D simulations ?

> Incidentally, it may be noted that the computed SAF values are rather low (basically between 1 and 3), compared to the observed SAF at Casaglia (Fig. 5.11, up to 8 around 1.5 s): the reason for this large discrepancy is not clear for me, and is not commented in the report which focuses on the comparison of variabilities. May be it is not an issue, and the two SAF are not comparable, I cannot appreciate since the characteristics of the outcropping bedrock used as reference for the computed SAF are not detailed in this report.

The third one uses 1D linear equivalent models to investigate the sensitivity of amplification function to the input motion, using the accelerograms selected in the previous section. The 1D model is not fully described (is the NL curve displayed in Fig 5.9 used for all depths from 20 to 90 m, or is it modulated as a function of depth to take into account the confining pressure ?), and the amount of non-linearity reached for the selected inputs is not indicated (what are the maximum strain values ?). This information would be helpful to check whether this model is consistent with the conclusions of only very weak nonlinearities derived from KiKnet data.
The results, once again, are discussed mainly in terms of variability, which is found smaller for spectrally matched input motions (sets "b") than for the original accelerograms (sets "a"): it is not clear whether this is an effect of non-linearity (the spectra of original accelerograms shown in Figure 4.3 (sets a) vary by a factor up to 4, while the spectra of the tuned accelerograms (sets b) are identical within a few %) or simply an effect of the identical spectral content for the sets "b": it would be interesting to have a plot similar to Fig 5.10, for input accelerograms 10 times smaller.

The last subsection presents the observed SAF variability for a surface / downhole pair in Casaglia. Unfortunately, the variability σ is derived from only a limited set of recordings (6 events with unknown magnitudes and distances), which is certainly too little to fully capture the "in-situ" variability of SAF. Al already mentioned before, the observed SAF exhibits much higher levels than the computed ones (1D and 3D): it would be useful to be given some comments of the origin of these differences, which make me feeling very uncomfortable with the results of the modeling.

The issue of epistemic uncertainties in site response is not addressed in this section: usually it is accounted for through a logic tree with different acceptable assumptions regarding the velocity profile, the NL characteristics, and the modeling approach, with some weighting based on "expert opinion". In the present study, choices regarding the models and computational approaches were actually made, which can be seen as "drastic" choices since only one option was kept, thus corresponding to one single branch: the rationale behind these choices is most often given, it can be understood, but I doubt these choices will be systematically shared by other experts: I thus think the epistemic uncertainties are in fine underestimated in the present approach.

Conclusions (p.44-46):

The conclusion section wraps up the partial findings of each section. I will also briefly wrap up my main questions / comments about each of them, following the sequence used by the authors on their conclusion

- The dropping of the FpS approach is based on the claimed absence of clear non-linearities in KiK-net data corresponding to deep soil sites. I feel uncomfortable with this conclusion as a) some other studies on sometimes overlapping Kik-net data conclude at significant NL effects and b) the apparent range of PSV^R for the used data seems to be much lower than the PSV^R values experienced during the 2012 sequence and predicted by the 3D numerical simulations: additional comments and discussions on this issue would be welcome
- The comparison between the observed (KiK-net deep soils, + Casaglia) and computed σ (3D simulations) on SAF would benefit from a display of the corresponding (M,R) distribution, as I anticipate the computed SAF correspond to larger and closer sources, which would explain the larger variability. In the same paragraph, I do not understand the comparison between σ_{SAF} and single station sigma (which was already mentioned on p.36) : the latter cannot be reduced to the former, as it includes also source and path terms.
- The approach followed for the selection of appropriate input motion fitting a given target spectrum is very convincing and I do recommend it for the whole SIGMA project. I think however that three issues would deserve additional discussions or information
    - the characterization of the reference bedrock (V_{S30} only, V_{S30} + κ, …)
    - the choice of the target spectrum (here UHS on rock, rather than CMS), especially for very long return periods. The present approach however is both on the safe side and much simpler
    - the resulting variabilities for 1D LNEQ response would benefit from a comparison with the 1D linear case, to better isolate the individual components due to NL and variability of the spectral content in the input motion.
- The conclusions about the effects of small scale variability of the velocity profile (which I personally interprete as part of the aleatory variability – but this should be checked with the authors) are hampered – in my mind – by the lack of information on the quality of the various velocity profiles considered for the analysis
- Table 6.1 present a good summary of the variability values obtained in this report. I did not understand very clearly what is to be done with these values, especially the last row (i.e., $[\sigma^2_{soilprofile} + \sigma^2_{input}]^{0.5}$). From the sentence on p. 46 top about Monte-Carlo simulations, it seems that it should be added to the aleatory variability on rock. If this understanding is the correct one (to be checked with the authors), I think it will lead to an overestimation of the total σ: this issue was faced in the Pegasos project, and the latest models decided not to add this kind of aleatory variability because it is somehow already included in the rock σ (rock velocity profiles also include some kind of layering), and it would lead to double counting. The only "missing" component in the latter is the possible additional site response variability due to NL behavior. This is another incitation to perform a few additional 1D linear response computations to identify the individual effect of NL behavior in the 1D site response variability.
- I do not understand the first sentences of the last paragraph, as it mixes "σ", i.e., the aleatory variability, with the epistemic uncertainties related to soil profile and NL characteristics

I therefore feel somewhat frustrated at the end of the report. It is very rich, it presents many results, but it lacks some background information to decide how it can be applied. The incorporation of site-specific response in PSHA studies is a huge, multifold and difficult issue. The focus on deep soils considered here is definitely interesting and worth. I hope the oral presentation will better clarify the way to manage the specific epistemic uncertainties and aleatory variabilities linked to site response, to be added to their corresponding counterparts on rock hazard, and also the key issue of the importance (or not) of the NL effects, in both computed and observed site response. Especially as a linear behavior simplifies a lot the integration of site response into PSHA.

Grenoble, 02/11/2013

Pierre-Yves BARD

APPROACHES TO ACCOUNT FOR SITE EFFECTS IN THE PSHA OF SELECTED SITES IN THE PO AREA

RESPONSE TO REVIEWERS

1. General

This Deliverable has undergone major modifications, aiming at accounting for the reviewers comments as well as for the main concerns raised in the discussion during the Lyon meeting.
Particularly, Chapter 5 was completely rewritten and new calculations have been done to investigate different sources of epistemic uncertainties in the site response of Casaglia site. This was also permitted by the availability of new records for the Casaglia borehole site, which allowed us to calibrate an updated Vs profile.
Also, the chapter of Conclusions was rewritten in light of the updated results.

2. Response to reviewers comments: Pierre-Yves Bard

2.1. Approaches p.6-7/Table 1.1

2.1.1. Decoupling of PSHA at rock and soft sites in the presence of NL effects

In Chapter 5 a thorough investigation of how the selected approach is used to quantify the extent of non-linear site effects in the Po Plain is now illustrated. Instead, the use of Po-plain GMPEs was not addressed in this report, while it was addressed in the companion deliverable D4-94.

2.1.2. Approaches for specific-site response analysis

The reviewer states correctly that the numerical simulations for specific site response analyses may not be limited to 1D models. Table 1.1 was modified accordingly.

2.2. Observations on the conditioned site amplification functions (p.9-17 + Appendix A)

2.2.1. NL effects on the Kik-net records

- Based on the reviewer's comment, we have modified all figures concerning the conditioned SAFs from the Kik-net, in order for the levels of PSV on rock to be discernible on the plots.
- To clarify the points raised by the reviewer on this issue, we have significantly extended the comments on results (see Conclusion section 2.4), including comments on the comparison of these results with those of Régnier et al (2013). However it should be remarked that pointing out the scanty evidence of NL effects in the soil response at deep soil Kik-net sites has no direct implication on the selected approach to account for site effects in the PSHA. As it is clear in the application to Casaglia site, the NL soil response is considered.
- Therefore, we did not rule out the Bazzurro and Cornell approach because of missing NL effects in the Kik-net sites. Rather, we ruled it out because its application implies a much larger variability in site response than observed (at least on the Kik-net records and on the Casaglia site) and it does not allow one to disaggregate easily the different sources of uncertainty in site response. The large variability implied by the B&C approach is probably a consequence of scaling the same set of records to encompass a wide amplitude range of motion at rock, thus producing a variability of input motions that is much larger than is actually provided by nature (see e.g., note 10 in Chapter 6 and the example presented in the Lyon meeting for a site in the Po Plain). Instead, the careful selection of input motions, conditioned to the rock uniform hazard spectrum (UHS) at the specific return

period, as thoroughly illustrated in Chapter 4, is the key to provide the rational coupling of PSHA at rock with site response analyses.

- Minor, more technical comments

- Based on the discussion in Lyon on the double counting of aleatory variability due to random soil profile, we disregarded this effect and quantified only sources of epistemic uncertainty;

- An example of situations where the site amplification factor can be affected by source directivity has been added;

- The reviewer is right to point out that the PGD for low magnitude levels may be controlled by high frequencies. Thus, the sentence has been softened and a reference where this type of dependency has been studied was added.

2.3. Selected approach to account for specific site effects in the PSHA

- We have clarified in the text that we considered a “standard” rock site (Vs>800 m/s) for which the PSHA of use for the Po Plain may be provided. Typically, this is the engineering bedrock encountered at the base of the alluvial sediments of the Plain.

- In the present version of the report, we addressed in Chapter 5 the quantification of epistemic uncertainty due to selection of the NL approach and of the NL soil model.

2.4. Selection of input motions compatible with PSHA at rock sites

The reviewer points out a key issue, that is, the comparison of results from different “philosophies” for selection of input motions, such as fitting the UHS spectrum or using the CMS approach. Although not addressed in this report, a comparison of CMS vs UHS compatibility was carried out by the authors to assess its role on the response of bridge structures, as was also shown in the presentation in Lyon. It was pointed out that this role is marginal, that is results are similar both in terms of average response and variability, provided that real unscaled (or moderately scaled) records are used in both approaches.

2.5. Quantification of uncertainties

Chapter 5 was rewritten, to account for the comments of the reviewers and of discussion raised during the Sigma meeting in Lyon. The aims of this updating aimed mainly at quantifying only sources of epistemic uncertainty in the analysis of seismic site effects at Casaglia, that is:

<u>Vs profile</u>: quantification of the effect of the different Vs profiles available at the same site, based on different techniques of investigation;
<u>Non-linear approach</u>: difference of results from linear equivalent vs fully non-linear analyses;
<u>Non-linear models</u>: effect of different assumptions in terms of curves of degradation of shear modulus and damping;

Selection of input accelerograms.

We have dropped out the discussion of the effect of random variability of the soil profile, because we agreed that it may be already included within the aleatory contribution to sigma coming from the PSHA results at rock.

2.6. Conclusions

We hope that the present version of the report and of its conclusions, supported by the discussion in Lyon, may have clarified all the remarks made by the reviewer.

3. Response to reviewers comments: Frank Scherbaum

The general remarks made by this reviewer mostly come from misunderstanding the objective of the deliverable. As a matter of fact, and explained in the Lyon meeting, the objective of the Italian team within Sigma was to provide results for site-specific PSHA at several location in the Po Plain of interest to Enel. This is the reason why we aimed at producing site-specific results, rather than providing a general framework encompassing as a state-of-art the pros and cons of the different approaches available to carry out site-specific PSHA studies. This objective was clearly stated in the title itself, as well as in the Introduction of the report.

Anyway, also taking advantage of the criticisms of the reviewer and of the discussions during the Sigma meeting in Lyon, a thorough revision of this deliverable was made, especially as regards the site-specific analysis in Casaglia (Chapter 5), which was not yet at its final stage when the first release of the report was delivered. Based on these updated results, also the Conclusions (Chapter 6) were deeply revised.

Answer to the specific comments

Ergodic assumption

Further records at Casaglia were recently made available and are now introduced and analysed in a deeper detail (see section 5.2.2). Unfortunately, those records do not encompass a sufficiently large range of amplitudes to detect possible non-linear effects in the conditioned seismic amplification functions.

Observed variability of SAFs at Kik-net deep soil sites

Although limited to a relatively small range of amplitudes, the records of Casaglia definitely confirm the small variability of site amplification functions that was deduced based on the analysis of the selected Kik-net deep soil stations. The interesting result is that, at low levels of amplitude of bedrock motion and in spite of the very different earthquake sequences included in the different sets, the seismic response in Casaglia is governed in all cases by the 1D soil layering effects (see Table 5.2 and Fig. 5.5).

In the updated version of the report, Figure 2.6 was added, which may help explaining the nature of variability of the observed site amplification functions. In this picture the SAFs from short distance large magnitude earthquakes recorded at station NIGH11 are superimposed to the average SAFs from low amplitude events. It is quite clear that the “large amplitude” SAFs suffer of moderate non-linear effects in the short period range, with values that fall within the lower band of variability from small events. Much more interesting is the fact that at long periods the “large amplitude” SAFs fall well above the range of variability from small events. This can only be explained by 3D source-to-site propagation effects, and the corresponding variability range at long periods is well predicted by the 3D numerical simulations in the Po Plain.

The explanation on **why** the variability both at Casaglia and at the Kik-net deep-soil stations is much smaller than that predicted by the papers the reviewer is referring to, is likely to be found in the criteria for selection of input motions, as thoroughly discussed in this report and stressed in the Conclusions section (see note at bottom p. 65). We cannot play with input motions and scale them beyond physical limits. The price to pay is an artificial increase of variability of results, contrary to the experimental evidence.