SIGMA Integrated Exercise for site-specific PSHA

AUTHORS			REVIEW			APPROVAL		
NOM	DATE	VISA	NOM	DATE	VISA	NOM	DATE	VISA
G. Ameri (GEOTER)	29/05/15		Ph. Renault			JM. Thiry		
			F. Pacor			G. Senfaute		

DISSEMINATION: *Authors; Steering Committee; Work Package leaders, Scientific Committee, Archiving.*

GEOTER SAS

Pôle Geoenvironnement
3, rue Jean Monnet
34 830 Clapiers - France
Tel: + 33 (0)4 67 59 18 11
Fax: + 33 (0)4 67 59 18 24
Email: geoter@geoter.fr
Website: http://www.geoter.fr

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SIGMA Integrated Exercise for site-specific PSHA

Realization:

GEOTER SAS
Pole Geo-environnement
3, rue Jean Monnet
34 830 Clapiers

Tel.: 04 67 59 18 11
Fax: 04 67 59 18 24
Email: geoter@geoter.fr
Website: www.geoter.fr

Command: n° 3000-4210054770

Date: 09/04/2015

Client approval:
EDF/SQR/TEGG
Gloria SENFAUTE
905, avenue du Camp de Menthe BP 605
13 093 AIX-EN-PROVENCE Cedex 02
Tel. : 04 42 95 95 00
Email : gloria.senfaute@edf.fr

Date	Written by	Reviewed by	Approved by
29/05/2015	G.AMERI	D.BAUMONT	C.MARTIN
Visas			

EXECUTIVE SUMMARY

In the framework of the SIGMA Project, an exercise is conducted aiming to integrate the different contributions from the SIGMA work packages (WPs) into a site-specific PSHA for two virtual sites in the French area of interest. This is called the SIGMA Integrated Exercise (IE). The overall objective of the IE is to compare the results from a site-specific PSHA and a generic PSHA.

The generic PSHA is performed for the two sites by considering the appropriate values of the site parameters used in the GMPEs (e.g., Vs30). In this way, the uniform hazard spectra (UHS) resulting from the PSHA are directly obtained at the surface.

The site-specific PSHA is more complex. The PSHA calculations are performed at the base of the sediment layers, i.e., for bedrock conditions. Because such conditions are typically characterized by high Vs, which are outside the range of applicability of current GMPEs, the GMPEs need to be adjusted to such large Vs values. Moreover, the bedrock conditions are also characterized by a site-specific kappa value. The kappa parameter, which is a measure of high-frequency energy dissipation in the top 1 to 2 km of the crust (Anderson and Hough, 1984), is not considered in empirical GMPEs and, therefore, GMPEs need to be also adjusted to account for kappa. Once GMPEs are adjusted for the site-specific bedrock, the PSHA is performed. Then, the UHS and the hazard deaggregation at bedrock level are used to select acceleration time-histories and to run site-response analysis. The amplification factors derived by the site-response analysis are used to multiply the UHS at the bedrock in order to obtain ground motion response spectra (GMRS) at the surface.

Different WPs are in charge of different aspects of the SIGMA IE:

- WP2 is in charge of selecting the GMPEs for the IE and of providing adjusted GMPEs using one method developed within the SIGMA project by Bora, 2014 (called “method 1” in this report);
- WP3 is in charge of the site–response analysis and of the calculation of amplification factors. Moreover, WP3 provides adjusted GMPEs using an alternative approach by Al Atik et al., 2014 (called “method 2” in this report);
- WP4 is in charge of the PSHA calculations at the surface using generic GMPEs and at bedrock level, using Vs-kappa adjusted GMPEs;
- WP5 is in charge of the time-histories selection and modification to be used for site-response analysis.

In this study we performed site-specific PSHA for two virtual sites: the first characterized by a hard bedrock and about 200 m of soil layers with a Vs30=185 m/s; the second characterized by very-hard bedrock and thick soil deposits with a Vs30=370 m/s. The median ground motion from a set of GMPEs selected for the PSHA is first adjusted form the generic host conditions to the Vs and kappa values of the target bedrock for each site. The host-to-target Vs-kappa adjustment is performed following two approaches. The first is based on the adjustment factors derived by Bora (2014) that are applied to the other three GMPEs (i.e., Ameri, 2014; Boore et al., 2014 and Cauzzi et al., 2014). The second approach is based on the methodology detailed in Al Atik et al. (2014) that makes use of the IRVT to derive Fourier amplitude spectra for each GMPE in order to estimate the host kappa and to apply the Vs-kappa scaling. The total sigma of the GMPEs is reduces by applying a single-station sigma model in order to account for the fact that the repeatable site term is included using amplification factors from site response analysis performed in the second part of the study.

The bedrock UHS calculated from both Vs-kappa adjustment methods and hazard deaggregation at 10’000 years return period are used to select acceleration time histories to perform linear, equivalent-linear and nonlinear site response analysis for both soil profiles. The mean amplification factors are used to calculate site-specific mean ground motions response spectra (GMRS) that are compared with generic mean UHS calculated only based on the Vs30 at the sites.

The final results, expressed in terms of mean spectra, show that the comparison between site-specific spectra and generic ones is quite similar for both sites. The site-specific spectra at short periods (T< 0.1s - 0.3s) considering linear soil response are larger than the generic ones for Vs-kappa adjustment method 1 and consistent with the generic ones for Vs-kappa adjustment method 2. For longer periods, both Vs-kappa adjustment methods provide spectral values lower than the generic ones. Considering the equivalent-linear and nonlinear soil response site-specific spectra are substantially lower (up to 40-50 %) than the generic ones at all spectral periods.

TABLE OF CONTENTS

TABLE OF ILLUSTRATIONS

SIGMA Integrated Exercise for site-specific PSHA

1. INTRODUCTION

In the framework of the SIGMA Project, an exercise is conducted aiming to integrate the different contributions from the SIGMA work packages (WPs) into a site-specific PSHA for two virtual sites in the French area of interest. This is called the SIGMA Integrated Exercise (IE). The overall objective of the IE is to compare the results from a site-specific PSHA and a generic PSHA.

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The main differences in the ground motion characterization for a site-specific and generic PSHA are illustrated in Figure 1.

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- WP4 is in charge of the PSHA calculations at the surface using generic GMPEs and at bedrock level, using Vs-kappa adjusted GMPEs;
- WP5 is in charge of the time-histories selection and modification to be used for site-response analysis.

This deliverable summarizes the input obtained by the different WPs and presents the results of the SIGMA IE.

Section 2 presents the characteristics of the target sites considered for the IE.

Section 3 summarizes the ground-motion logic tree used for generic and site-specific PSHA and illustrates the adopted single station sigma model.

Section 4 discusses the Vs-kappa adjustment factors approaches used in the IE and provide adjustment factors for the two sites and for the set on considered GMPEs.

Section 5 presents the site-specific PSHA results at bedrock for the two sites.

Section 6 presents the results of the site-response analyses.

Section 7 finally compares the site-specific and generic PSHA results at the surface for the two sites.

A detailed explanation of the nonlinear site response analysis conducted for the two sites is reported in the Annex 1 and Annex 2.

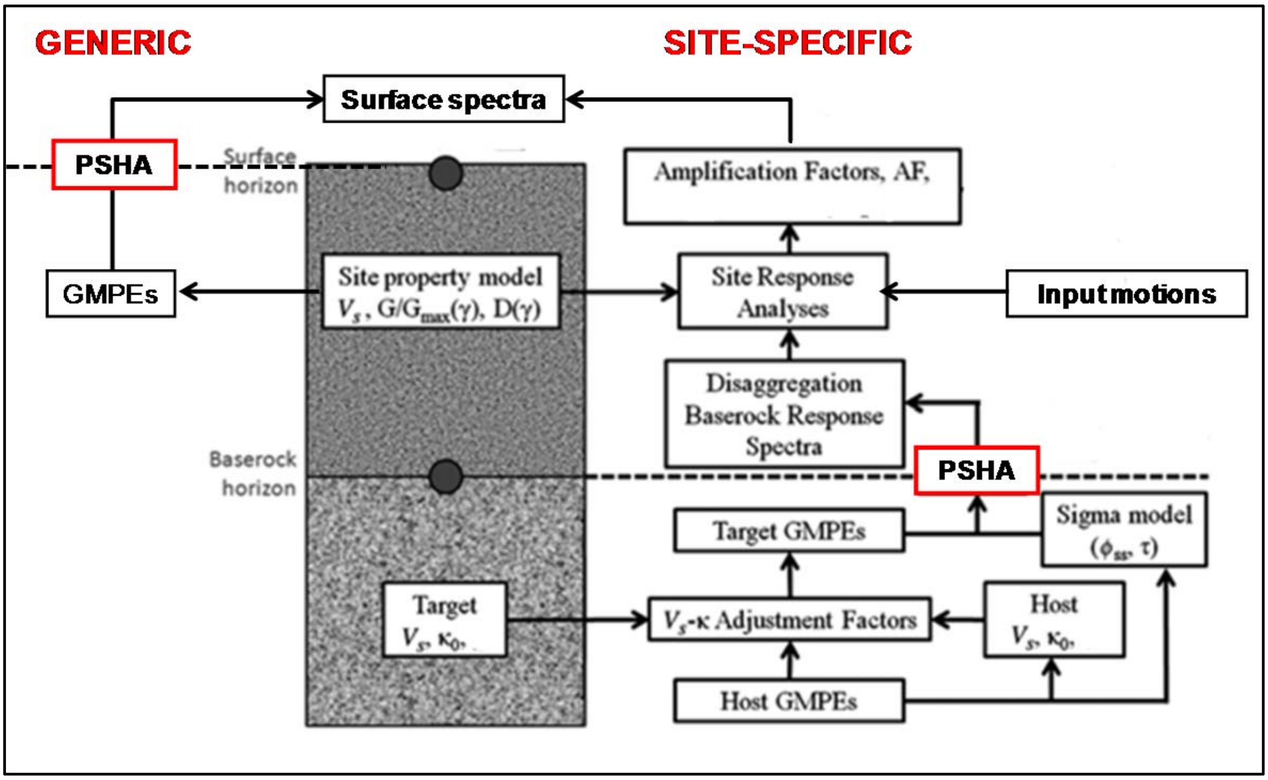

Figure 1 : Schematic representation of generic and site-specific hazard calculations for a considered site. Modified from Rodriguez-Marek et al. (2014).

For sake of clarity we recall here that the scope of work is limited to the consideration of best-estimate site parameters so that the following uncertainties are not considered in the SIGMA IE, mainly due to the limited time frame (see also the Discussion and Conclusions section):

- Epistemic uncertainties in target Vs30, Vs profiles & kappa for bedrock and in parameters for the non-linear and linear-equivalent soil model (Vs, Damping and G/Gmax curves);

- Epistemic uncertainties in host Vs profiles and kappa. Although kappa host uncertainties are considered, to some extent, by using in the calculations the whole set of kappa-host values derived for several scenarios for each GMPE;
- Epistemic uncertainties in single-station sigma model.

2. TARGET SITES

The geographical position of the site for the PSHA is the city of Valence. For this site location, several site conditions are assumed for the purpose of the SIGMA IE. Four generic site conditions are considered:

- rock condition with a Vs30 of 800 m/s;
- rock condition with a Vs30 of 1500 m/s;
- soil condition with a Vs30 of 185 m/s;
- soil condition with a Vs30 of 370 m/s.

Two site-specific conditions are considered (Table 1), characterized by different Vs30 at the surface, different Vs and thickness of the soil layers, different Vs of the bedrock and different kappa values at the bedrock:

- Soil site with a Vs30 of 185 m/s overlying a bedrock at 183 m depth with a Vs30 of 1500 m/s and a kappa=0.03s (named site 1-V);
- Soil site with a Vs30 of 370 m/s overlying a bedrock at 690 m depth with a Vs30 of 3200 m/s and a kappa=0.01s (named site 2-G).

The Vs profiles (up to 1 km depth) for site 1-V and site 2-G are presented in Figure 2. Note that the “soil” profiles defined by WP3 extend down to 183 m for site 1-V and to 690 m for site 2-G, reaching in both cases a Vs = 800 m/s. The deeper part of the profiles represents the bedrock, characterized by generic Vs profiles determined in this study (as described in section 4.2.

For the purpose of the numerical simulations of the soil columns transfer functions calculated by WP3, a value of Qs=Vs/10 is used.

The site-specific bedrock conditions define the target parameters for the Vs-kappa adjustment of the GMPEs in Section 4.

name	Geometry	Thickness of the soil profile	V_{s30} (surface)	V_s of target bedrock	kappa
1-V	1D	183 m	185 m/s	1500 m/s	0.03 s
2-G	1D/2D	690 m	370 m/s	3200 m/s	0.01 s

Table 1 : Parameters for the selected site conditions.

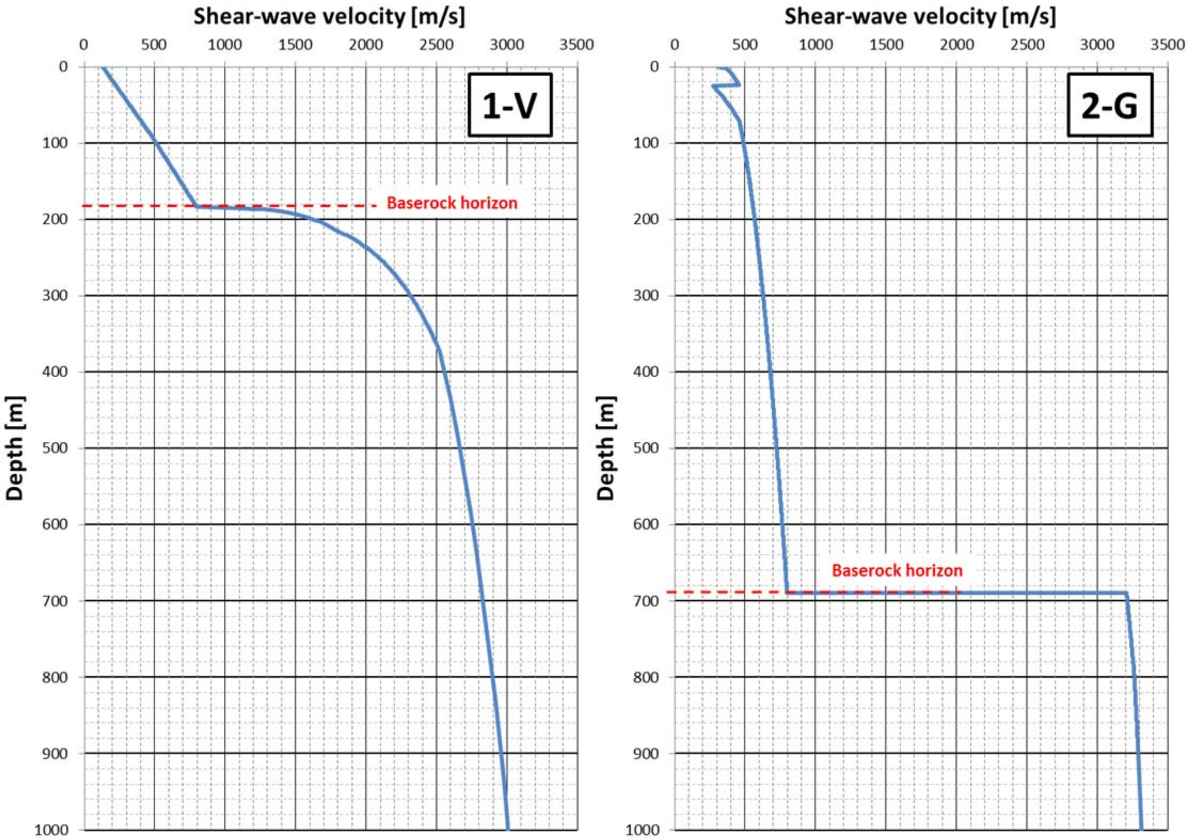

Figure 2 : Vs profiles (top 1 km) for the two considered site-specific conditions.

3. THE PSHA LOGIC TREE

The PSHA logic tree used for the SIGMA IE is essentially the same as the one used in the SIGMA 2012 PSHA model for the French Southeastern ¼ with an updated set of GMPEs (Figure 3). We refer to Carbon et al., (2012) for details of the model and for justification of the weights. The seismic source characterization (SSC) logic tree is composed as follows:

- 3 seismotectonic models based on area sources:
  - Area sources based on a previous GEOTER model;
  - Model based on the identification of fault systems (Belledone Fault, Nîme fault, Provence faults system and the specific cluster of Tricastin);
  - Area sources based on a previous IRSN model;
- 2 catalogues of seismicity with associated completeness periods :
  - SIGMA 2012 catalogue (homogenized in Mw using the original instrumental catalog and macroseismic database available for France);
  - A synthetic catalogue that considers variability on the estimation of earthquake magnitude and location (one single realization);
- 100 combinations of maximum magnitude and recurrence parameters for each seismic source model.

We stress that, for the purpose of the IE, the SSC logic tree, has a minor importance and it serves only as for computational purposes. The modification of the SSC logic tree is outside the scope of work of the IE. The ground motion characterization logic tree is discussed in the next section, being modified with respect to the 2012 model for the purpose of the IE.

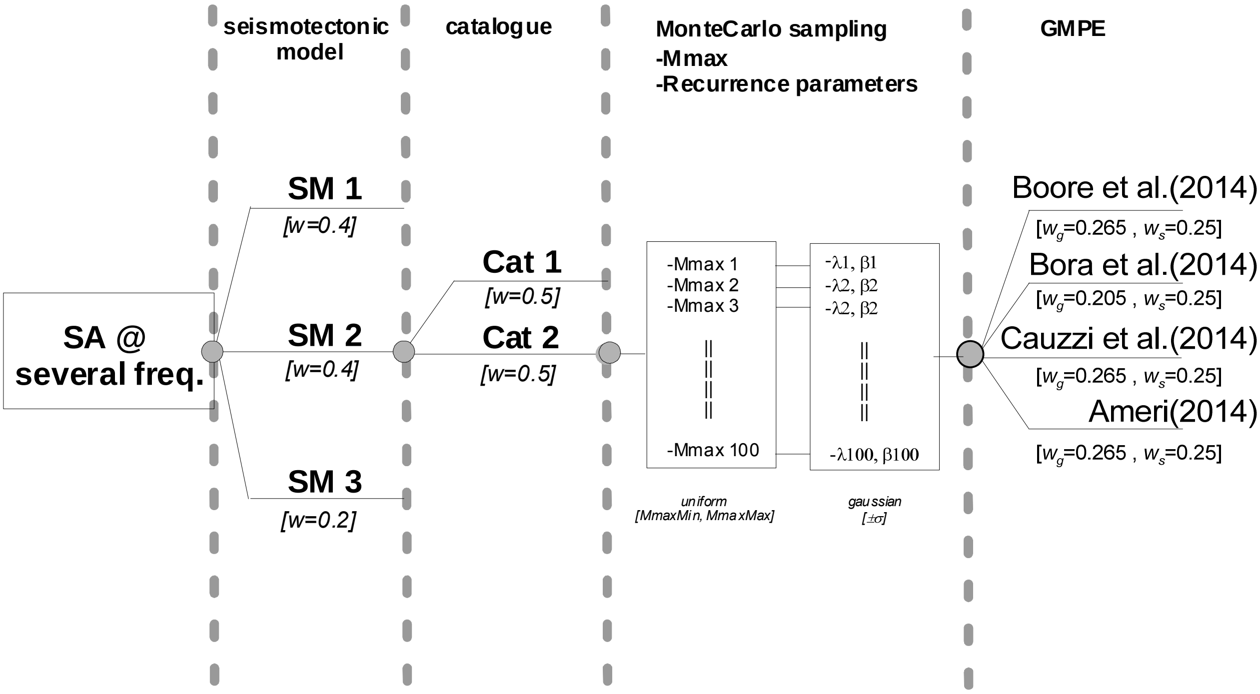

Figure 3 : The SIGMA 2012 PSHA logic tree updated with the GMPEs selected for the IE.

3.1 GMC LOGIC TREE

After the November 2013 SIGMA Scientific Committee meeting, it has been decided to select for the IE a different set of GMPEs with respect to the ones used in the 2012 PSHA logic tree. The selection of the new set of GMPEs and their weight was discussed in a Workshop organized by the WP2 leaders on March 25th 2014 in Paris. The GMPEs selected for the IE are:

- Boore et al. (2014), w_g*=0.265;* w_s*=0.25;*
- Bora (2014), deliverable SIGMA-2014-D2-130 ; w_g*=0.205;* w_s*=0.25;*
- Cauzzi et al. (2014), w_g*=0.265;* w_s*=0.25;*
- Ameri (2014) , deliverable SIGMA-2014-D2-131; w_g*=0.265;* w_s*=0.25;*

Where w_g and w_s represents the weights assigned for generic and site-specific PSHA calculations (see section 2).

The weights have been assigned by during the WP2 meeting by a group of experts composed by F. Cotton, P-Y. Bard, P. Traversa, G. Ameri and E. Faccioli. Each expert assigned a weight to each GMPE with possibility of different weights for generic or site-specific calculations. The final weights represent an average of the weights given by each expert.

It is important to mention that at the time of the WP2 meeting the model by Bora was not the one detailed in SIGMA-2014-D2-130 (and used in this study), but the “previous” version published in Bora et al. (2014). Some experts questioned some components of this model (i.e., duration model, sigma model). This is why it has lower weight for the generic PSHA. For the site-specific PSHA these downweighting of the Bora et al. (2014) model is counter-balanced by the fact that it was judged more adapted than the other models for adjustment purposes (providing directly the empirical model of the Fourier spectrum). For this reason, in site-specific calculation it has the same weight as the other GMPEs.

Note that all the GMPEs use Vs30 as site parameter except the Ameri (2014) model, which considers EC8 site classes. Moreover, the Boore et al. (2014) GMPE considers basin depth z1 (depth from the ground surface to the 1.0 km⁄s shear-wave horizon).

3.1.1 Standard deviation (sigma) model

We used two different models for the standard deviation (sigma) of the GMPEs depending on the generic or site-specific PSHA.

- In case of generic site conditions, the sigma of each selected GMPE is used as it was published in the relative papers;
- In case of site-specific conditions, we used the concept of single-station sigma (Rodriguez-Marek et al., 2013). Indeed, in the site-specific PSHA, the GMPEs are first adjusted to site-specific rock conditions (Vs-kappa adjustment) and then site response analysis is performed to account for local amplification of the sedimentary layers. For this reason, the part of the total sigma of the GMPEs that is due to site-to-site variations among sites characterized by the same site parameterization (e.g., Vs30 value) should be removed because these variations are not present when considering a single site. If the repeatable contributions to the seismic motion at the site of interest can be modeled through an appropriate adjustment to the median ground-motion predictions, then the sigma value can be reduced by an amount that reflects the variability in the site term.

The single station sigma (SSS) model by Rodriguez-Marek et al. (2013) is used in this study as decided within WP2. This single station sigma (σ_{ss}) is defined as follows.

$$\sigma_{ss} = \sqrt{\phi_{ss}^2 + \tau^2}$$

Where τ is the event-to-event variability and ϕ_{ss} is referred to as the event-corrected single-station standard deviation. Rodriguez-Marek et al. (2013) compiled a large database of ground motions from multiple regions to obtain global estimates of these parameters. Results show that the event-corrected single-station standard deviation (ϕ_{ss}) is remarkably stable across tectonic regions. They proposed different model for ϕ_{ss}, a constant model (only function of spectral period), a magnitude-dependent and a distance-dependent model. In this study, we used the constant model reported in Table 2.

Period [s]	Constant ϕ_{ss} [ln]	Constant ϕ_{ss} [$\log_{10}$]
PGA	0.46	0.20
0.1	0.45	0.20
0.2	0.48	0.21
0.3	0.48	0.21
0.5	0.46	0.20
1	0.45	0.20
3	0.41	0.18

Table 2 : Constant model for ϕ_{ss} proposed by Rodriguez-Marek et al. (2013).

The other necessary ingredient for the calculation of σ_{ss} is the event-to-event variability (τ). One possible approach is to use the τ value defined in each GMPE. This way a σ_{ss} is defined for each GMPE. Another approach is to use one single τ value, believed to be the best representative of the event-to-event variability in the study area. This way one single σ_{ss} is defined and used for all GMPEs. This second approach has been used in a recent PSHA SHAAC Level 3 project for a NPP site in South Africa (Rodriguez-Marek et al., 2014; Bommer et al., 2014) and it is used in the present study. During the WP2 Workshop, it was decided to use the τ value of the Ameri (2014) GMPE because this model is the only one considering French events in the dataset.

Figure 4 shows the sigma values of the GMPEs selected for the IE, the ϕ_{ss} proposed by Rodriguez-Marek et al. (2013), the τ of the Ameri (2014) GMPE and the σ_{ss} model finally used in this study.

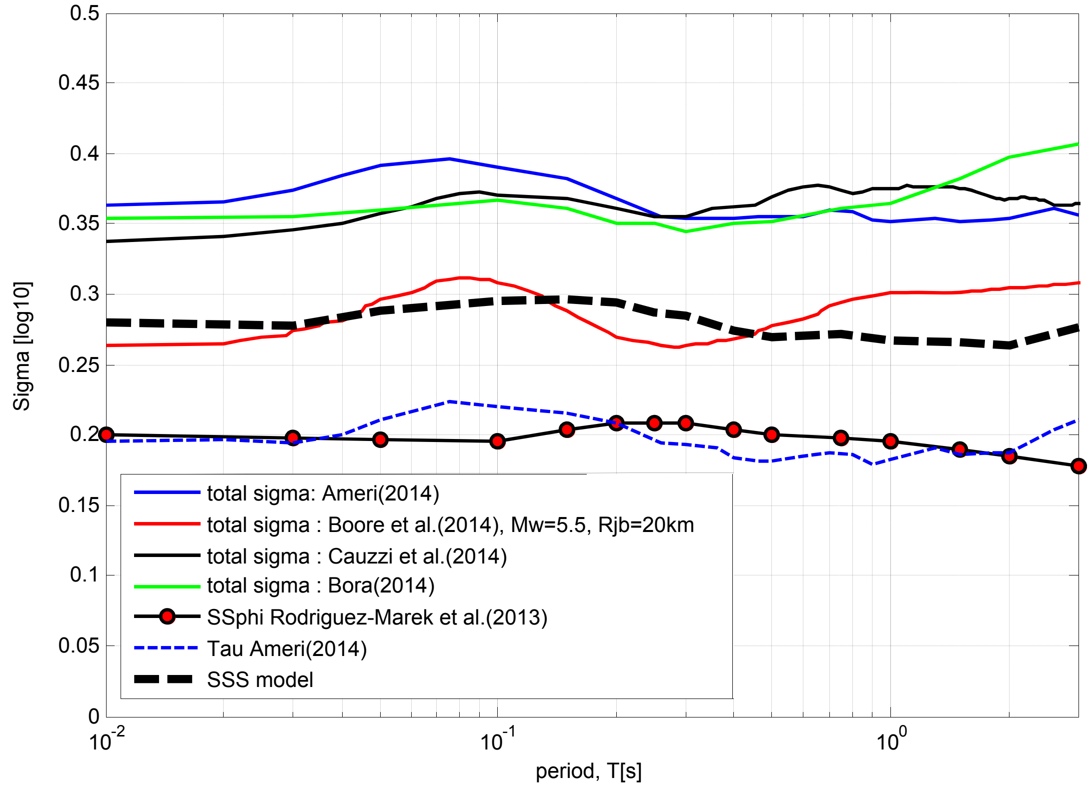

Figure 4 : Standard deviation (sigma) models as a function of spectral period used in this study. The single-station sigma (SSS) model is showed by the dashed black line.

4. VS-KAPPA ADJUSTMENT OF THE GMPES FOR SITE-SPECIFIC ROCK CONDITIONS

In order to perform the PSHA for the site-specific rock conditions defined for sites 1-V and 2G, the GMPEs need to be adjusted. In section 3.1.1 we have explained how the single station sigma approach is implemented in order to account for the fact that, in a site-specific case, the site effect is repeatable and thus its variability should be removed from the aleatory standard deviation of the GMPEs. In this section, we show how we modify the median estimates of the GMPEs to account for the site-specific Vs-kappa conditions.

4.1 DESCRIPTION OF THE METHODOLOGY

The host-to-target Vs-kappa adjustment aims to modify the GMPEs for generic (i.e., host) rock conditions to site-specific (i.e., target) rock conditions defined in terms of Vs profile and kappa value.

The adjustment factors for each GMPE are calculated by WP2 and WP3. Two alternative approaches are used to perform the Vs-kappa adjustment:

- Method 1 (or approach 1) is based on the work by S. Bora and F. Scherbaum, (detailed in the Deliverable SIGMA-2014-D2-130), referred to as Bora (2014). The authors developed empirical Fourier amplitude spectrum and duration models based on RESORCE database. Several parameters such as corner frequency, stress drop and kappa are inverted for each record in the dataset in order to use them as explanatory variables in the derivation of the empirical Fourier spectra model. The Fourier and the duration models are combined via RVT in order to provide response spectra. Thus, the spectral acceleration can be directly predicted for a specific target kappa value (or stress drop value). Adjustment factors can be obtained by dividing the response spectral amplitude for the target conditions (Vs-kappa for the two sites) with respect to those for the host conditions. The host conditions are Vs30=800 m/s and κ=0.042 s, which correspond to an average kappa value for the dataset considered by Bora (2014). Using this approach, the adjustment factors for each case (1-V and 2-G) depend on magnitude, distance and spectral period. As Bora (2014) pointed out, these adjustment factors can only be applied to GMPEs that are derived on the same (or very similar) database. In the SIGMA IE it was decided that Method 1 for Vs-kappa adjustment consists to apply the Bora (2014) factors to the other three considered GMPEs in order to perform PSHA calculations. It is important to note that when applying the adjustment factors to the other GMPEs we make the strong assumption that their host characteristics are similar to the Bora (2014) ones. While this may be reasonable for the Ameri (2014) GMPE, which is derived based on a similar dataset with respect to Bora (2014), it may not be the case for the other two GMPEs. In particular, the average kappa-host values may be quite different for the Cauzzi et al. (2014) and the Boore et al. (2014) models because the underlying datasets are remarkably different with respect to the one used by Bora (2014). Within the SIGMA IE, no action was planned to verify in a rigorous way the applicability of the adjustment factors derived by Bora (2014) to the other selected GMPEs. The adjustment factors derived by this approach for the two site-specific conditions are shown in section 4.4 for Mw=5.5 and R_{JB}=20 km (M-R couple largely contributing to the hazard at 10'000 years return period).

  Method 2 (or approach 2) is based on the method proposed by Al Atik et al. (2014) and used is a recent PSHA for a NPP project in South Africa (Rodriguez-Marek et al., 2014). The methodology is based on the use of the inverse random vibration theory (IRVT) in order to produce a Fourier spectrum compatible with the response spectrum of a GMPE for a specific scenario. The value of the kappa host is estimated by the slope of the high-frequency part of the Fourier amplitude spectrum (FAS). Once that the kappa host is defined, the kappa scaling, $\exp(-\pi f(\kappa_{target}-\kappa_{host}))$, is applied to the Fourier spectrum and the RVT is then used to obtain an adjusted response spectrum. Figure 5 presents the flowchart of the method. In order to derive combined Vs and kappa scaling factors for GMPEs, the procedure above can be modified by including an additional step that multiplies the κ scaled FAS by the ratio of target-to-host crustal amplification functions to obtain Vs–kappa scaled FAS. The Vs– kappa scaled FAS are then converted to response spectra using RVT and Vs –kappa scaling factors are computed by dividing the Vs– kappa scaled response spectra by the

GMPE response spectra. The Al Atik et al. (2014) approach is used to derive adjustment factors for the Cauzzi et al. (2014), the Ameri (2014) and the Boore et al. (2014) GMPEs. The Bora (2014) GMPE is not adjusted using method 2 because this would be inappropriate since this model directly provide the possibility to correct empirical Fourier amplitude spectra for Vs and kappa without the need of using IRVT to derived an equivalent FAS. Overall, method 2 implies three GMPEs adjusted with the Al Atik et al. (2014) approach and the Bora (2014) model, for which the predictions are the same as in method 1. The Vs – kappa scaling factors derived from method 1 will be detailed in section 4.3.

An important difference of method 2 with respect to method 1 is that each GMPE will potentially have a different kappa scaling, whereas in method 1 the same kappa scaling is used for all GMPEs. On the other hand, it is important to mention that the Vs scaling (illustrated in section 4.2) on the Fourier spectrum is the same in the two methods, the only (but important) difference being that in method 1 the FAS is empirically derived whereas in method 2 is derived via IRVT from the response spectrum of a GMPE. This may cause differences in the Vs scaling for the response spectra.

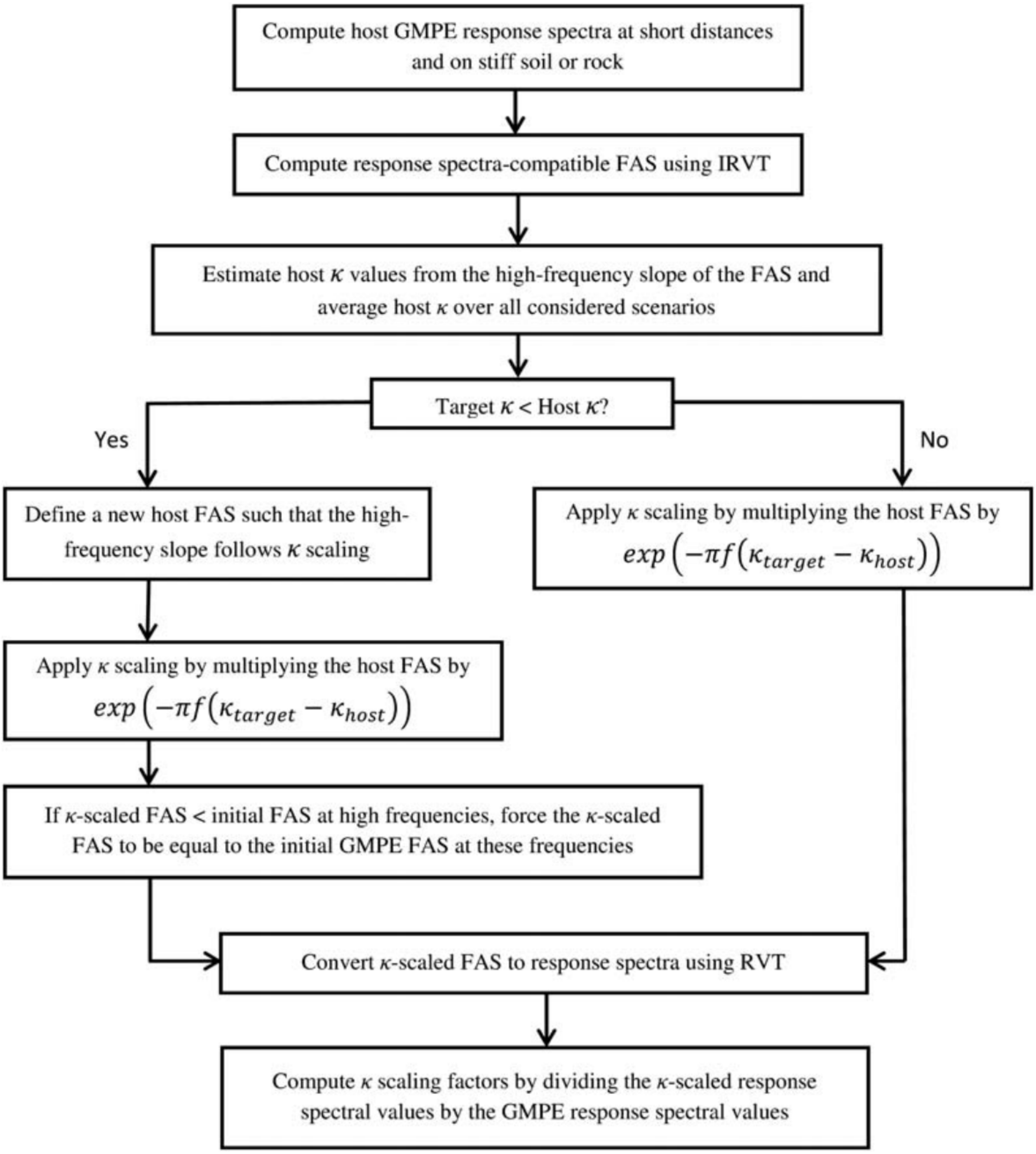

Figure 5 : Flowchart of the k-adjustment methodology proposed by Al Atik et al., 2014.

4.2 VS ADJUSTMENT

The Vs adjustment aims to modify the median estimates of GMPEs derived for generic Vs30 to a site-specific target Vs profile. This is needed because the GMPEs predictions are not constrained for large Vs value representative of bedrock conditions. In the context of the IE, the target bedrock conditions for the two sites are defined in terms of Vs and kappa (see Table 1) thus, representative Vs profiles need to be defined. In the same way, host Vs profiles representative of generic site conditions associated with a Vs30 value shall be defined in order to scale the ground motion from the host to the target Vs profiles.

4.2.1 Generic rock profiles and crustal amplifications for the host and target conditions

The Vs adjustment of the GMPEs is based on the use of generic rock profiles representative of the host and target rock conditions. We used the approach proposed by Cotton et al. (2006) to derive generic rock profiles by interpolating the rock and hard-rock profiles of Boore & Joyner (1997). The interpolation method is slightly modified with respect to the Cotton et al (2006) as described by D. Boore (details are provided at http://www.daveboore.com/daves_notes/daves_notes_on_interpolating_two_given_velocity_profiles_to_obtain_a_velocity_profile_with_specified_v30_v1.0.pdf).

In this way, generic Vs profile for Vs30= 800 m/s, 1000 m/s and 1500 m/s are produced. For the case of the 3200 m/s Vs profile, this approach cannot be used because it would require extrapolation. For this reason we decided to use the hard-rock profile by Boore & Joyner (1997) removing the shallow part with Vs<3200 m/s in order to have a profile with a Vs=3200 m/s at the surface. The Vs profiles considered in the SIGMA IE are presented in Figure 6 and Figure 7.

The generic profile with a Vs30=800 m/s is used as host Vs profile for the Boore et al. (2014), Bora (2014) and Cauzzi et al. (2014) GMPEs. The site model of the Ameri (2014) GMPE is based on EC8 site classes and not on a continuous function of the Vs30. This is due to the fact that not all the stations in their dataset were characterized by a Vs30 value and for a lot of them only information on site category based on local geology was available. As a consequence, it is more difficult to associate a representative Vs30 values to predictions for class A sites. Based on the fact that EC8 class A sites are defined by Vs30>=800 m/s and on the analysis of the dataset used by Ameri (2014) we decided to use a Vs profile with a Vs30=1000 m/s for this GMPE.

The target Vs profiles for the two sites are characterized by Vs30=1500 m/s and Vs30=3200 m/s.

We used the software SITE_AMP developed by D. Boore to calculate the quarter-wavelength amplification of the considered Vs profiles. The amplification functions are reported in Figure 8. Once that amplification functions are calculated, the adjustment from the host to the target Vs profiles are simply obtained by dividing the amplification of the target profile by that of the host profile. Obtained host-to-target amplifications (in the Fourier domain) are shown in the right panel of Figure 8.

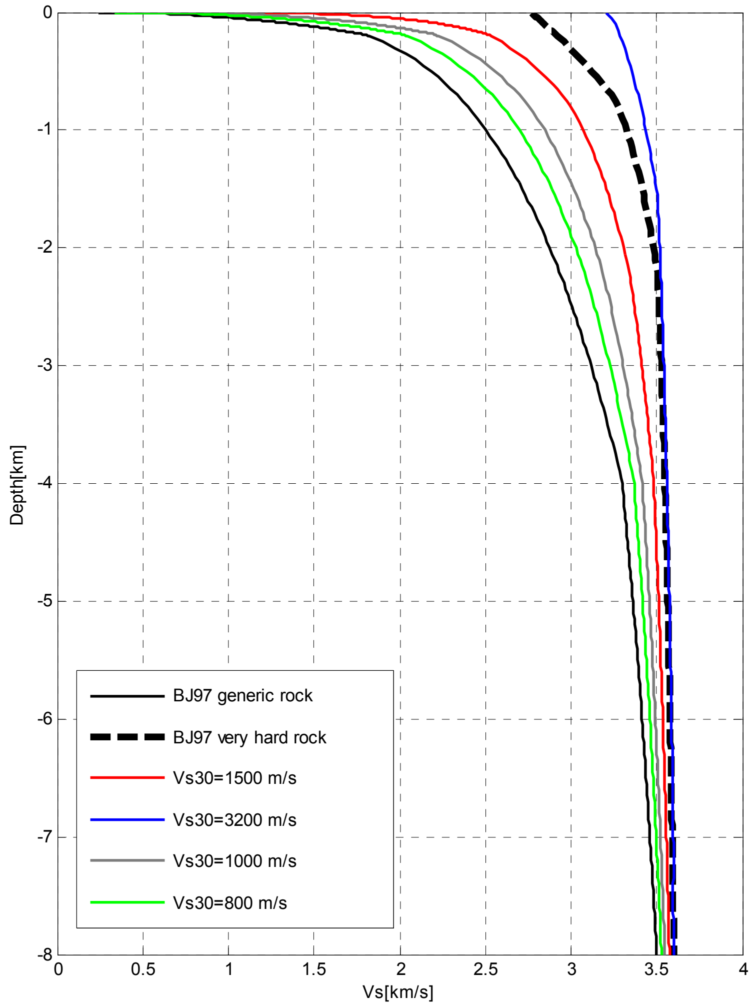

Figure 6 : Generic Vs profiles calculated for different values of Vs30 based on interpolation of rock and very-hard rock profiles of Boore and Joyner (1997), BJ97. Note that the two target profiles (Vs30=1500 m/s and Vs30=3200 m/s) represent profiles for depths below the baserock horizons, which is different for the two target sites (see also Figure 2)

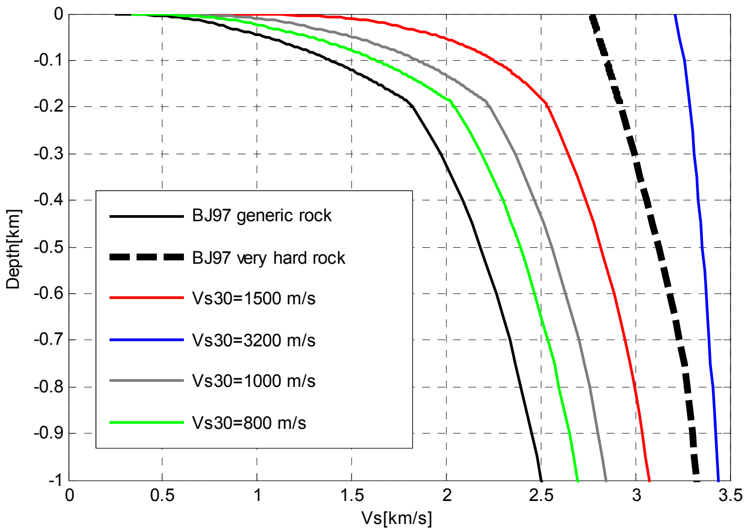

Figure 7 : Same as previous figure but zooming on depths smaller than 1 km.

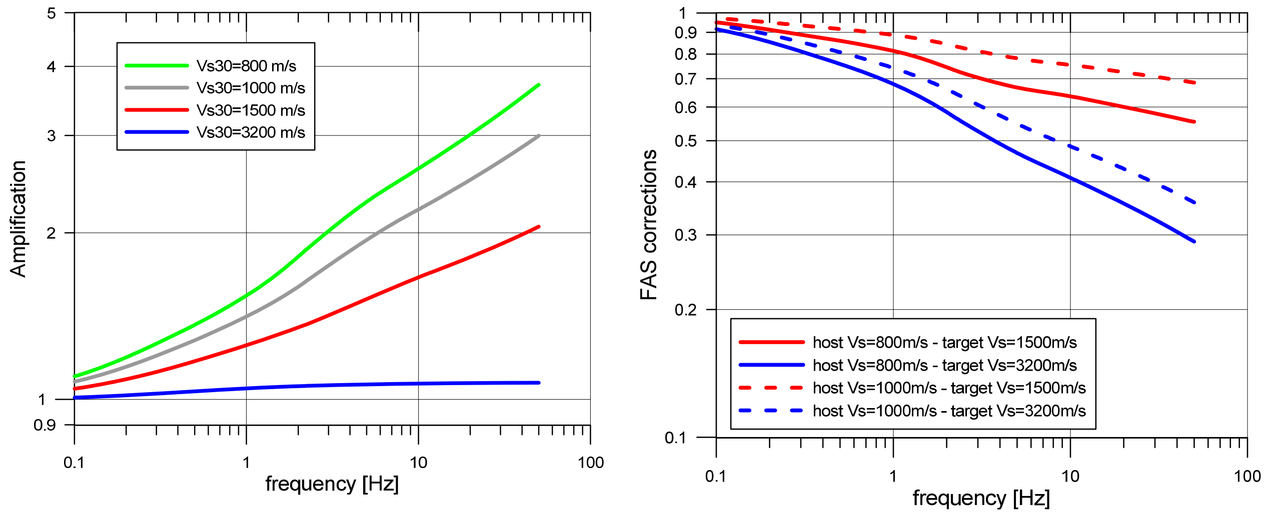

Figure 8 : Left: quarter-wavelength amplifications for the 4 considered generic rock Vs profiles. Right: host-to-target Vs corrections, in the Fourier domain, based on generic profiles.

4.2.1 Vs adjustment factors

The Vs host-to-target adjustment factors derived in the Fourier domain are applied to the Fourier spectrum of the GMPEs derived by application of the IRVT (method 2). As already mentioned, the same approach is applied in method 1 the only difference being that the Fourier spectrum of the Bora (2014) GMPE is empirically derived.

The Vs host-to-target adjustment factors for the two target sites are presented in Figure 9 for Vs30 host=800 m/s and Vs30 host=1000 m/s.

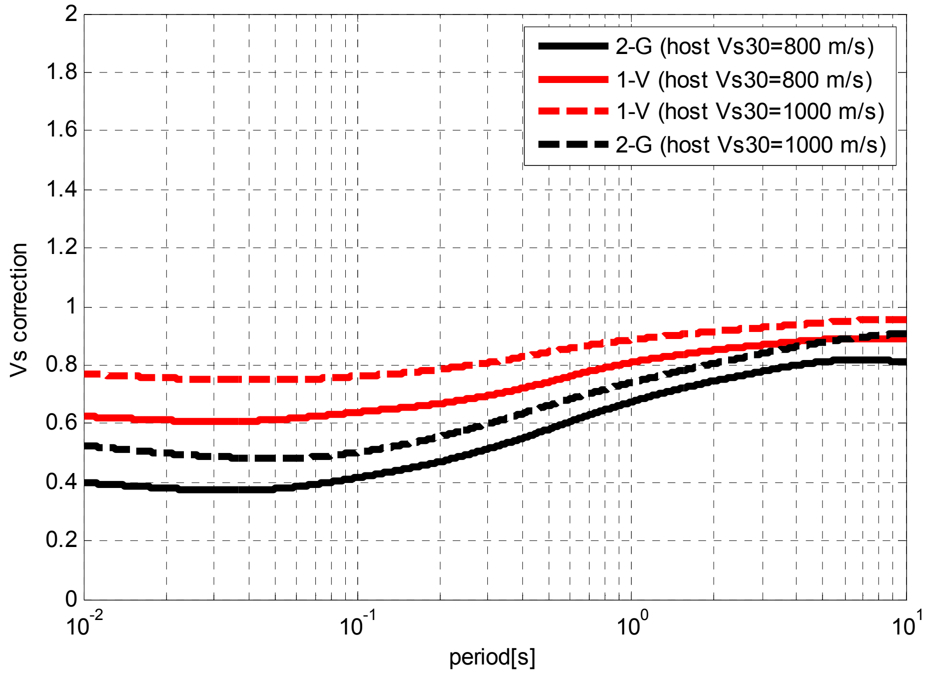

Figure 9 : Host-to-target Vs adjustment factors, in terms of response spectra, for Vs30 host =800 m/s (continuous curves) and s30 host =1000 m/s (dashed curves) and Vs30 target =1500 m/s (red curves) and 3200 m/s (black curves).

4.3 VS-KAPPA ADJUSTMENT

The Vs adjustment factors detailed in the previous section are combined with the kappa adjustment factors derived according to method 2, as described in section 4.1.

The derivation of host kappa values for the Boore et al. (2014), Cauzzi et al (2014) and Ameri (2014) models and the consequent Vs-kappa scaling factors for the two considered sites are detailed in the following sections. In order to estimate the host kappa values, we calculate IRVT-derived FAS for several scenarios using the three GMPE. The considered scenarios are Mw= 5.0; 5.5; 6.0; 6.5 at distances of 5, 10 and 20 km. The selected magnitudes cover the range of interest for the seismic hazard at the selected sites for 10'000 years return period. The use of short distances scenarios is necessary to avoid as much as possible contamination by anelastic attenuation (Q) in the estimated kappa values. Moreover such distances mostly contribute to the hazard at the sites. Then, for each scenario, the kappa function, A*exp(-πfκ), is fitted to the high-frequency part of the FAS in order to estimate κ.

4.3.1 Adjustment of the Boore et al. (2014) GMPE

4.3.1.1 Estimation of host kappa

Figure 10 shows the estimated kappa host for two scenarios of the Boore et al. (2014) GMPE. The exponential kappa function is fitted to the high frequency part of the FAS between two frequencies f1 and f2. The selection of these two frequencies is a source of uncertainties and the resulting kappa scaling value may be affected by the selected range (see section 8 for more discussion on this). The frequency f1 should be larger than the frequency corresponding to the maximum amplitude of the FAS and f2 should be selected such as the FAS decay is linear (in a lin-log plot) between f1 and f2. We performed several tests and the final selected frequency bands are reported in Table 3 with the relative kappa values for the considered scenarios. We note that two groups of kappa host values are obtained: values of about 0.03s for Mw=5 and 5.5 scenarios and values around 0.04s for larger magnitude.

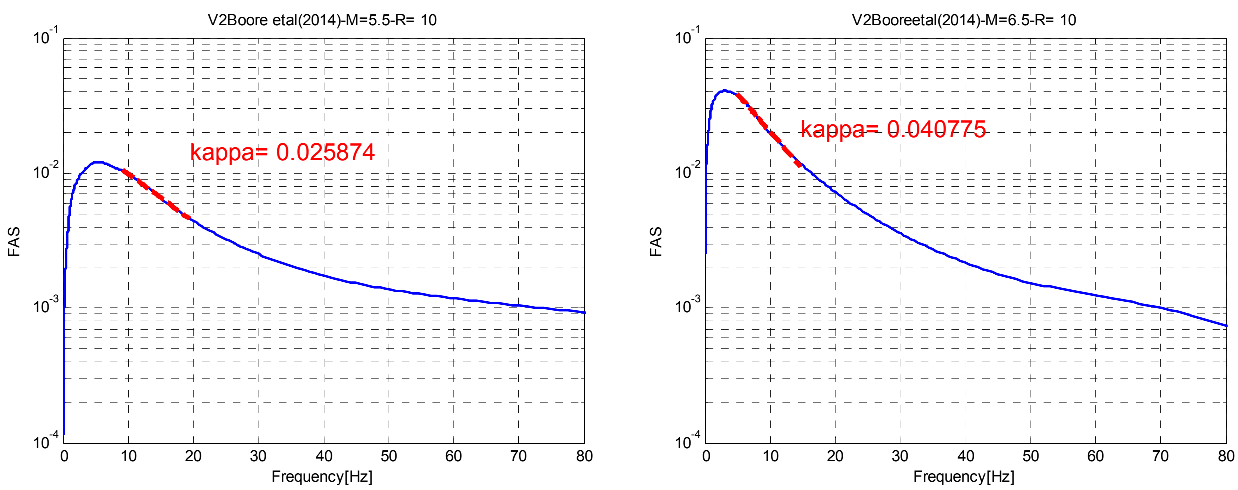

Figure 10 : Example of kappa-host estimation by fitting the high-frequency part of the IRVT-derived FAS for the Boore et al. (2014) GMPE. Left: Mw=5.5 and Rjb=10 km scenario. Right: Mw=6.5 and Rjb=10 km scenario. The ground motion predictions are performed for a Vs30=800 m/s and a strike-slip mechanism.

Mw	R [km]	kappa host[s]	f1[Hz]	f2[Hz]
5	5	0.029	7.7	19.2
5	10	0.030	7.6	18.5
5	20	0.030	7.0	19.0
5.5	5	0.029	8.5	19.2
5.5	10	0.030	8.8	19.1
5.5	20	0.031	8.8	18.4
6	5	0.041	5.2	16.3
6	10	0.042	5.4	15.2
6	20	0.043	5.4	15.2
6.5	5	0.040	4.9	16.5
6.5	10	0.041	4.9	14.8
6.5	20	0.041	5.0	15.3
	mean=	0.035		
	std=	0.0061		

Table 3 : Estimated kappa host values for the Boore et al. (2014) as a function of the M-R scenario. The frequency band for the kappa estimation is also reported (f1 - f2).

4.3.1.2 Vs-kappa adjustment for Site 2-G (Vs=3200 m/s, kappa=0.01s)

Based on the derived host Vs profile and kappa, the Boore et al. (2014) GMPE is adjusted for the target rock conditions of site 2-G: Vs=3200 m/s and kappa = 0.01s. The adjustment is performed for all considered M-R scenarios. The adjusted acceleration response spectra for two M-R scenarios are presented in Figure 11 and compared with the original spectra.

Figure 12 shows the Vs-kappa adjustment factors for site 2-G for all the considered M-R scenarios calculated as the ratio between the adjusted spectra and the original ones. Note the two distinct sets of correction factors related to the different kappa host values for moderate and large magnitude scenarios. The correction factors for PGA (assumed here equal to T=0.01s) range from 0.8 for the moderate magnitudes to 1.2 for the largest magnitudes. At T=0.03s the correction factors range from 1.2 to 1.8 for moderate and large magnitudes respectively. Finally, at T=1s the correction factors are about 0.7 for all scenarios. Indeed at these spectral periods, the effect of kappa adjustment is almost negligible and the Vs adjustment is dominant.

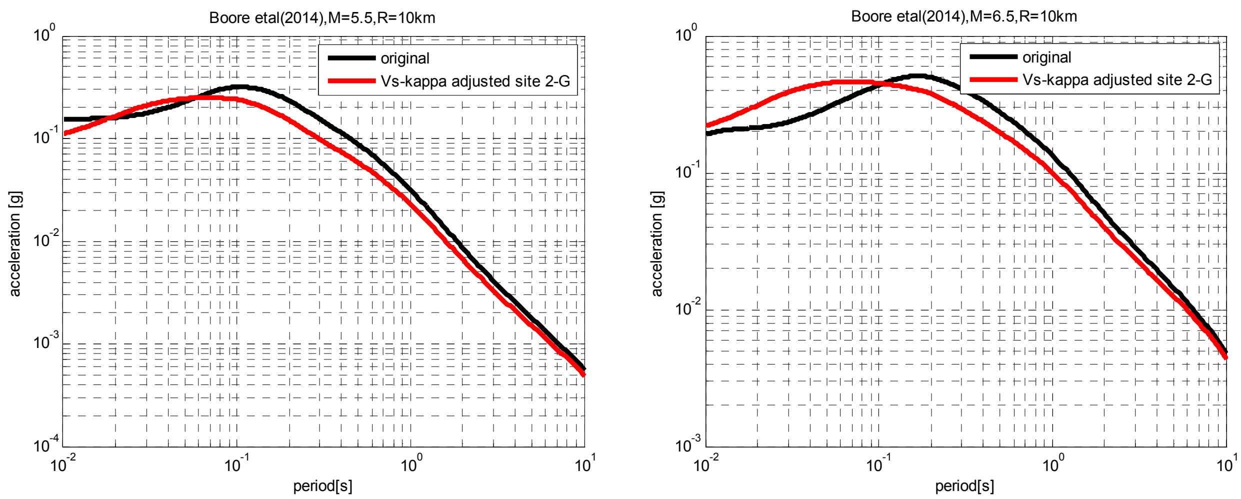

Figure 11 : Boore et al. (2014) GMPE, example of Vs-kappa adjusted acceleration response spectra for two scenarios at site 2-G: Mw=5.5 and R=10km (left) and Mw=6.5 and R=10 km (right).

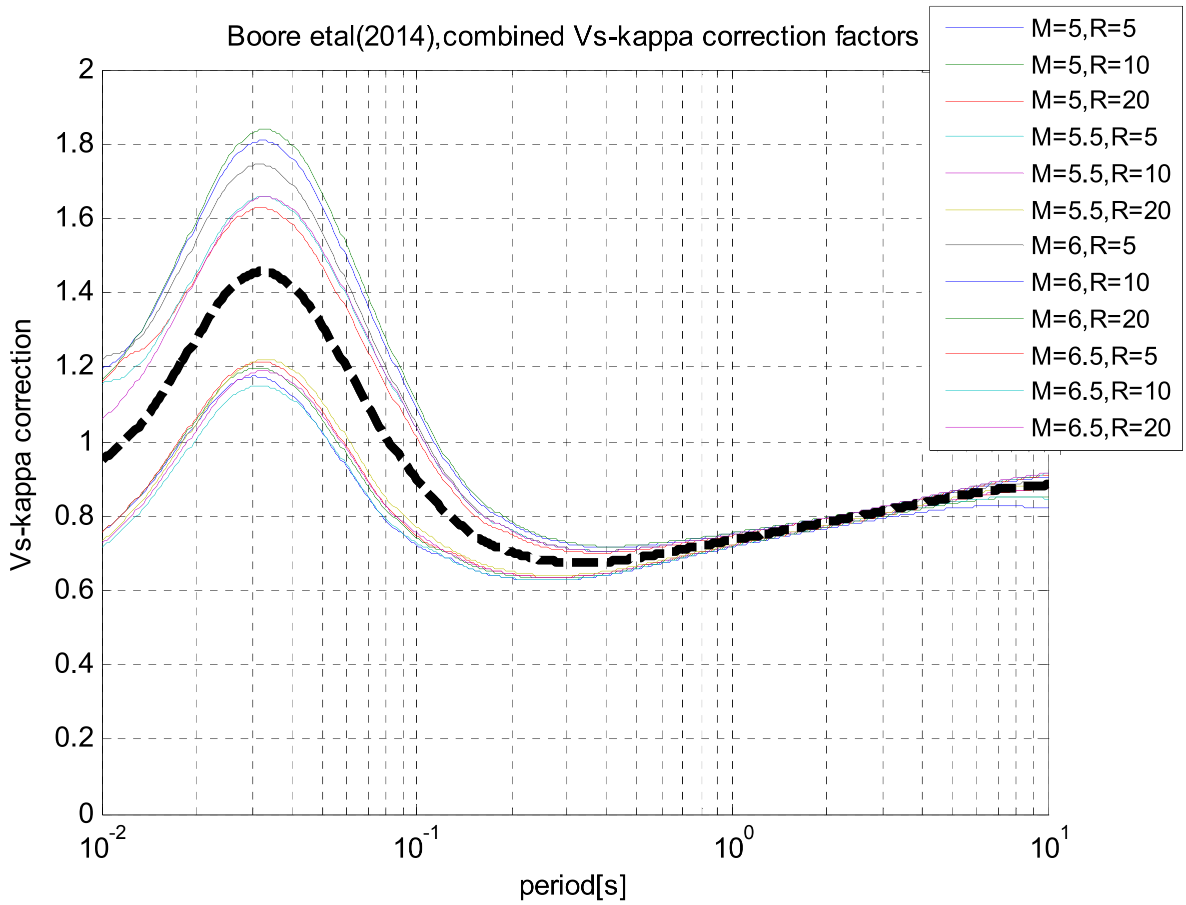

Figure 12 : Vs-kappa host-to-target correction factors for site 2-G and the Boore et al. (2014) GMPE. The mean correction factor is shown by the black dashed line.

4.3.1.3 Vs-kappa adjustment for Site 1-V (Vs=1500 m/s, kappa=0.03s)

The target rock conditions of site 1-V are Vs=1500 m/s and kappa = 0.03s. The adjustment is performed for all considered M-R scenarios. The adjusted acceleration response spectra for two M-R scenarios are presented in Figure 13 and compared with the original spectra.

Figure 14 shows the Vs-kappa adjustment factors for site 1-V for all considered M-R scenarios. The correction factors for PGA (T=0.01s) range from 0.5 for the moderate magnitudes to 0.8 for the largest magnitudes. At T=0.03s the correction factors range from 0.6 to 1.0 for moderate and large magnitudes respectively. Finally, at T=1s the correction factors are about 0.8 for all scenarios. Again, at these spectral periods, the effect of kappa adjustment is almost negligible and the Vs adjustment is dominant.

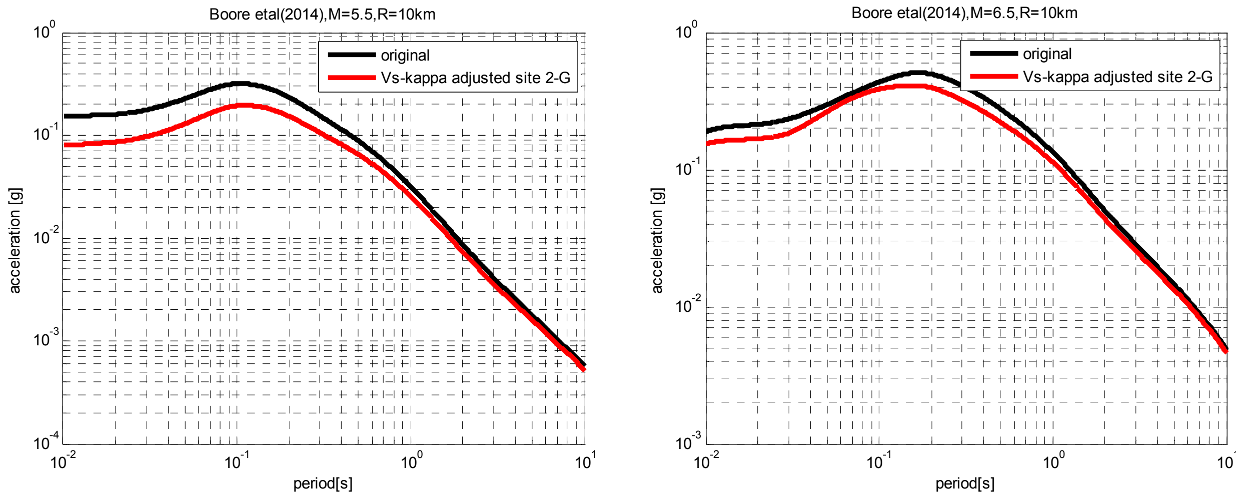

Figure 13 : Boore et al. (2014) GMPE, example of Vs-kappa adjusted acceleration response spectra for two scenarios at site 1-V: Mw=5.5 and R=10km (left) and Mw=6.5 and R=10 km (right).

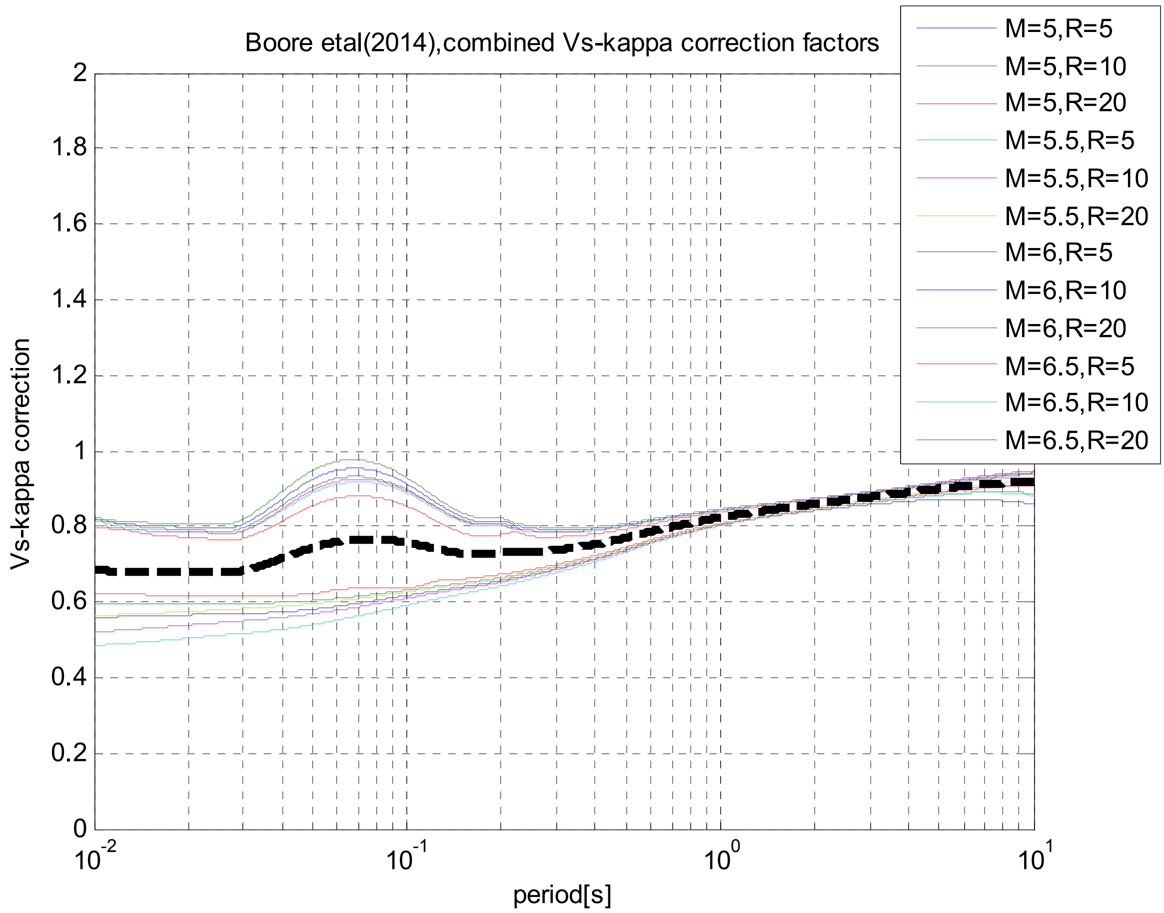

Figure 14 : Combined (Vs-kappa) host to target correction factor for site 2-G and the Boore et al. (2014) GMPE. The mean correction factor is shown by the black dashed line.

4.3.2 Adjustment of the Cauzzi et al. (2014) GMPE

4.3.2.1 Estimation of host kappa

For the estimation of the host kappa of the Cauzzi et al (2014) GMPE, we selected a host Vs30=800 m/s and strike-slip mechanism.

The same procedure employed for the Boore et al. (2014) GMPE is used and the same magnitude-distance scenarios are considered for kappa host estimation.

Figure 15 shows the estimated kappa host for two scenarios of the Cauzzi et al. (2014) GMPE. The kappa host values for the other considered scenarios are reported in Table 4. We note that the kappa host estimated for the Cauzzi et al. (2014) model do not vary significantly with respect to the magnitude and distance compared to what was observed for the Boore et al. (2014) GMPE. Moreover almost the same frequency band can be used to fit the kappa function for all the considered magnitudes providing a reasonable fit with the FAS. The mean kappa host is 0.025s. The small variability of the derived kappa-host values for the Cauzzi et al. (2014) model with respect to the other two GMPEs may have several explanations. On the one hand, it may reflect a higher quality of the strong motion dataset used in the Cauzzi et al. (2014) model. This would reflect in less high-frequency noise in the IRVT-derived FAS and in more stable kappa values. On the other hand, it may be due to the dominance of data from one single region (i.e. Japan) in the Cauzzi et al. (2014) dataset. In other words, we may hypothesize that rock sites in Japan are characterized by, on average, smaller kappa values than rock sites elsewhere. These explanations need to be further investigated in order to provide insights on the causes of the observed variations in kappa-host values.

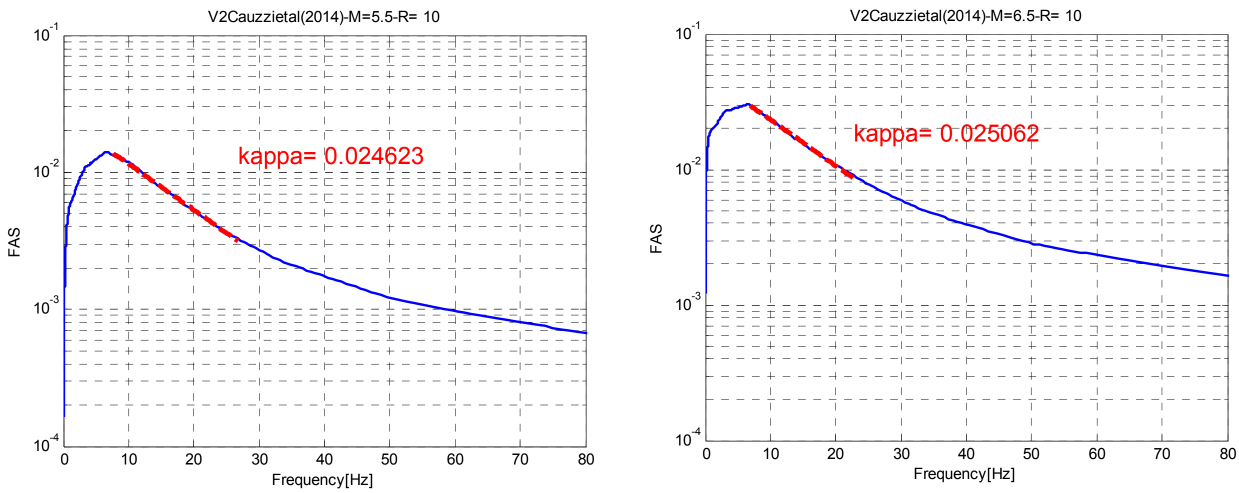

Figure 15 : Example of kappa-host estimation by fitting the high-frequency part of the IRVT-derived FAS for the Cauzzi et al. (2014) GMPE.

Mw	R [km]	kappa host[s]	f1[Hz]	f2[Hz]
5	5	0.025	7.6	23.9
5	10	0.025	7.2	25.4
5	20	0.026	7.9	27.0
5.5	5	0.024	7.2	26.9
5.5	10	0.025	7.6	26.9
5.5	20	0.025	7.7	26.0
6	5	0.024	7.0	26.2
6	10	0.024	7.4	26.9
6	20	0.025	7.6	25.6
6.5	5	0.026	6.9	20.2
6.5	10	0.025	6.7	22.7
6.5	20	0.025	6.7	22.7
	mean=	0.025		
	std=	0.0006		

Table 4 : Estimated kappa host values for the Cauzzi et al. (2014) as a function of the M-R scenario. The frequency band for the kappa estimation is also reported (f1 - f2).

4.3.2.2 Vs-kappa adjustment for Site 2-G (Vs=3200 m/s, kappa=0.01s)

The adjusted acceleration response spectra for site 2-G for two M-R scenarios are presented in Figure 16 and compared with the original spectra.

Figure 17 shows the Vs-kappa adjustment factors for site 2-G for all considered M-R scenarios calculated as the ratio between the adjusted spectra and the original ones. The adjustment factors are practically independent from magnitude and distance. The correction factors for PGA (T=0.01s) are about 0.7 and about 1 at T=0.03s. The correction factors at longer periods (T>1s) are the same as already observed for the Boore et al. (2014) model because the Vs adjustment is the same for all GMPEs.

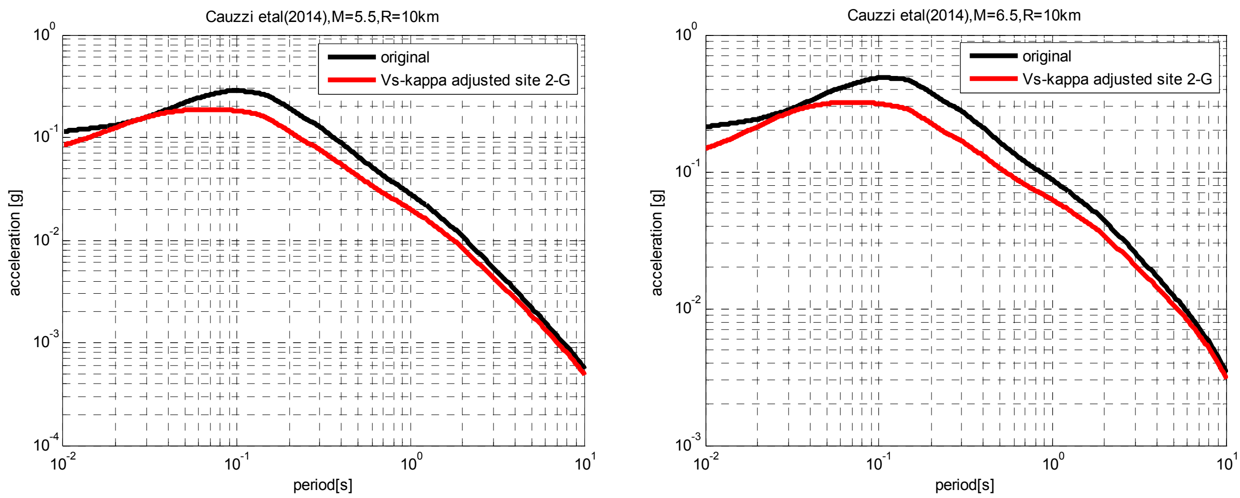

Figure 16 : Cauzzi et al. (2014) GMPE, example of Vs-kappa adjusted response spectra for two scenarios at site 2-G: Mw=5.5 and R=10 km (left) and Mw=6.5 and R=10 km (right).

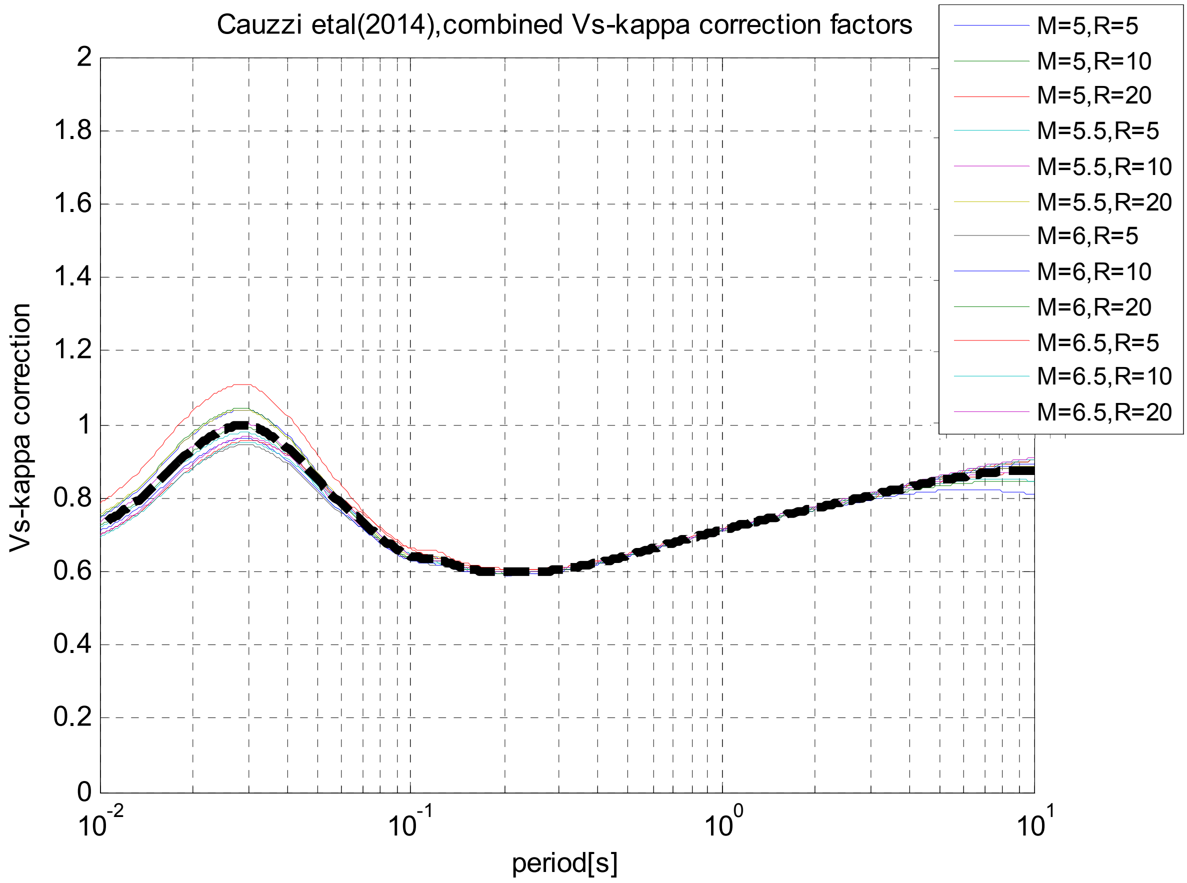

Figure 17 : Site 2-G. Vs-kappa adjustment factors for the Cauzzi et al. (2014) GMPE. The mean correction factor is shown by the black dashed line.

4.3.2.3 Vs-kappa adjustment for Site 1-V (Vs=1500 m/s, kappa=0.03s)

The adjusted acceleration response spectra for site 1-V for two M-R scenarios are presented in Figure 18 and compared with the original spectra.

Figure 18 shows the Vs-kappa adjustment factors for site 1-V for all considered M-R scenarios calculated as the ratio between the adjusted spectra and the original ones. As for the other site, the adjustment factors are practically independent from magnitude and distance. The correction factors for PGA (T=0.01s) and T=0.03s are about 0.5. The correction factors at longer periods (T>1s) are the same as already observed for the Boore et al. (2014) model because the Vs adjustment is the same for all GMPEs. At this site, because of the estimated kappa host for the Cauzzi et al. (2014) GMPE, the effect of both Vs and kappa adjustment is to reduce the acceleration amplitudes at shorter periods.

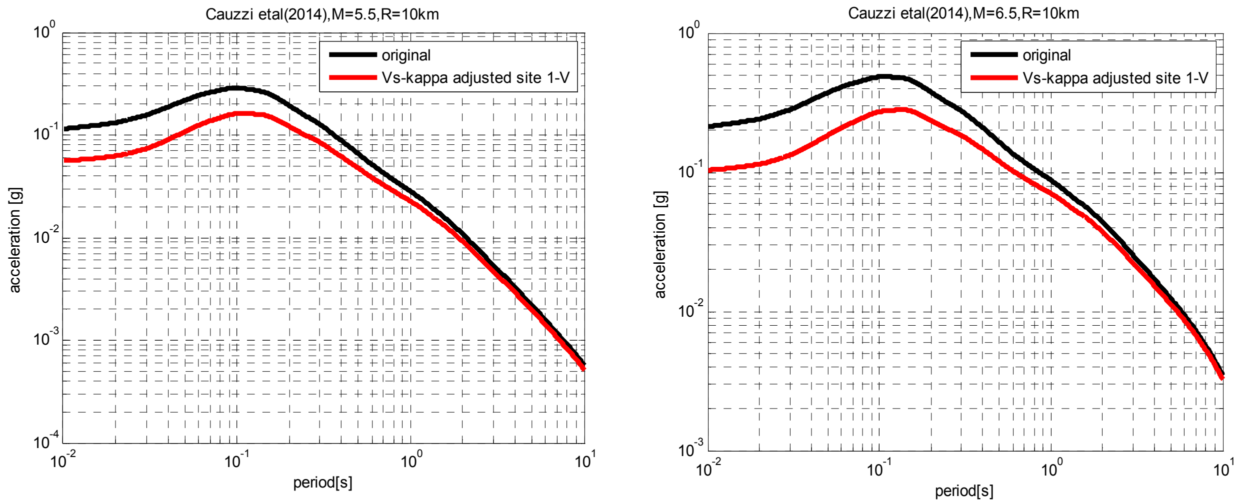

Figure 18 : Cauzzi et al. (2014) GMPE, example of Vs-kappa adjusted response spectra for two scenarios at site 1-V: Mw=5.5 and R=10 km (left) and Mw=6.5 and R=10 km (right).

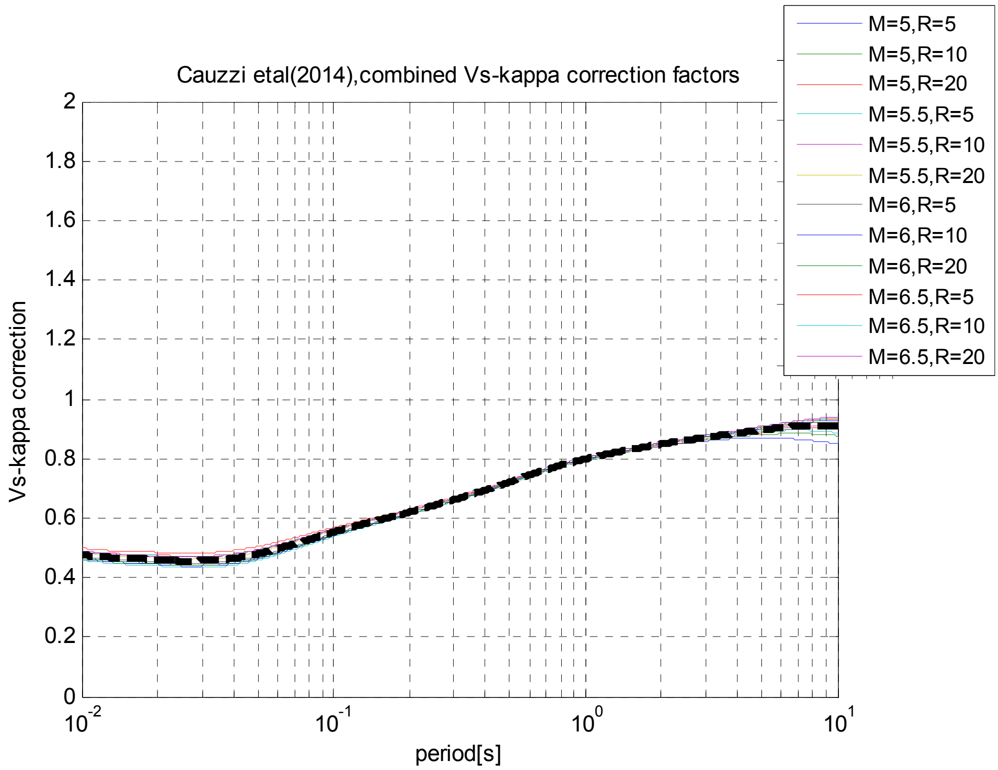

Figure 19 : Site 1-V. Vs-kappa adjustment factors for the Cauzzi et al. (2014) GMPE. The mean correction factor is shown by the black dashed line.

4.3.3 Adjustment of the Ameri (2014) GMPE

4.3.3.1 Estimation of host kappa

The estimation of the host kappa for the Ameri (2014) GMPE is done on the model for EC8 class A site and strike-slip mechanism. No value of stress parameter was specified and so the generic model proposed by Ameri (2014) was used.

The same procedure employed for the other GMPEs is used and the same magnitude-distance scenarios are considered for kappa host estimation.

Figure 20 shows the estimated kappa host for two scenarios. The kappa host values for the other considered scenarios are reported in Table 5. The kappa host estimated for the Ameri (2014) shows weak variations with respect to magnitude and distance with lower kappa estimated for smaller magnitudes. The considered frequency band is also variable with f1 around 5 Hz and f2 around 17 Hz. The mean kappa host is 0.033s.

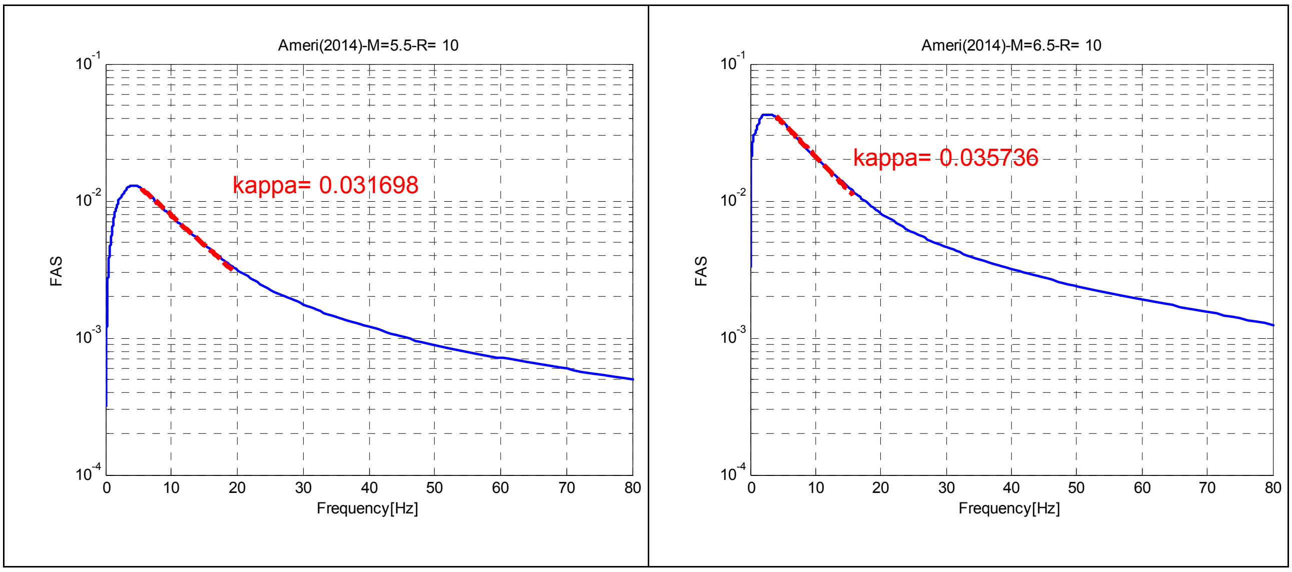

Figure 20 : Example of kappa-host estimation by fitting the high-frequency part of the IRVT-derived FAS for the Ameri (2014) GMPE. The fit is performed between 8Hz and 20 Hz for two M-R scenarios.

Mw	R[km]	kappa host[s]	f1[Hz]	f2[Hz]
5	5	0.025	5.6	20.0
5	10	0.028	7.0	18.9
5	20	0.030	6.6	18.5
5.5	5	0.030	5.2	19.9
5.5	10	0.032	5.3	19.3
5.5	20	0.035	5.2	16.4
6	5	0.034	4.9	19.3
6	10	0.035	5.1	18.6
6	20	0.037	4.9	17.5
6.5	5	0.036	3.4	15.4
6.5	10	0.036	3.8	15.7
6.5	20	0.039	3.7	12.4
	mean=	**0.033**		
	std=	**0.0041**		

Table 5 : Estimated kappa host values for the Ameri (2014) as a function of the M-R scenario. The frequency band for the kappa estimation is also reported (f1 - f2).

4.3.3.2 Vs-kappa adjustment for Site 2-G (Vs=3200 m/s, kappa=0.01s)

The adjusted acceleration response spectra for site 2-G for two M-R scenarios are presented in Figure 21 and compared with the original spectra.

Figure 22 shows the Vs-kappa adjustment factors for site 2-G for all considered M-R scenarios calculated as the ratio between the adjusted spectra and the original ones. The correction factors for PGA (T=0.01s) range from 0.8 for the moderate magnitudes to 1.2 for the largest magnitudes. At T=0.03s the correction factors range from 1.1 to 1.7 for moderate and large magnitudes respectively. Finally, at T=1s the correction factors are about 0.8 for all scenarios. We remind that the Vs host profile for this GMPE has a Vs30=1000 m/s and thus, the Vs adjustment factors are different with respect to what used for the other GMPEs.

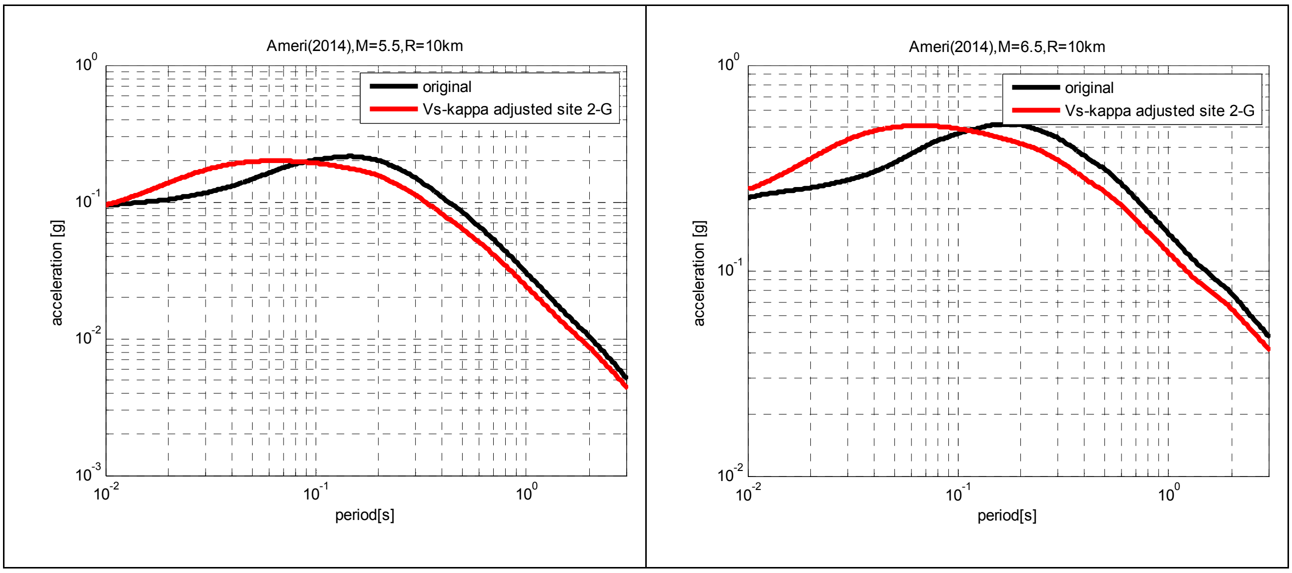

Figure 21 : Ameri (2014) GMPE, example of Vs-kappa adjusted response spectra for two scenarios at site 2-G: Mw=5.5 and R=10 km (left) and Mw=6.5 and R=10 km (right).

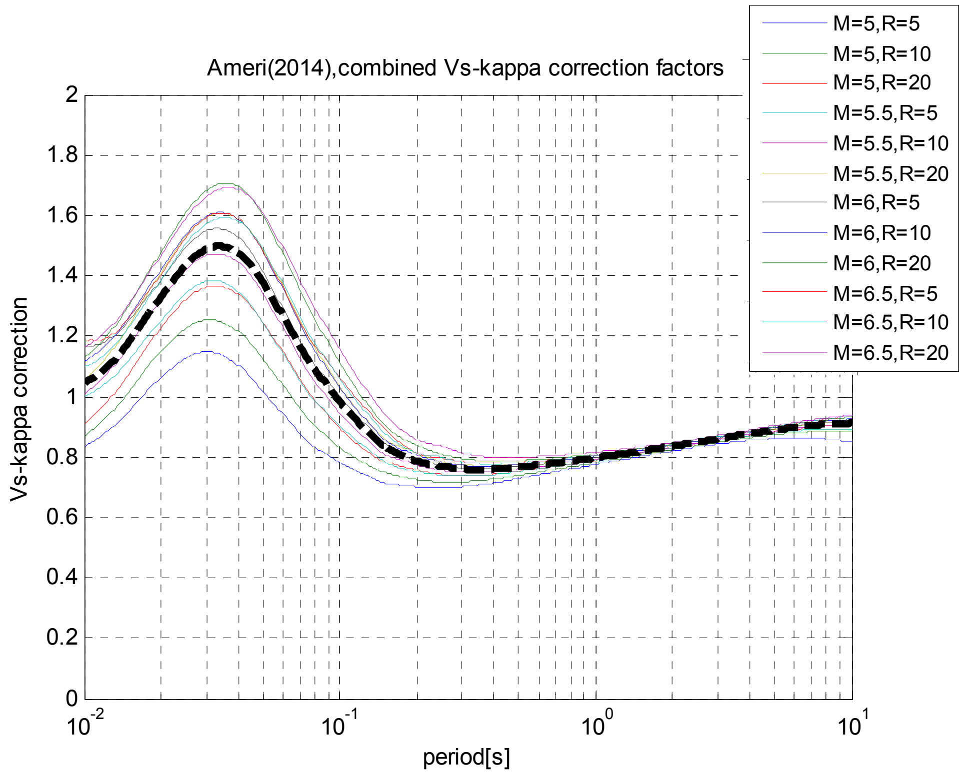

Figure 22 : Site 2-G. Vs-kappa adjustment factors for the Ameri (2014) GMPE. The mean correction factor is shown by the black dashed line.

4.3.3.3 Vs-kappa adjustment for Site 1-V (Vs=1500 m/s, kappa=0.03s)

The adjusted acceleration response spectra for site 1-V for two M-R scenarios are presented in Figure 23 and compared with the original spectra.

Figure 24 shows the Vs-kappa adjustment factors for site 1-V for all considered M-R scenarios. The correction factors for PGA (T=0.01s) range from 0.6 for the moderate magnitudes to 0.9 for the largest magnitudes. At T=0.03s the correction factors range from 0.7 to 1.0 for moderate and large magnitudes respectively. Finally, at T=1s the correction factors are about 0.9 for all scenarios. Again, at these spectral periods, the effect of kappa adjustment is almost negligible and the Vs adjustment is dominant.

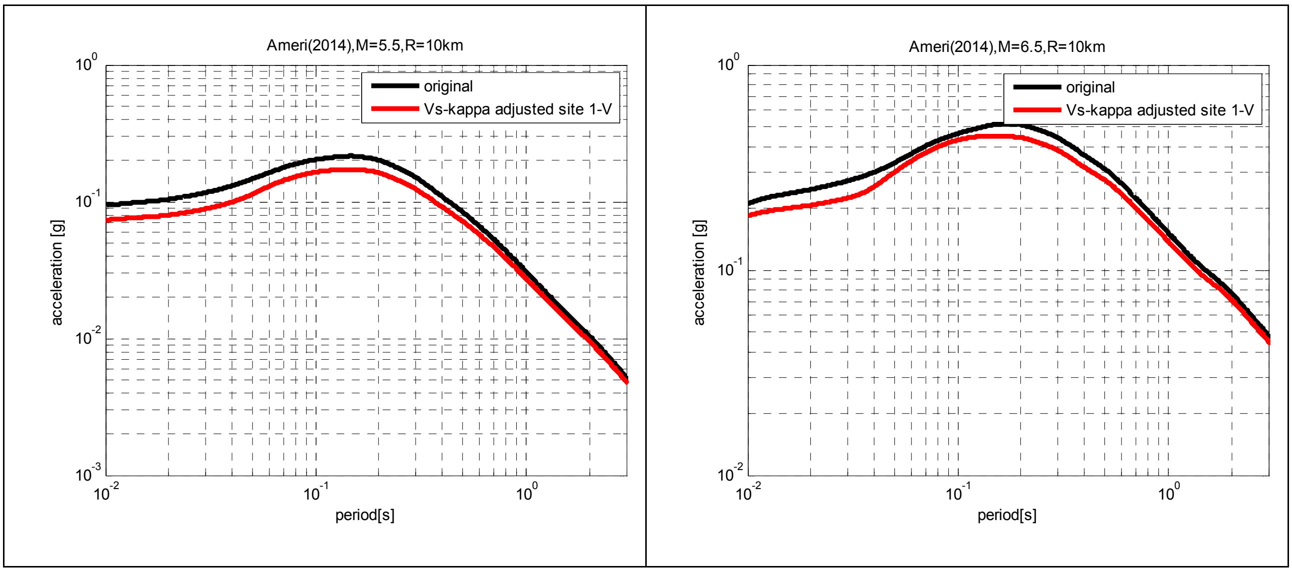

Figure 23 : Ameri (2014) GMPE, example of Vs-kappa adjusted response spectra for two scenarios at site 1-V: Mw=5.5 and R=10 km (left) and Mw=6.5 and R=10 km (right).

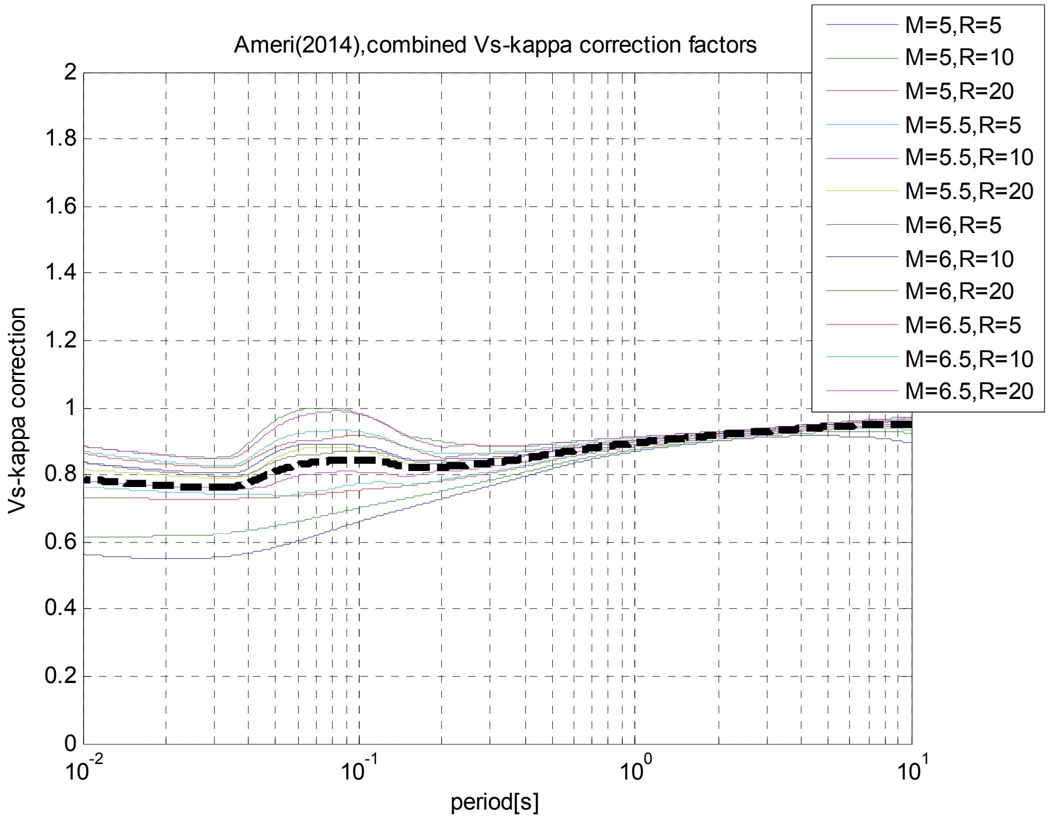

Figure 24 : Site 1-V. Vs-kappa adjustment factors for the Ameri (2014) GMPE. The mean correction factor is shown by the black dashed line.

4.4 COMPARISON OF VS-KAPPA ADJUSTMENT FACTORS FOR THE SELECTED GMPES

The Vs-kappa adjustment factors derived for the two sites for each GMPE are compared in Figure 25. The adjustment factors derived by Bora (2014) are illustrated for Mw=5.5 and Rjb=20 km. The factors derived by the Al Atik et al. (2014) IRVT approach (method 2) are reported for a Mw=5.5.

Considering site 1-V, the Cauzzi et al. (2014) provide the smallest adjustment factors at short periods, due to the relatively small kappa-host values estimated for this GMPE. The other three GMPEs provide larger factors relatively similar each other (around 0.8). At longer periods (e.g., T=1 s), the effect of the kappa adjustment become negligible and the adjustment factors are more similar for the four GMPEs. Overall, the adjustment factors range from 0.5 to 0.85 at T=0.01s and from 0.8 to 1 at T=1s. In other words, for all GMPEs, the Vs-kappa adjustment for site 1-V reduce the median ground motion estimates with respect to generic conditions at Vs30=800 m/s.

Considering site 2-G, we observe larger adjustment factors at short periods compared to site 1-V due to the lower target kappa for site 2-G. The Cauzzi et al.(2014) and Boore et al. (2014) GMPEs provide adjustment factors that are on average smaller than 1, whereas Ameri (2014) and Bora (2014) provide factors larger than 1 for periods smaller than 0.1s. The Bora (2014) model provides the largest factors. Overall, the adjustment factors range from 0.7 to 1.1 at T=0.01s, from 1 to 1.6 at T=0.03s and from 0.7 to 0.9 at T=1s.

The results of Figure 25 shows that the adjustment factors derived by the Bora (2014) are quite different from those derived for the other GMPEs, especially for site 2-G. In interpreting these results we have to keep in mind that the kappa host estimated by Bora (2014) for his model is κ=0.042 s, thus generally larger than the kappa host we estimated for the other GMPEs. Moreover the strong-motion datasets used for the development of the four GMPEs are different, although both Bora (2014) and Ameri (2014) used similar subsets of the RESORCE database. Indeed, the Bora (2014) factors are somehow closer to the Ameri (2014) ones but it is important to stress that the host Vs profile is different for this latter GMPE (Vs30 = 1000 m/s). The differences in the adjustment factors presented in Figure 25 are thus partially related to the different host characteristics of the datasets used in the selected GMPEs but also to the different methodologies to derive the adjustment factors.

Another issue that needs to be further investigated is why the Bora (2014) model provide adjustment factors at long periods that are larger than the other GMPEs (in particular values slightly larger than 1 for T>1s and site 1-V).

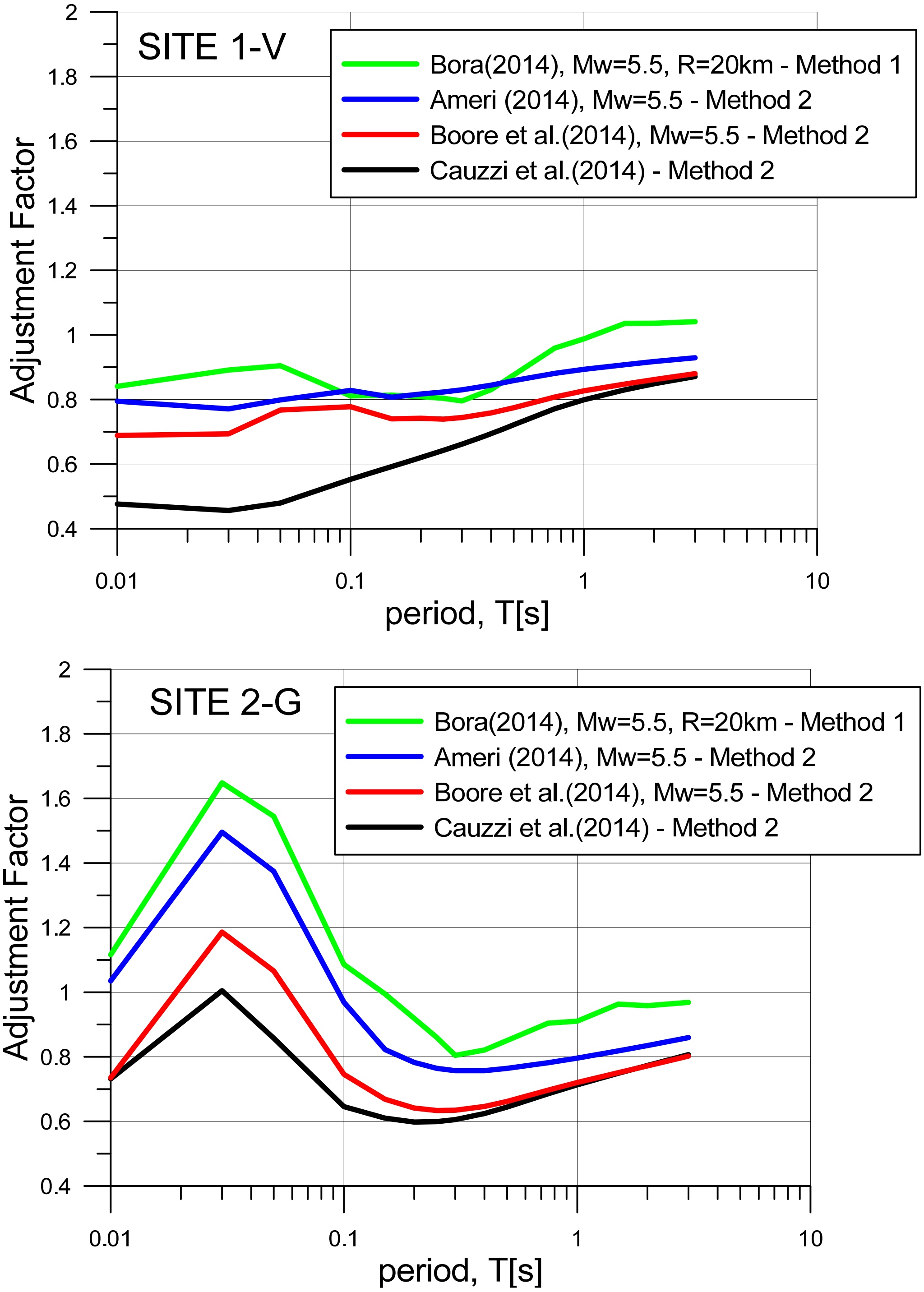

Figure 25 : Host-to-target Vs-kappa adjustment factors for the considered GMPEs.

5. PSHA RESULTS

The Vs-kappa adjustment factors presented in Section 4.4 are used to modify median values of the GMPEs in the PSHA logic tree described in Section 3 . As we have shown, the adjustment factors depend primarily on the spectral period, but for the Ameri (2014) and Boore et al (2014) models, the adjustment also depend on magnitude (due to the lower kappa host estimated for smaller magnitudes). We decided to keep this magnitude dependency of the adjustment factors so that the adjustment depends on magnitude and spectral period for the Ameri (2014) and the Boore et al. (2014) models and is period-dependent only for Cauzzi et al. (2014). For the Bora (2014) model, the adjustment factors depend on magnitude, distance and spectral period, as derived by the authors.

The UHS calculated for the specific bedrock conditions of the two sites are presented in this section for 10’000 years return period. In order to show the impact of the Vs-kappa adjustment, the UHS are also presented for each GMPE considering the two adjustment methods.

We recall that the site-specific PSHA is performed by adjusting the GMPEs median estimates with two approaches:

- “Method 1” consists in applying the adjustment factors by Bora (2014) to the other three GMPEs (Ameri 2014; Boore et al., 2014 and Cauzzi et al., 2014). As recognized by Bora (2014), the adjustment factors should not be applied to GMPEs based on different datasets because we do not know if the host characteristics are comparable. Despite this drawback, it is decided, in the context of the SIGMA IE, to pursue the calculations using this method in order to show the effect on the final results. Further analyses are needed to understand how to verify the applicability of the Bora (2014) adjustment factors to other GMPEs
- “Method 2” consists in using the Al Atik et al. (2014) approach to apply the Vs-kappa adjustment to the Ameri 2014, Boore et al., 2014 and Cauzzi et al., 2014 models. The Bora (2014) model is used as in method 1.

Figure 26 and Figure 27 show the UHS, for each GMPE, for the 1-V and 2-G site, respectively. For comparison, the UHS obtained without considering any adjustment of GMPEs (generic Vs30=800 m/s) and using the single-station sigma model (SSS) are also presented.

It is interesting to note that, for both sites, the UHS calculated using the adjustment method 1 show a larger variability with respect to what is obtained for method 2. This suggests, as already mentioned, that the application of method 1 to GMPEs based on a dataset different than that used in Bora (2014) needs to be further investigated.

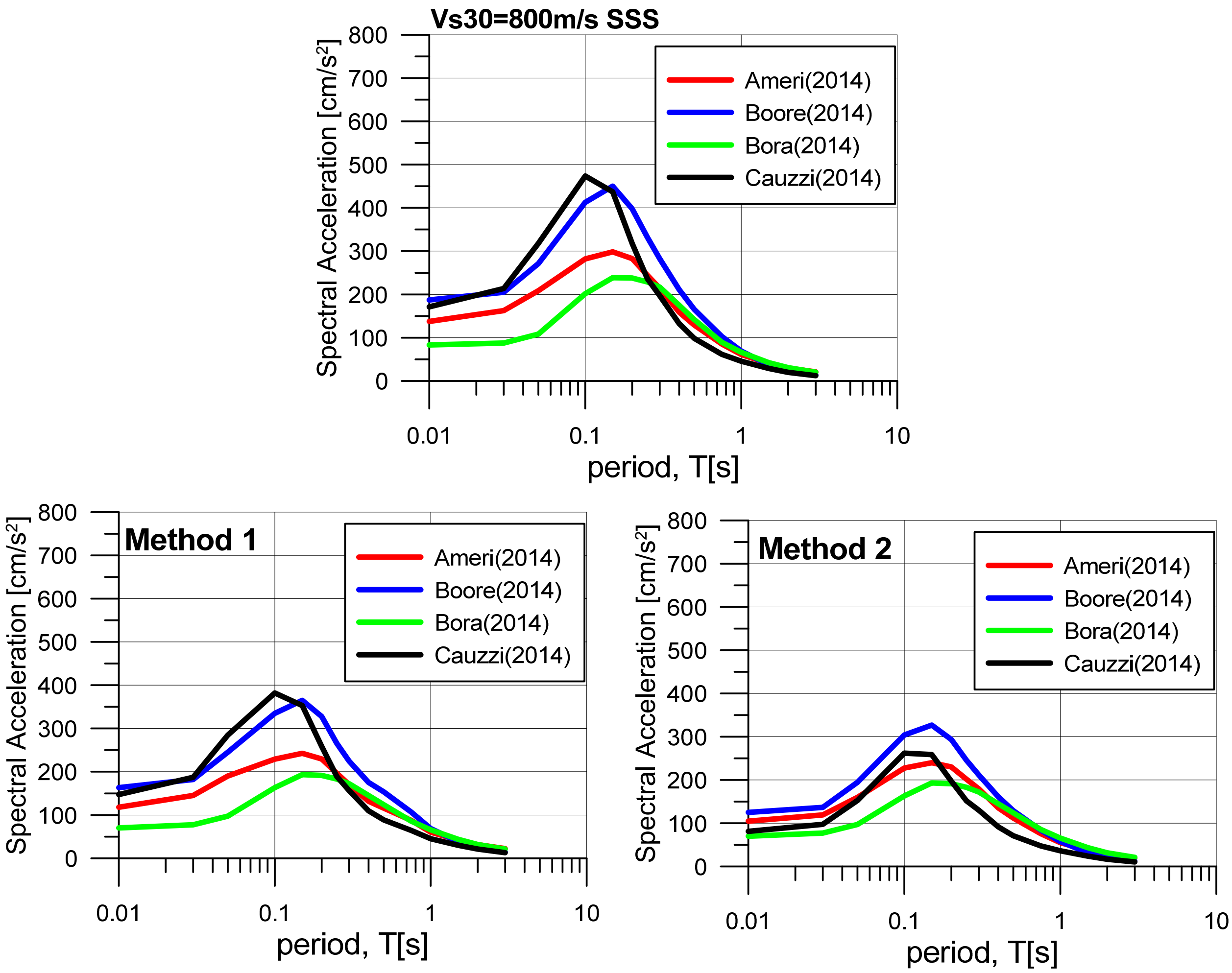

Figure 26 : Mean Uniform Hazard Spectra at 10'000 years return period for site 1-V obtained for each GMPE. Top panel: PSHA is performed without any GMPEVs-κ adjustment. The UHS are for Vs30=800 m/s and the single station sigma model is used. Bottom left panel: PSHA is performed adjusting the GMPEs using method 1. Bottom right panel: PSHA is performed adjusting the GMPEs using method 2.

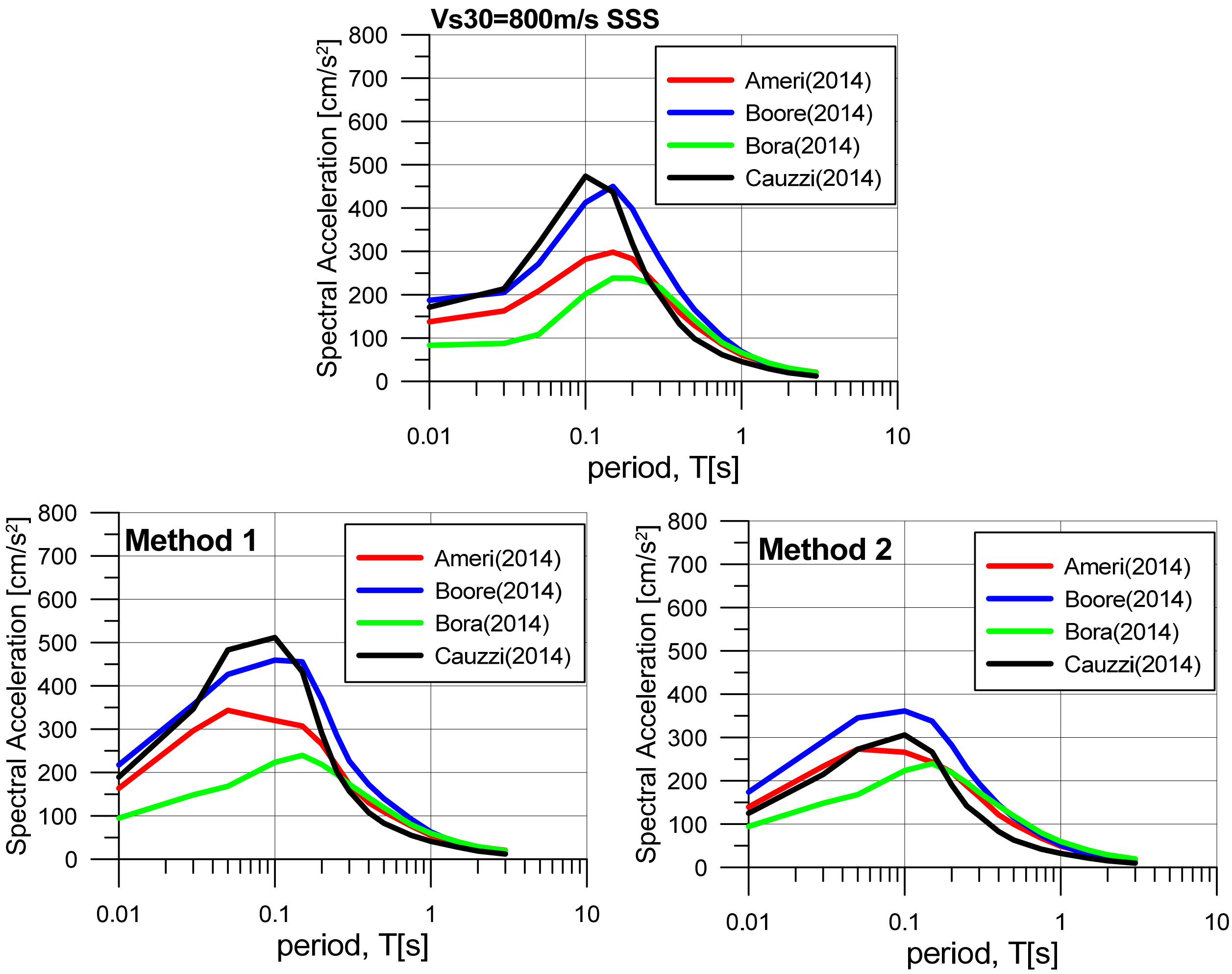

Figure 27 : Mean Uniform Hazard Spectra at 10'000 years return period for site 2-G obtained for each GMPE. Top panel: PSHA is performed without any GMPEVs-k adjustment. The UHS are for Vs30=800 m/s and the single station sigma model is used. Bottom left panel: PSHA is performed adjusting the GMPEs using method 1. Bottom right panel: PSHA is performed adjusting the GMPEs using method 2.

The mean UHS obtained for the two sites from the whole PSHA logic tree (i.e., considering the four GMPEs with weights as defined in section 3.1.1) are presented in Figure 28 and Figure 29. The site-specific UHS at bedrock are presented for the two considered adjustment methods and are compared with generic UHS obtained for different Vs30 values. In particular, for site 1-V the site-specific UHS are compared to UHS obtained without any GMPE adjustment and considering Vs30 =800 m/s, Vs30 =1500 m/s and Vs30 =185 m/s. This latter value represents the Vs30 of the soil profile defined for this site. The other two Vs30 values are for reference purposes. Considering site 2-G the site-specific UHS are compared to UHS obtained considering Vs30 =800 m/s and Vs30 =370 m/s, the latter being the Vs30 of the soil profile.

The UHS for adjustment method 1 provide higher accelerations at short periods (about T<0.3s) with respect to those for method 2. The difference is about 20% for site 1-V and 30 % for site 2-G. It is interesting to note that the spectral shape of the UHS for site 2-G is remarkably different between the generic rock conditions and the site-specific conditions. This is clearly the effect of the kappa adjustment which enhance the amplitudes for T<0.1s.

In the next section, we will present the results of the site response analyses and provide site-specific acceleration spectra at the surface to compare with UHS for the generic Vs30 site conditions.

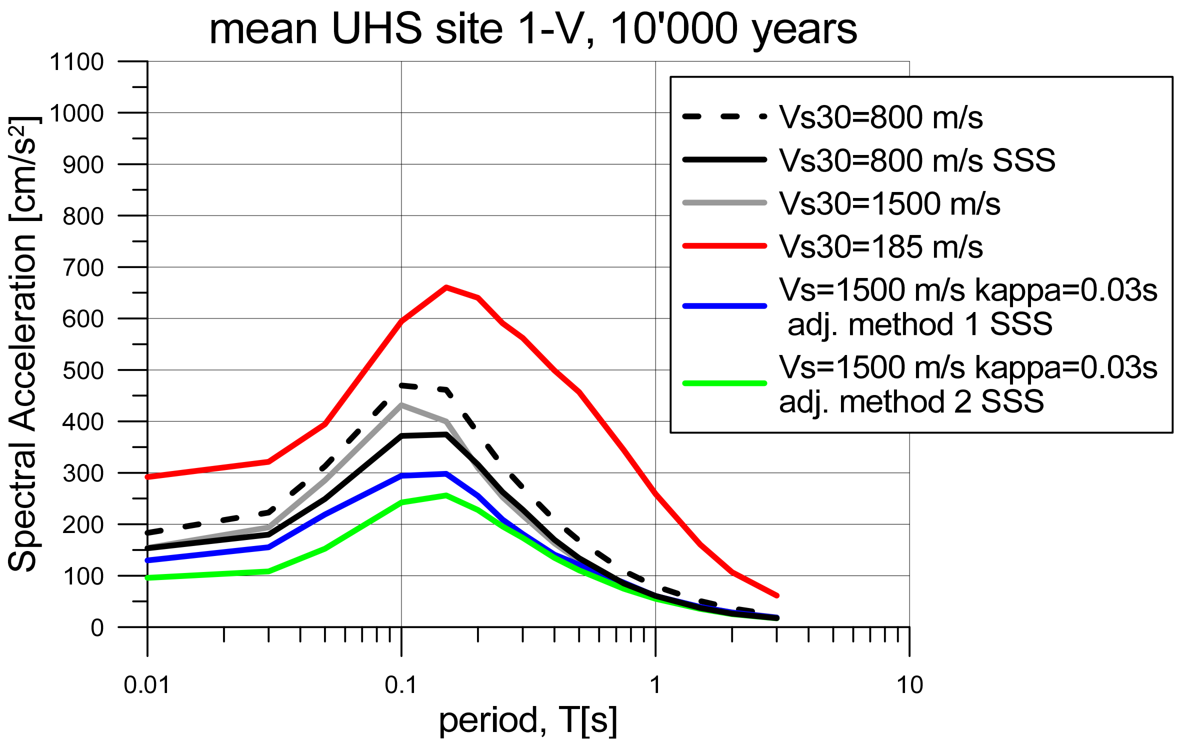

Figure 28 : Site 1-V, mean UHS for 10'000 years return periods obtained from generic and site-specific PSHA calculations.

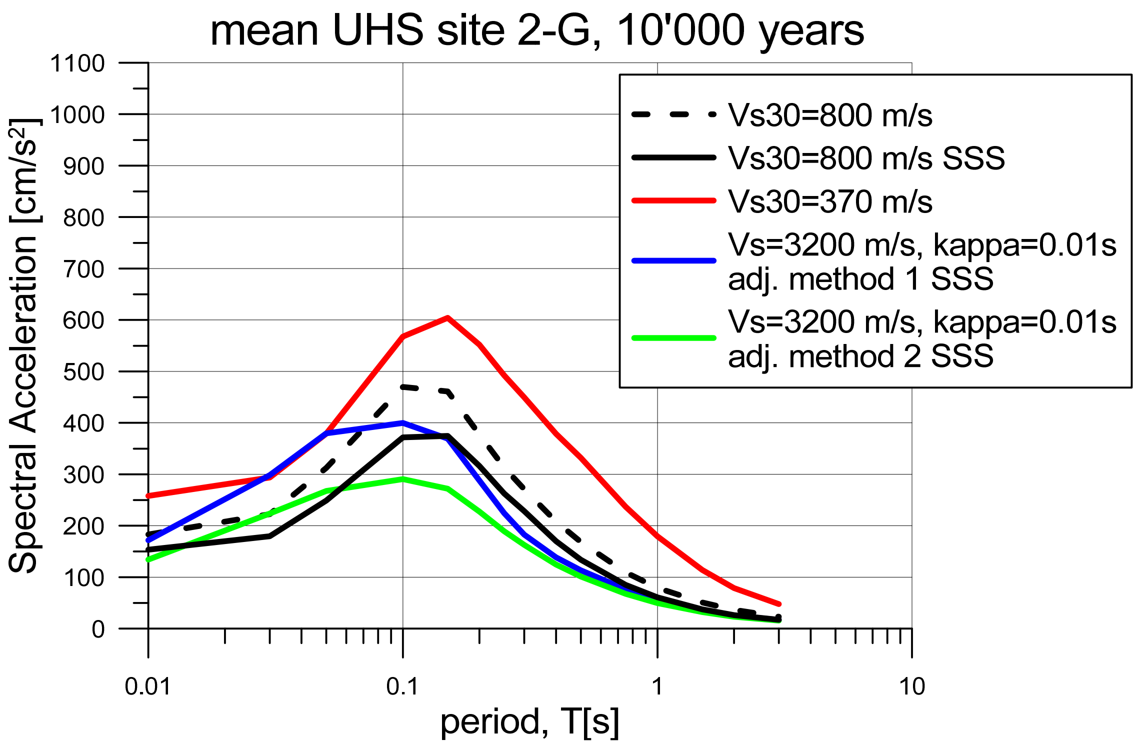

Figure 29 : Site 2-G, mean UHS for 10'000 years return periods obtained from generic and site-specific PSHA calculations.

6. SITE RESPONSE ANALYSIS

In the previous sections, we discussed the calculation of the site-specific UHS at bedrock level for the two target sites. In order to account for the two specific soil profiles, linear, equivalent-linear and nonlinear site response analyses are performed within the WP3. The objective is to define amplification factors to be applied to the UHS derived at bedrock in order to obtain ground motion response spectra (GMRS) representative of the hazard at the surface.

6.1 SELECTION OF INPUT MOTIONS

The selection of acceleration time histories for the site response analysis is performed within the WP5 based on the output of the PSHA:

- the mean UHS at 10'000 years return period obtained from the considered logic tree considering adjustment methods 1 and 2;
- the M-R-Epsilon hazard deaggregation at 10'000 years return period.

Within the framework of the SIGMA IE, two teams provided acceleration time histories for site response analysis according to different criteria:

- One set is provided by R. Paolucci of the Politecnico di Milano. For each site (1-V and 2-G) and each adjustment method a set of 5 individually spectrally-matched acceleration time histories are provided. Before the spectral matching the motions are selected based on broadband spectral compatibility with the target UHS in the SIMBAD database (Smerzini et al., 2014). These motions are referred to as IT motions.
- One set is provided by F. Allain of EDF-SEPTEN. For each site (1-V and 2-G) and each adjustment method a set of ten scaled acceleration time histories are provided. The scaling is performed in a way that 5 motions are scaled so that their average spectrum match to the low-frequency (LF) part (above 0.2-0.3s) of the target UHS and 5 are scaled to the high-frequency (HF) part (below 0.2-0.3s). The motions are searched within the RESORCE database. The scaling factors are between 0.2 and 2. These motions are referred to as FR motions.

We refer to R. Paolucci and to F. Allain for further details on the selection and modification procedures and on the acceleration records.

6.1.1 Hazard deaggregation

The hazard deaggregation is performed in order to guide the magnitude-distance ranges for the selection of the acceleration time histories. Because the geographic position of the PSHA site is the same for the considered soil profiles the deaggregation results are essentially the same for the four hazard calculations (2 site profiles and 2 adjustment methods).

Figure 30 shows an example of M-R-Epsilon deaggregation of mean hazard at 10'000 years return period for site 2-G and adjustment method 2. The deaggregation is performed for 4 spectral frequencies: 0.5 Hz, 1 Hz, 5 Hz and 20 Hz in order to show the dominant M-R couples at different frequencies. The results of the deaggregation show that at low frequencies (0.5 Hz and 1 Hz) the hazard is controlled by magnitudes between 5.5 and 6.5 at distance smaller than 50 km. At higher frequencies (5 Hz and 20 Hz), the hazard is controlled by slightly lower magnitudes, between 4.5 to 6 and more local sources (distances smaller than 30 km).

Beside the M-R criteria the FR motions are also selected based on preferred site conditions as Vs30>500m/s or EC8 A, B or C categories (if Vs30 was not available in the database).

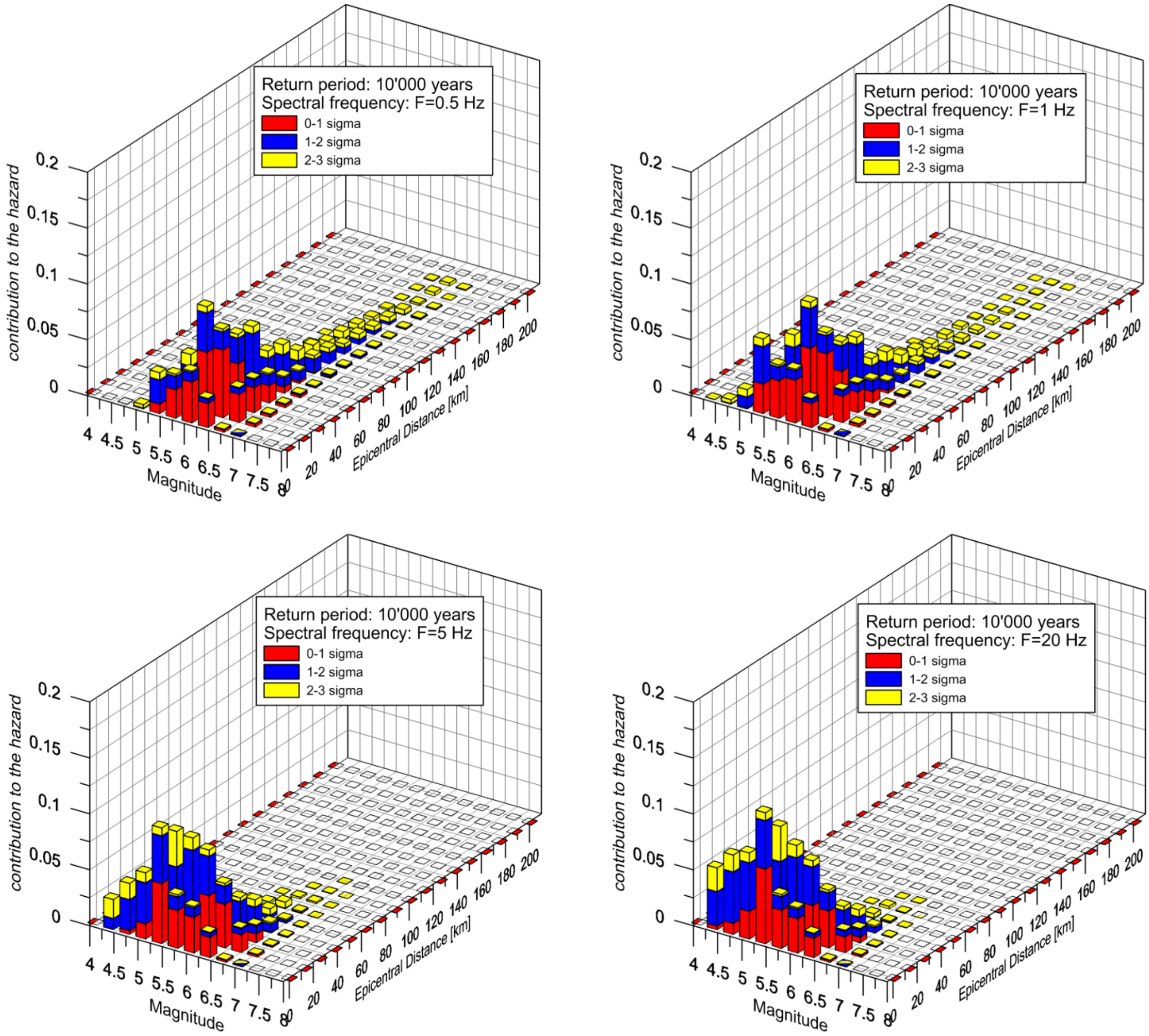

Figure 30 : Example of M-R-Epsilon hazard deaggregation for site 2-G method 2 at different spectral frequencies.

6.1.2 Input motions for site 1-V and site 2-G

The acceleration response spectra of the input motions selected by the two teams for site 1-V and site 2-G are briefly illustrated in this section and compared to the target UHS.

Figure 31 shows the response spectra of the IT acceleration time histories matched to the target UHS for site 1-V obtained considering the two Vs-kappa adjustment methods. Figure 33 shows the same plots for site 2-G.

Figure 32 shows the response spectra of the FR acceleration time histories for HF and LF motions. The mean of the HF spectra and the mean of the LF spectra are presented and compared to the target UHS for site 1-V obtained considering the two Vs-kappa adjustment methods. Figure 34 shows the same plots for site 2-G.

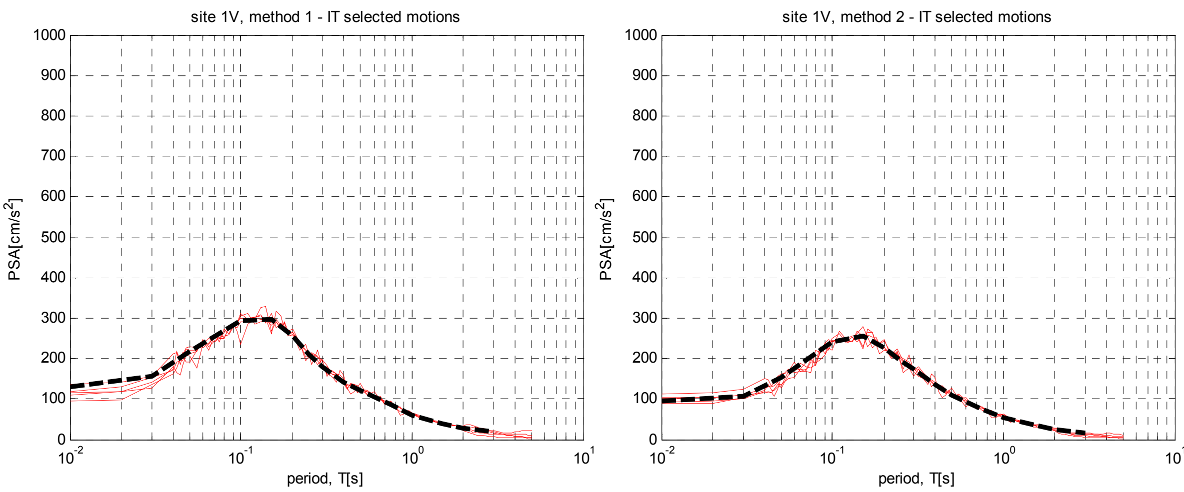

Figure 31 : Site 1-V. Acceleration response spectra of IT motions (in red) compared to the target UHS (in black) for GMPEs Vs-kappa adjustment method 1 (left) and method 2 (right).

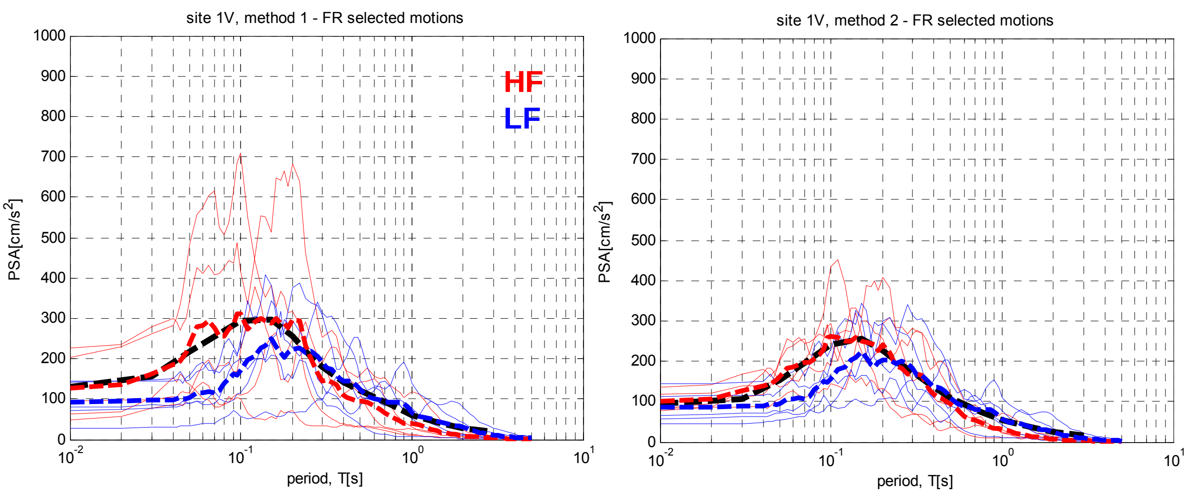

Figure 32 : Site 1-V. Acceleration response spectra of FR motions scaled to the HF part (in red) and to the LF part (in blue) of the target UHS (in black). The mean spectra for the HF and LF motions are shown by dashed red and dashed blue curves, respectively. The spectra scaled to the UHS for GMPEs Vs-kappa adjustment method 1 and method 2 are shown in the left and right panels, respectively.

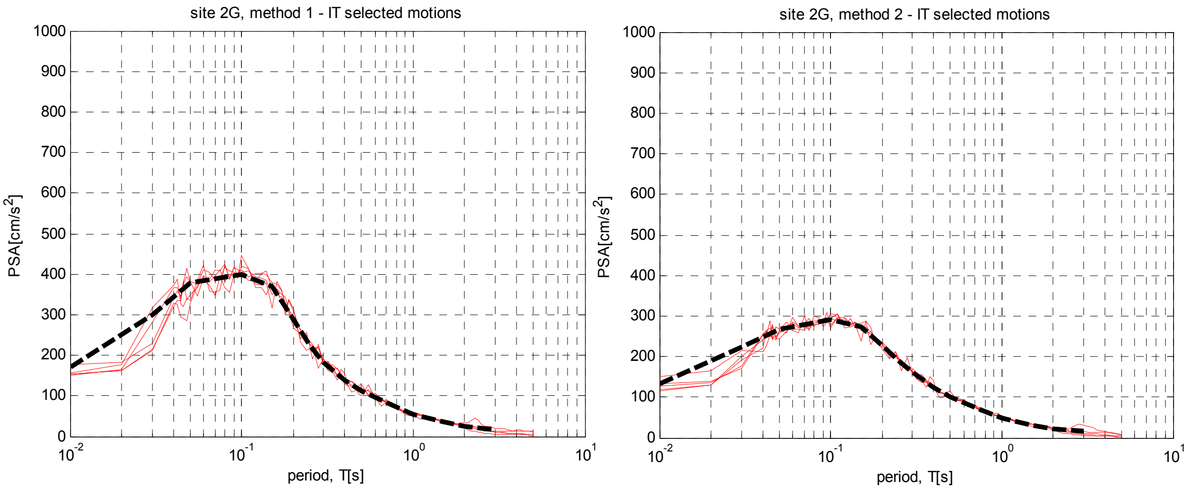

Figure 33 : Site 2-G. Acceleration response spectra of IT motions (in red) compared to the target UHS (in black) for GMPEs Vs-kappa adjustment method 1 (left) and method 2 (right).

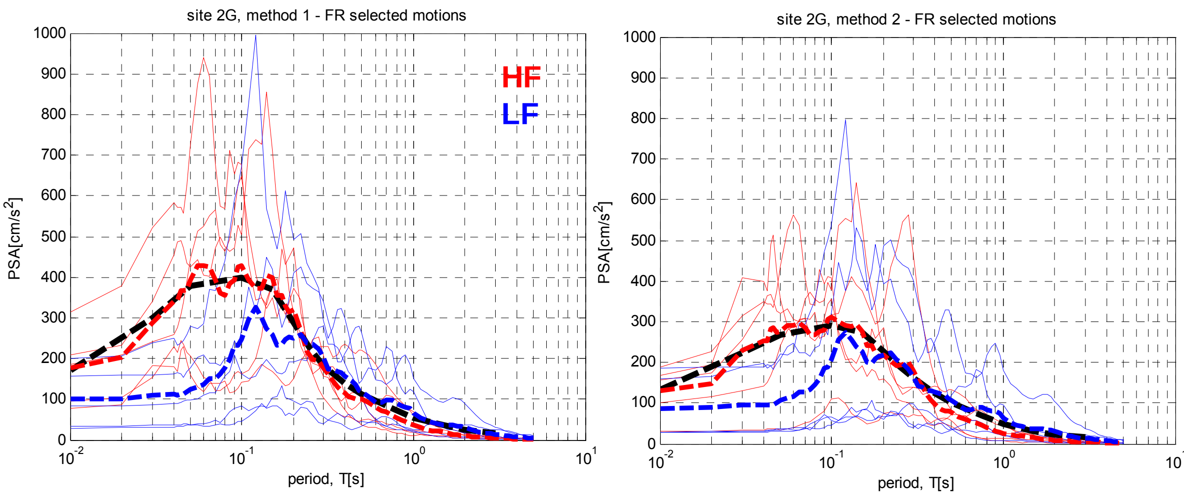

Figure 34 : Site 2-G. Acceleration response spectra of FR motions scaled to the HF part (in red) and to the LF part (in blue) of the target UHS (in black). The mean spectra for the HF and LF motions are shown by dashed red and dashed blue curves, respectively. The spectra scaled to the UHS for GMPEs Vs-kappa adjustment method 1 and method 2 are shown in the left and right panels, respectively.

6.2 LINEAR AMPLIFICATION FACTORS

The linear amplification factors are obtained by post-processing the simulations performed for the two sites by the group of Peter Moczo and Yozef Kristek at the University of Bratislava within the WP3. A detailed explanation of the simulation method can be found in Moczo and Kristek (2014). The simulations are performed using a viscoelastic model and the soil profiles described in section 2. The post-processing we performed consists on the following steps:

1. Derive a transfer function based on the simulations provided by WP3 by deconvolution of the input synthetic signal from the output synthetic signal at the surface. The input signal is a Gabor signal with appropriate frequency content (see Moczo and Kristek, 2014). The amplitude transfer functions for the two soil profiles are presented in Figure 35;

2. Convolve the set of IT and FR motions with the complex transfer function defined in step 1 in order to obtain acceleration time histories at the surface.

3. Calculate response spectra of the IT and FR motions at the surface;

4. Calculate the ratio between surface and input spectra in order to derive amplification factors.

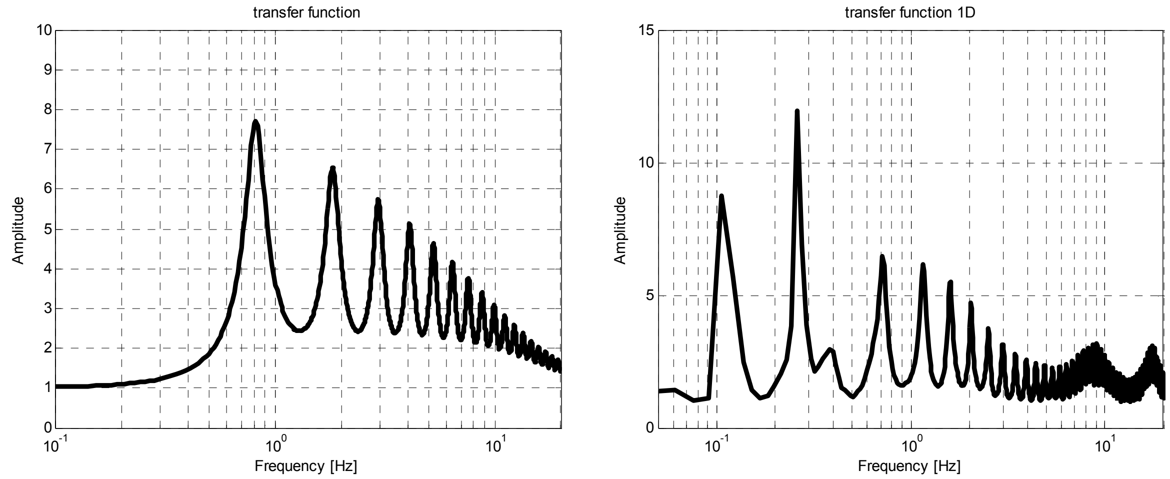

Figure 35 : Linear amplitude transfer functions for the 1D soil profile of site 1-V (left) and site 2-G (right).

6.2.1 Linear amplification factors for site 1-V

The response spectra at the surface and the amplification factors obtained from the linear calculations at site 1-V for IT motions are presented in Figure 36. The results for each time history are presented only for adjustment method 2 for simplicity. Anyway, as it will be shown later, the amplification factors calculated using the input motions selected based on the UHS for the two adjustment methods are very similar. The largest amplification factors of about 6 are found around T=1.2 seconds as expected from the transfer function. At the PGA (here assumed equivalent to T=0.01s) the amplification is about 3.

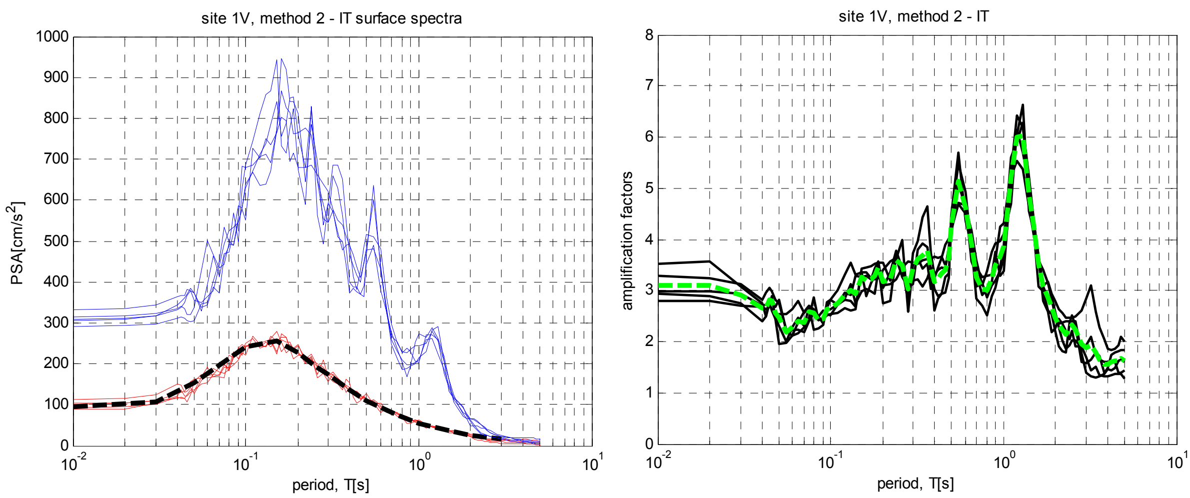

Figure 36 : Site 1-V. Left: Acceleration response spectra at the surface (in blue) obtained from linear site response for IT motions. The spectra of the input motions (in red) and UHS (in black) for adjustment method 2 are also shown. Right: Amplification factors calculated for each time history (in black) and mean amplification factor (in green).

Figure 37 presents the response spectra at the surface and the amplification factors obtained from the linear calculations at site 1-V for FR motions. Also in this case the results are only presented for adjustment method 2. The calculation of amplification factors is slightly different with respect to the IT case because the FR motions are scaled to the LF and HF part of the target spectrum. Thus, at the surface, we obtain 5 spectra representative of the HF motion and 5 representative of the LF motion. The amplification factor for each record is calculated as the ratio between the input and output spectra. The mean amplification factor (shown in green in the left panel of Figure 37) in calculated as:

$$mean\ AF = \frac{max(\text{mean surface LF spectrum},\ \text{mean surface HF spectrum})}{max(\text{ mean input LF spectrum},\ \text{mean input HF spectrum})}$$

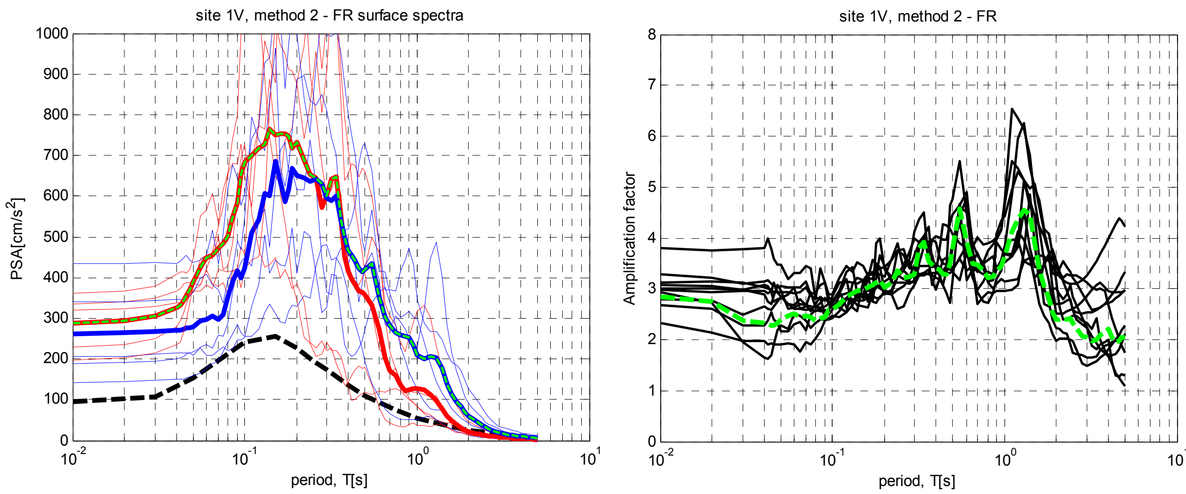

Figure 37 : Site 1-V. Left: Acceleration response spectra at the surface obtained from linear site response for FR motions. The thin blue and red curves represent the LF and HF spectra, respectively. The thick blue and red curves are the mean spectra over the five LF and the five HF spectra, respectively. The dashed green curve is the max of the mean LF and mean HF spectra. The UHS (in black) for adjustment method 2 is also shown. Right: Amplification factors calculated for each acceleration time history (in black) and mean amplification factor (in green).

Figure 38 shows the comparison of mean linear amplification factors obtained for site 1-V considering the IT and FR motions selected based on the UHS derived using the two Vs-kappa adjustment methods. The amplification factors obtained from IT and FR motions are consistent and provide similar values. The only remarkable difference is at the fundamental period of the soil profiles (about 1.3 seconds) where the FR motions provide smaller mean amplifications (a factor of 4.5 compared to a factor of 6 for IT motions). This may be caused by the lack of low-frequency energy in some of the input motions. Indeed the selection procedure adopted for the FR motions is based on the match between mean spectra, but individual spectra may have large variability.

The amplification factors derived using motions selected based on UHS with adjustment method 1 or method 2 are quite similar for both FR and IT sets. This is expected because linear amplification factors are largely independent from the average level on input motions.

Note that the response spectra are calculated up to 5 seconds although amplification factors will be used only up to 3 seconds because this is the largest spectral period defined in the UHS.

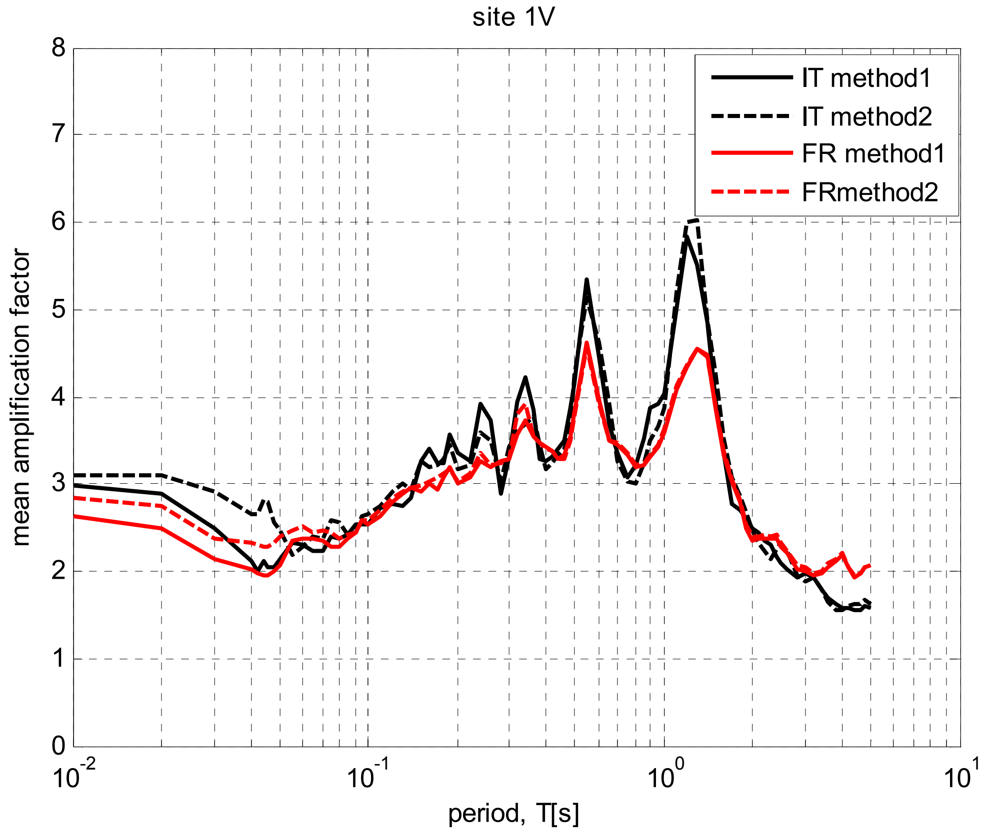

Figure 38 : Site 1-V. Mean linear amplification factors obtained considering the IT and FR motions selected based on the UHS derived using the Vs-kappa adjustment method 1 and method 2.

6.2.2 Linear amplification factors for site 2-G

The response spectra at the surface and the amplification factors obtained from the linear calculations at site 2-G are presented in Figure 39 and in Figure 40 for IT and FR motions, respectively. Also in this case the results are only presented for adjustment method 2.

Figure 41 shows the comparison of mean linear amplification factors obtained for site 2-G considering the IT and FR motions selected based on the UHS derived using the two Vs-kappa adjustment methods. As already observed for site 1-V, the amplification factors for adjustment method 1 and method 2 are similar. Moreover, the mean amplification factors from FR and IT motions are much closer with respect to what observed for site 1-V. Overall, the amplifications reach values of about 3.5 at spectral periods of 4s, 1.4s and 0.9s. At the PGA (T=0.01s) the amplification is about 1.5.

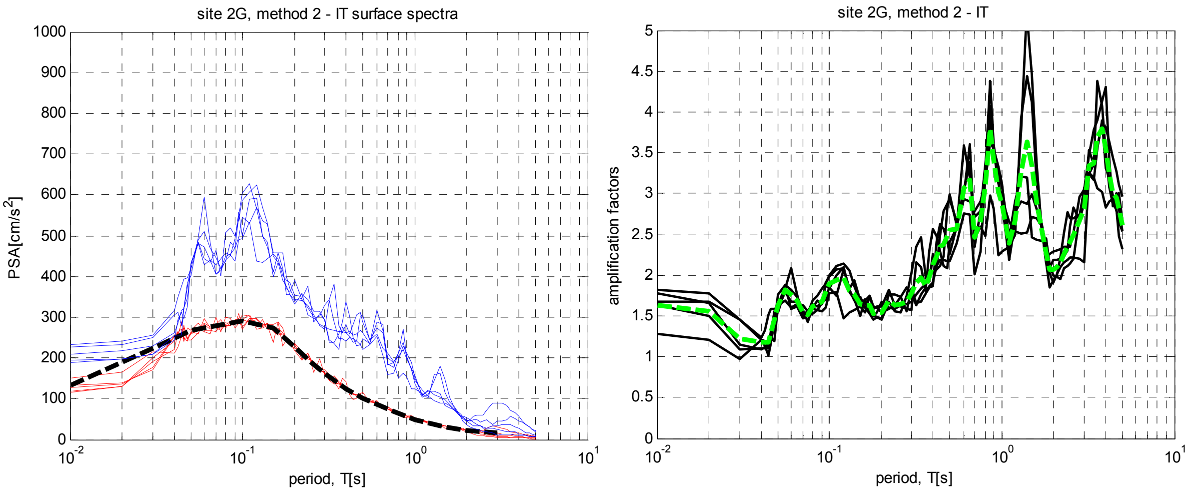

Figure 39 : Site 2-G. Left: Acceleration response spectra at the surface (in blue) obtained from linear site response for IT motions. The spectra of the input motions (in red) and UHS (in black) for adjustment method 1 are also shown. Right: Amplification factors calculated for each time history (in black) and mean amplification factor (in green).

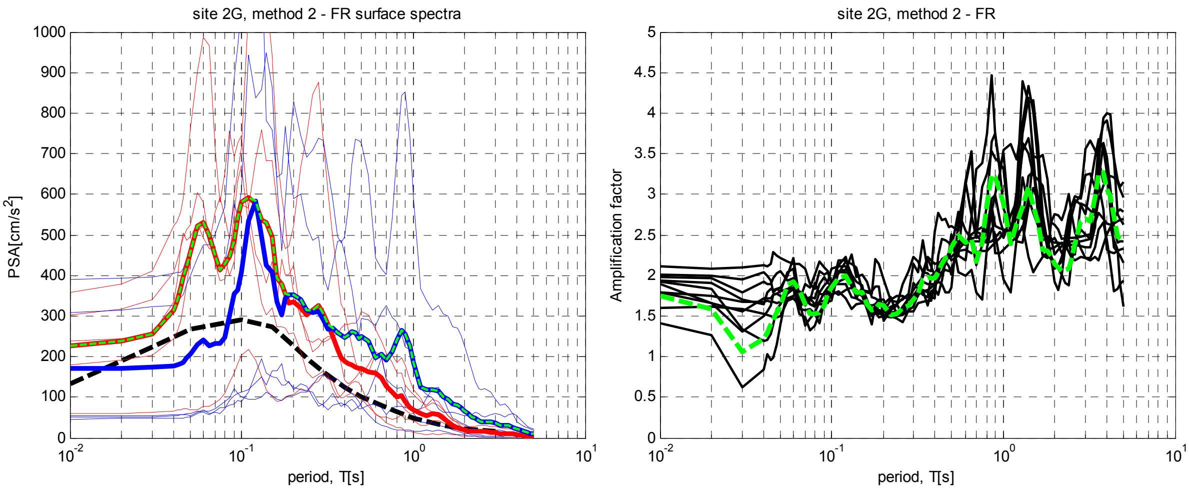

Figure 40 : Site 2-G. Left: Acceleration response spectra at the surface obtained from linear site response for FR motions. The thin blue and red curves represent the LF and HF spectra, respectively. The thick blue and red curves are the mean spectra over the five LF and the five HF spectra, respectively. The dashed green curve is the envelope of the mean LF and mean HF spectra. The UHS (in black) for adjustment method 2 is also shown. Right: Amplification factors calculated for each acceleration time history (in black) and mean amplification factor (in green).

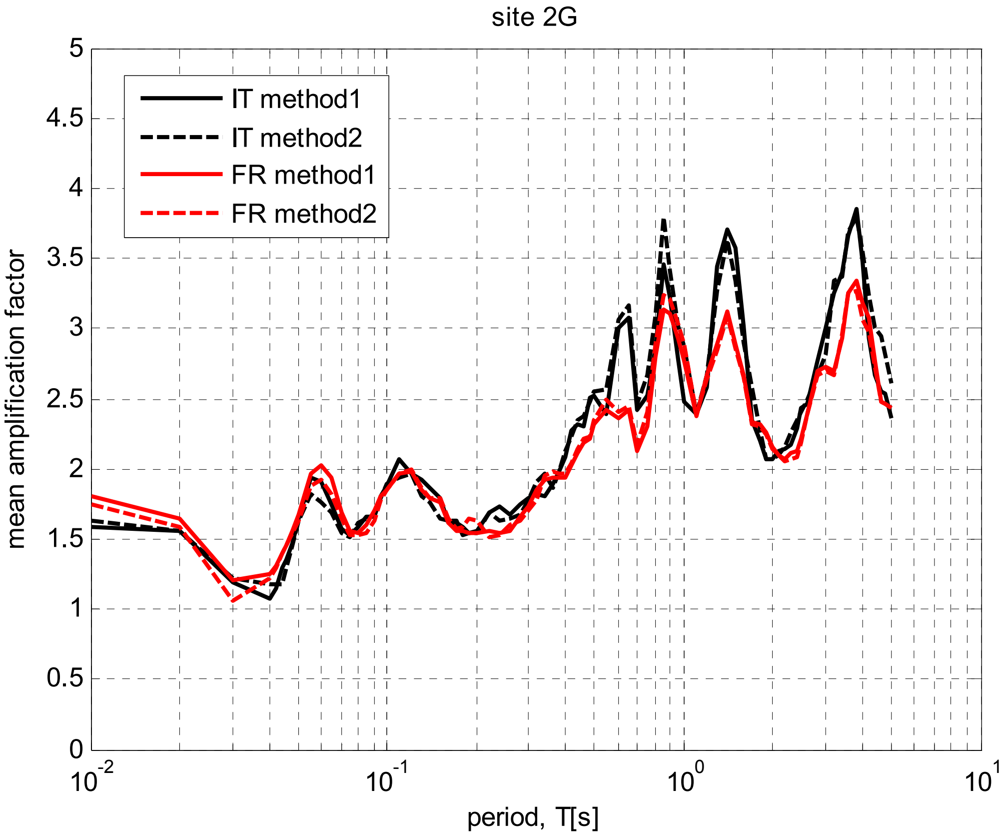

Figure 41 : Site 2-G. Mean linear amplification factors obtained considering the IT and FR motions selected based on the UHS derived using the Vs-kappa adjustment method 1 and method 2.

6.3 EQUIVALENT-LINEAR AND NONLINEAR AMPLIFICATION FACTORS

The equivalent-linear and nonlinear site response analyses are performed using DEEPSOIL 6.0 (Hashash et al 2015). DEEPSOIL is a one-dimensional site response analysis program that can perform both a) 1-D nonlinear and b) 1-D equivalent linear analyses. This means that the same input parameters are used for both equivalent-linear and nonlinear calculations. The adopted stiffness degradation curves and damping curves are shown in Figure 42 and Figure 43 for site 1-V and 2-G, respectively. The choice of the input model parameters for the two sites have been discussed and validated within the WP3. In this section we present the main results of the equivalent-linear and nonlinear site response analyses in terms of amplification factors. Detailed results for the nonlinear site response analyses performed for the two sites are presented in Annex 1.

Note that, a nonlinear site-response analysis for the 2-G site has also been performed using the same model but different (larger) input motions in WP3 (see Hollender et al., 2014).

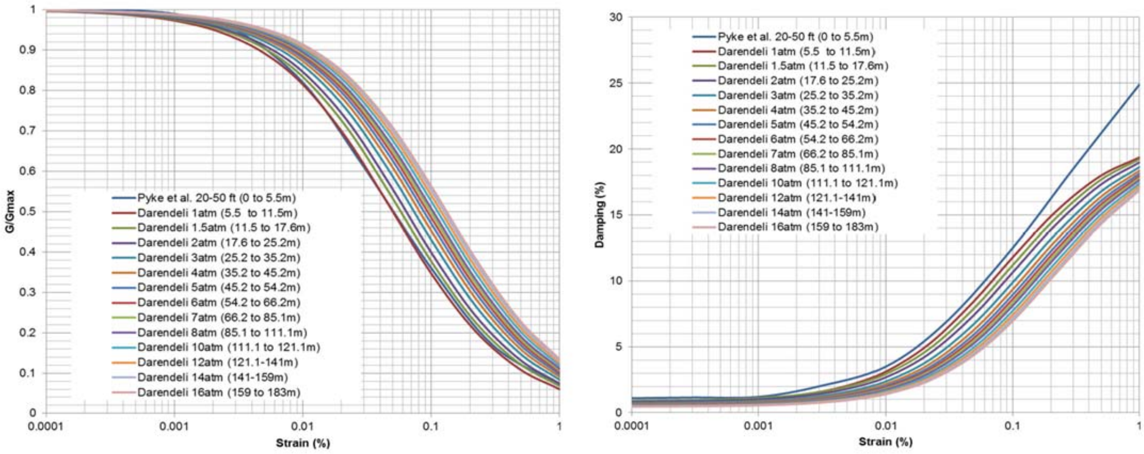

Figure 42 : Site 1-V, Stiffness degradation versus strain (left) and Damping ratio versus strain (right) as a function of soil depth. See Annex1 for further details.

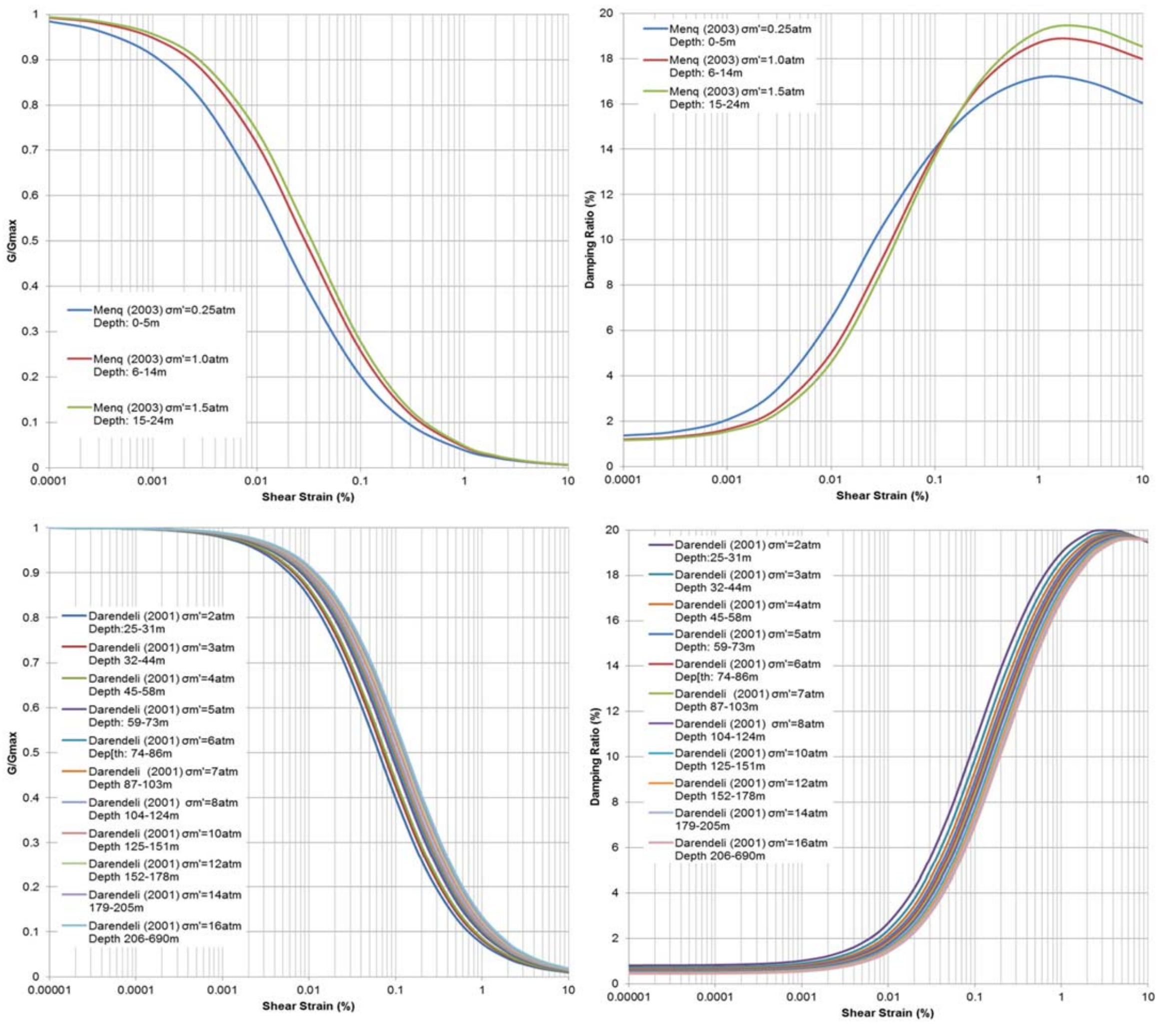

Figure 43 : Site 2-G, Stiffness degradation versus strain for cohesionless soil (top-left), Damping ratio versus strain (top-right) for cohesionless soil as a function of soil depth. Stiffness degradation versus strain for cohesive soil (bottom-left), Damping ratio versus strain for cohesive soil (bottom-right) as a function of soil depth. See Annex1 for further details.

The mean amplification factors derived from equivalent-linear and purely nonlinear site response analyses are presented in Figure 44 for site 1-V and are compared with the linear ones. The amplification factors are calculated separately for the IT and FR sets of motions and for the two Vs-kappa adjustment methods adopted in the PSHA. The equivalent-linear and nonlinear amplification factors highlight the same fundamental period as the linear results (though slightly shifted towards longer periods). However, amplifications at short periods are significantly reduced and the other resonance periods visible in the linear amplification factors disappear. The equivalent-linear and purely nonlinear amplification factors are remarkably consistent. Minor difference are visible at short periods (T<0.1s). The difference between results obtained with IT and FR motions are not significant except for T>2s where the FR motions provide slightly larger amplification factors. The differences between amplification factors based on the two adjustment methods are similar to what observed in the linear case. Minor differences arise at short periods (T<0.05s), where the difference between the two bedrock UHS is indeed larger. Adjustment Method 1 provides higher accelerations and generates slightly higher nonlinearity, leading to smaller amplification factors with respect to adjustment method 2.

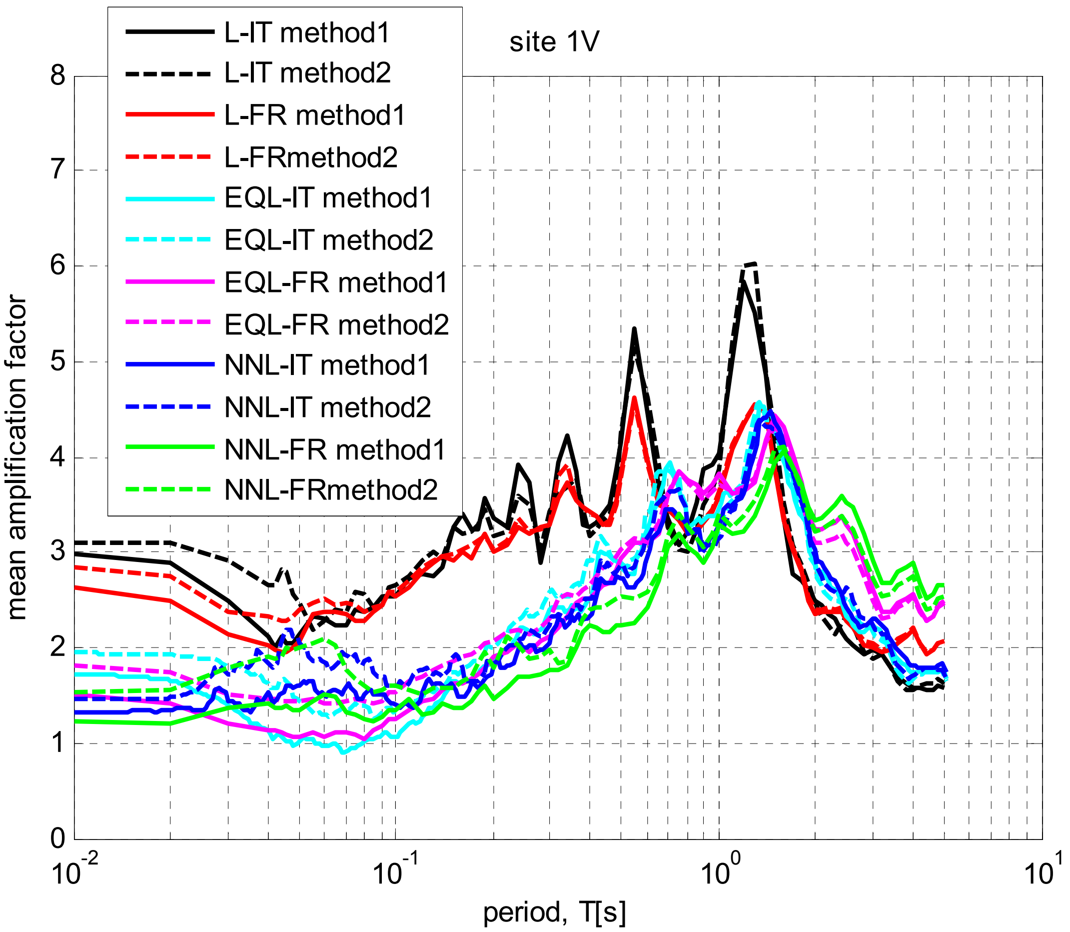

Figure 44 : Site 1-V: Linear, equivalent-linear and nonlinear mean amplification factors obtained using the IT and FR sets of acceleration time histories. The amplification factors are also separated according to the GMPEs adjustment method used in the calculation of the UHS for the bedrock conditions.

The mean amplification factors derived from the equivalent-linear and nonlinear site response analyses for site 2-G are presented in Figure 45. The linear, equivalent-linear and nonlinear amplification factors are quite consistent for periods longer than about 0.8 seconds, although also in this case we observe a slight shift of the main resonance periods. For shorter periods the equivalent-linear and nonlinear amplifications are smaller than the linear ones. Also for this site, the equivalent-linear and nonlinear amplification factors are provide very similar results. The differences among the amplification factors obtained for the different sets of motions and using the two adjustment methods are less pronounced for this site.

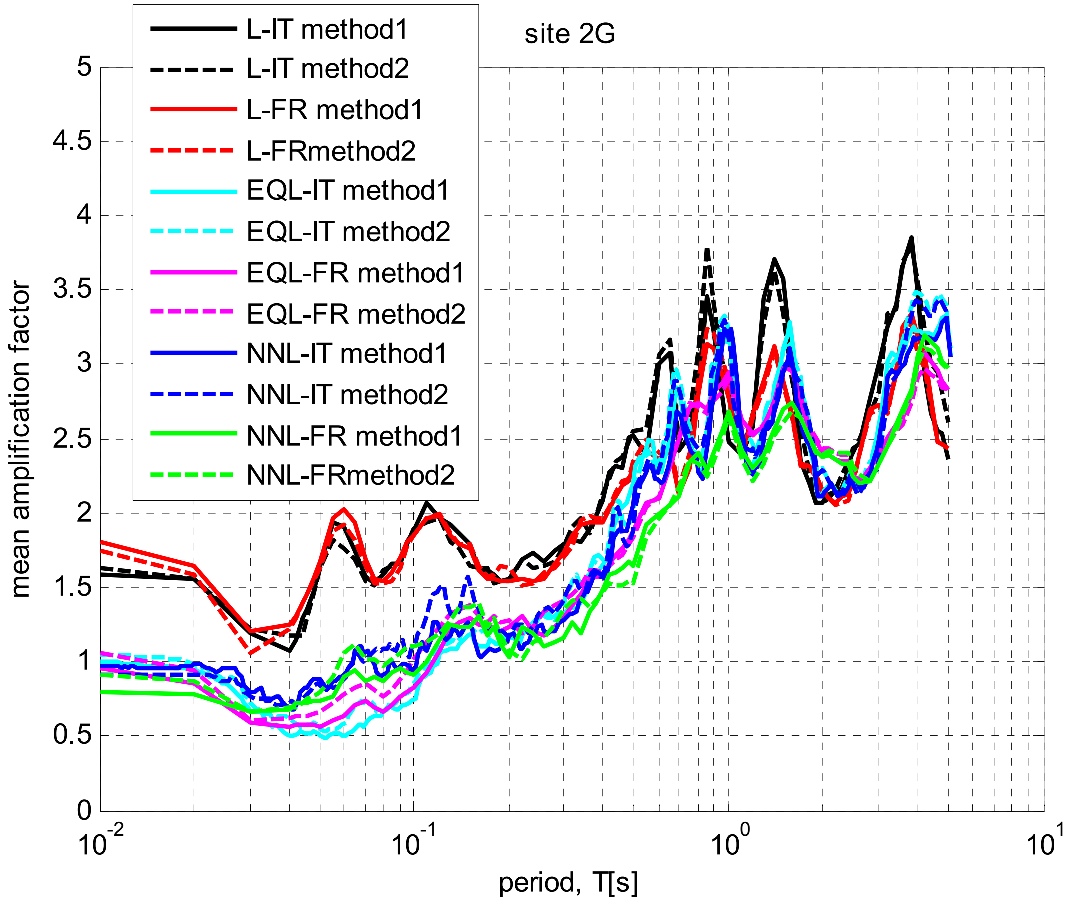

Figure 45 : Site 2-G: Linear, equivalent-linear and nonlinear mean amplification factors obtained using the IT and FR sets of acceleration time histories. The amplification factors are also separated according to the GMPEs adjustment method used in the calculation of the UHS for the bedrock conditions.

7. FINAL COMPARISON BETWEEN SITE-SPECIFIC AND GENERIC SPECTRA

In this section, we compare the final results of the generic and site-specific PSHA for the two sites. The results of the site-specific PSHA are presented in terms of ground motion response spectra (GMRS) at the surface obtained applying the Vs-kappa adjustment factors to the selected GMPEs and using linear, equivalent-linear and nonlinear site response analysis to characterize the response of the soil profiles. The GMRS are compared to the UHS calculated using generic GMPEs. All the comparisons are performed for a return period of 10’000 years. Moreover, we consider separately the GMRS obtained using amplification factors based on IT and FR acceleration time histories as well as the GMRS obtained using the two Vs-kappa adjustment approaches.

We recall that the PSHA logic trees for generic and site-specific calculations are identical except for the GMPEs (median and sigma values) and their weights (see section 3.1). In the generic PSHA, the site conditions are modeled in the GMPEs based on the Vs30 of the two sites and the total sigma is used. In the site-specific approach, the GMPEs are adjusted for bedrock Vs and kappa and the single-station sigma is employed. Then site-response analysis is performed to derive amplification factors for the soil profiles.

Figure 46 and Figure 47 show the results for site 1-V considering method 1 and method 2 for Vs-kappa adjustment of the GMPEs, respectively. In order to better quantify the differences with respect to the generic UHS, Figure 48 presents the spectral ratios of the GMRS for the various cases with respect to the generic UHS (with Vs30=185 m/s).

The mean GMRS obtained using linear amplification factors provide similar differences with respect to the generic UHS at periods larger than about 0.3s. In this period range, the GMRS are on average smaller than the UHS. For shorter periods, the GMRS obtained using adjustment method 2 provide accelerations similar to the generic UHS (within ± 20% difference) whereas the adjustment method 1 provide systematically larger GMRS (up to 40% larger than the UHS)

Considering equivalent-linear and nonlinear amplification factors the spectral accelerations are systematically lower (about 30-40 %) than the generic UHS for periods shorter than T=1s. Moreover, the differences with respect to the generic UHS are similar for all the equivalent-linear and nonlinear GMRS. As already noticed the equivalent-linear and the nonlinear simulations provide similar results.

At the fundamental period of the site (about 1.3 s) the results of all the GMRS are quite similar and consistent with the generic UHS. Finally we note that the difference between mean GMRS obtained using the set of FR or IT motions are not relevant.

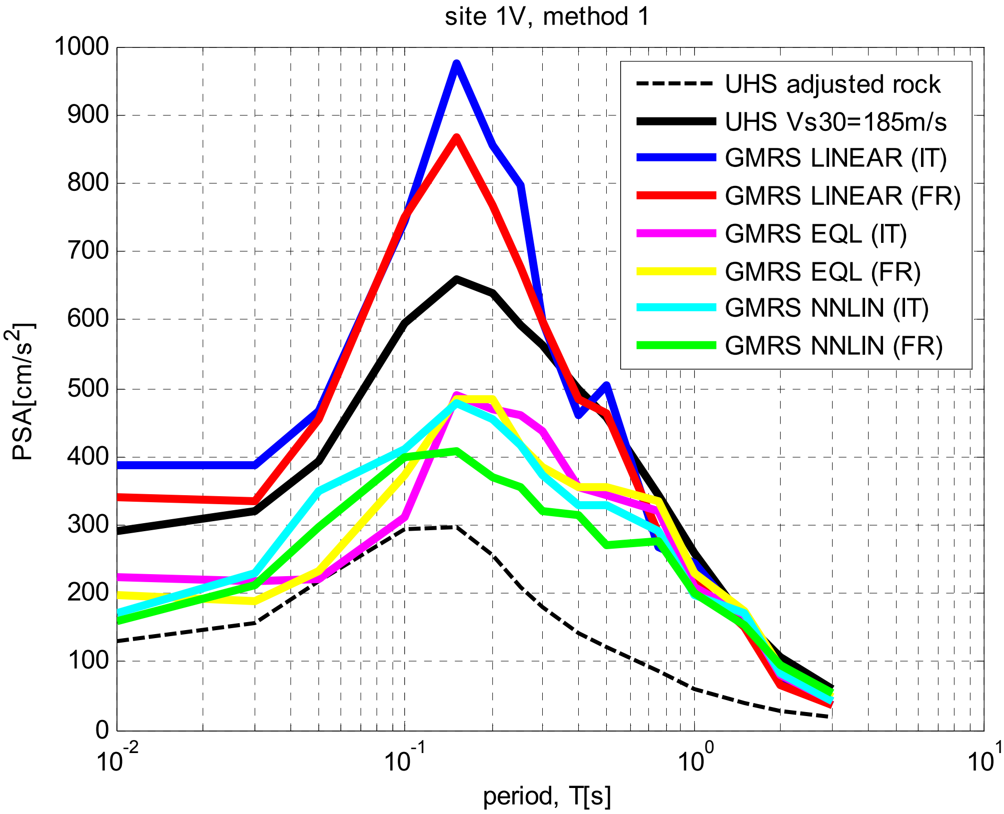

Figure 46 : Site 1-V. Comparison between generic mean UHS (Vs30=185 m/s) and site-specific mean GMRS obtained using linear, equivalent-linear and nonlinear site amplification factors and Vs-kappa adjustment method 1. The mean UHS for bedrock conditions is also shown by the dashed black curve.

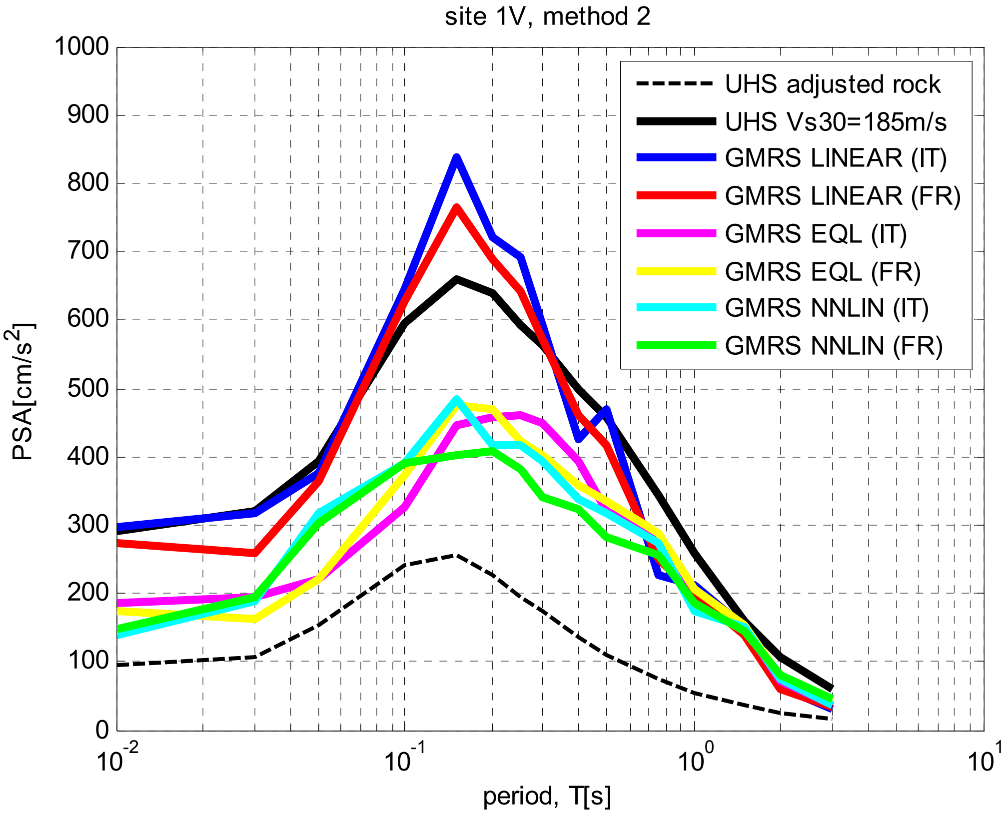

Figure 47 : Site 1-V. Comparison between generic mean UHS (Vs30=185 m/s) and site-specific mean GMRS obtained using linear, equivalent-linear and nonlinear site amplification factors and Vs-kappa adjustment method 2. The mean UHS for bedrock conditions is also shown by the dashed black curve.

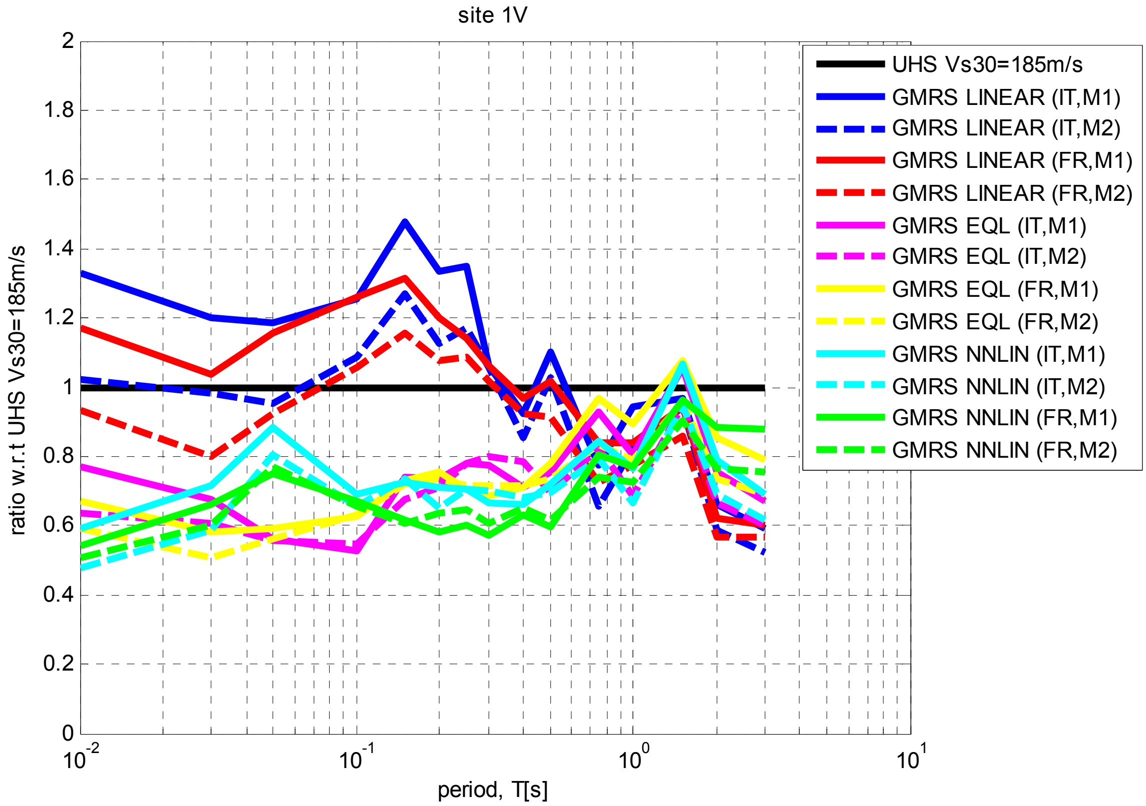

Figure 48 : Site 1-V. spectral ratios of the calculated mean GMRS for the different cases with respect to the generic mean UHS for Vs30=185 m/s.

Figure 49 and Figure 50 show the results for site 2-G considering method 1 and method 2 for Vs-kappa adjustment of the GMPEs, respectively. Figure 51 presents the spectral ratios of the GMRS for the various cases with respect to the generic UHS (with Vs30=370 m/s).

The general picture is similar to what observed for site 1-V. In particular, for site 2-G, it is interesting to note that all the GMRS provide spectral accelerations that are on average lower than the generic UHS, except those calculated using adjustment method 1 and linear site amplifications. These latter GMRS that are up to 60 % larger than the generic UHS in the short period range (T<0.2s). At long periods (T>1s) the various GMRS provide similar accelerations, that are about 20% smaller than the generic UHS. The equivalent-linear and nonlinear amplification factors provide GMRS about 40-50% lower than the generic UHS at periods smaller than 0.5s and about 20 % smaller at longer periods.

Also in this case the equivalent-linear and the nonlinear simulations provide similar results and the difference between mean GMRS obtained using the set of FR or IT motions are not relevant.

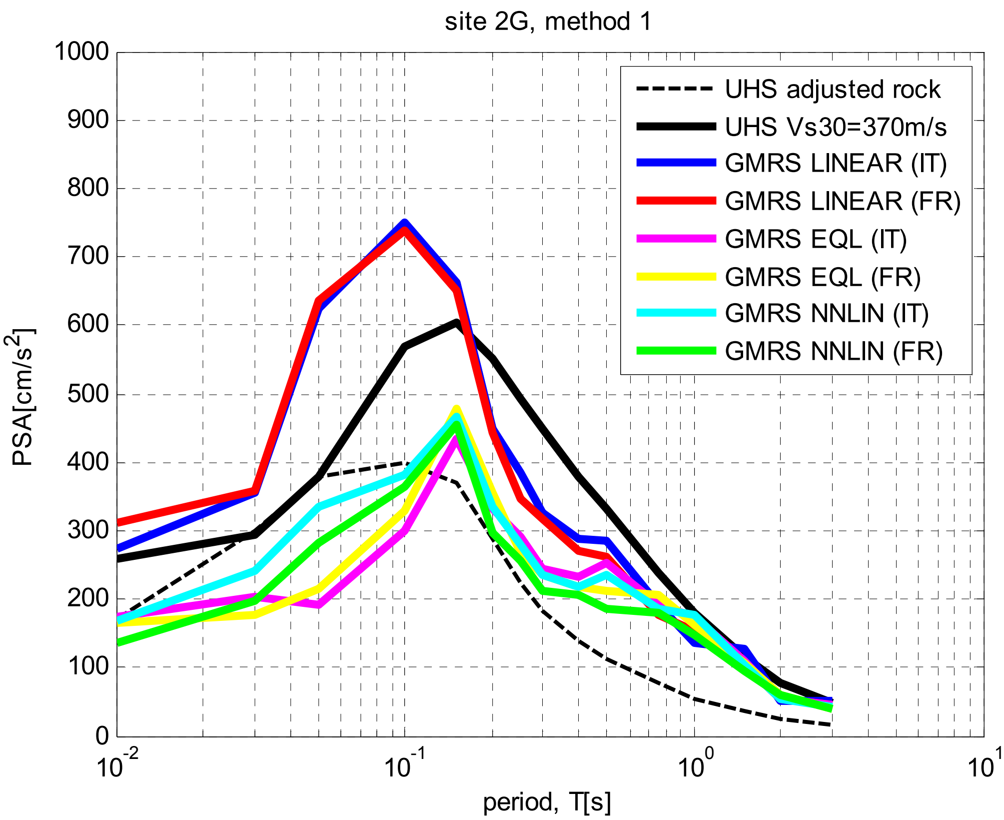

Figure 49 : Site 2-G. Comparison between generic mean UHS and site-specific mean GMRS obtained using linear, equivalent-linear and nonlinear site amplification factors and Vs-kappa adjustment method 1. The mean UHS for bedrock conditions is also shown by the dashed black curve.

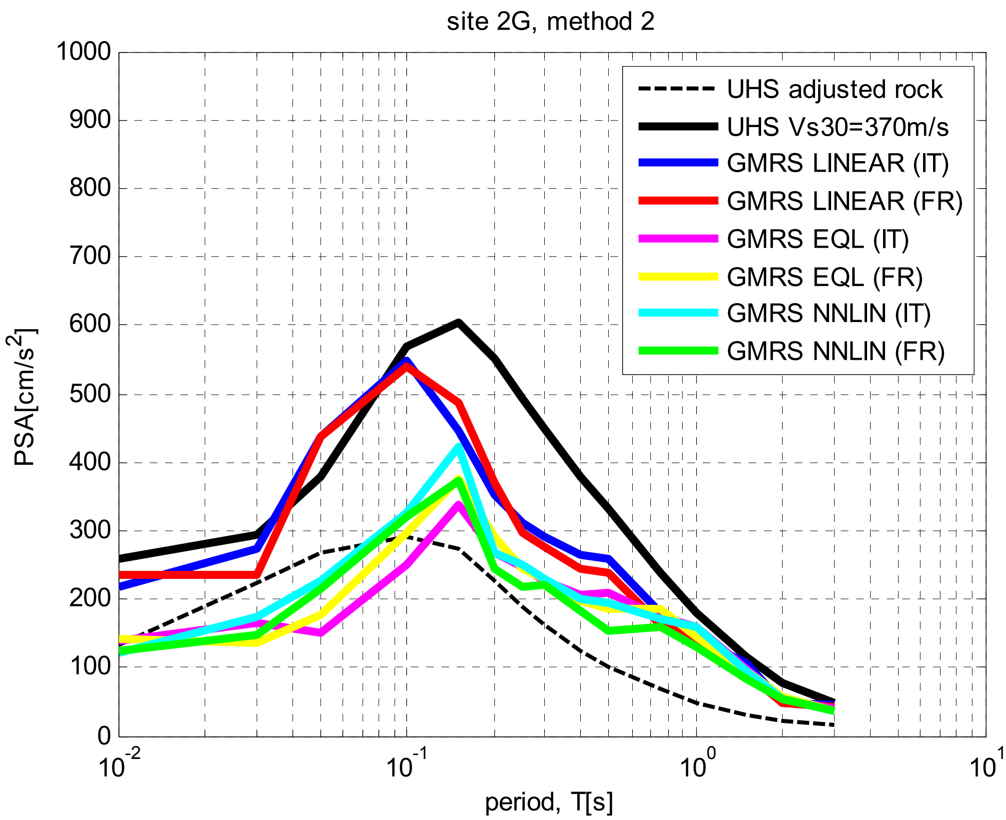

Figure 50 : Site 2-G. Comparison between generic mean UHS and site-specific mean GMRS obtained using linear, equivalent-linear and nonlinear site amplification factors and Vs-kappa adjustment method 2. The mean UHS for bedrock conditions is also shown by the dashed black curve.

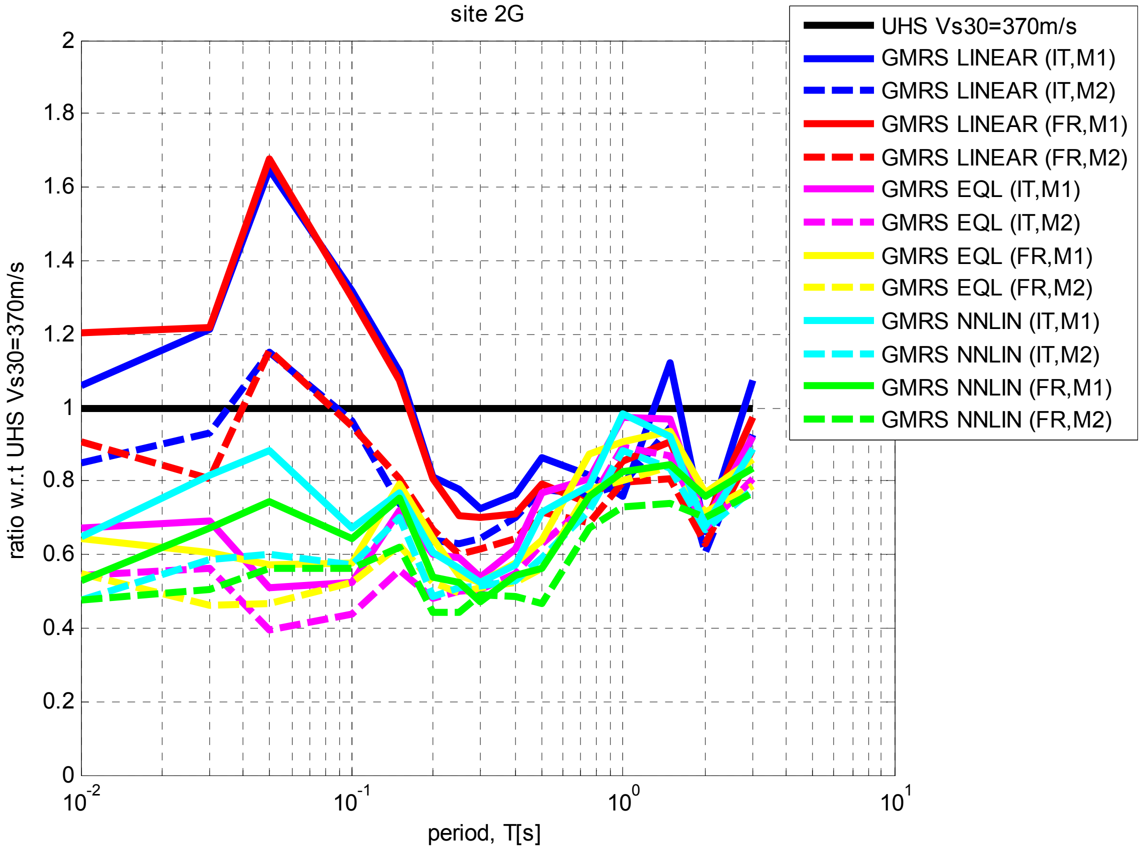

Figure 51 : Site 2-G. spectral ratios of the calculated mean GMRS for the different cases with respect to the generic mean UHS for Vs30=370 m/s.

8. DISCUSSION AND CONCLUSIONS

In this study we performed site-specific PSHA for two virtual sites characterized by different bedrock conditions and different soil profiles. The median ground motion from a set of GMPEs selected for the PSHA is first adjusted to the Vs and kappa values of the target bedrock for each site. The Vs-kappa adjustment is performed following two approaches. The first is based on the adjustment factors derived by Bora (2014) that are applied to the other three GMPEs (i.e., Ameri, 2014; Boore et al., 2014 and Cauzzi et al., 2014). The second approach is based on the methodology detailed in Al Atik et al. (2014) that make use of the IRVT to derive Fourier amplitude spectra for each GMPE in order to estimate the host kappa and to apply the Vs-kappa scaling. The total sigma of the GMPEs is reduces by applying a single-station sigma model in order to account for the fact that the repeatable site term is included using amplification factors from site response analysis performed in the second part of the study.

The bedrock UHS calculated from both Vs-kappa adjustment methods and hazard deaggregation at 10'000 years return period are used to select acceleration time histories to perform linear, equivalent-linear and nonlinear site response analysis for both soil profiles. The mean amplification factors are used to calculate site-specific mean ground motions response spectra (GMRS) that are compared with generic mean UHS calculated only based on the Vs30 at the sites.

The final results, expressed in terms of mean spectra, show that the comparison between site-specific spectra and generic ones is quite similar for both sites. The site-specific spectra at short periods (T< 0.1s -0.3s) considering linear soil response are larger than the generic ones for Vs-kappa adjustment method 1 and consistent with the generic ones for Vs-kappa adjustment method 2. For longer periods, both Vs-kappa adjustment methods provide spectral values lower than the generic ones. Considering the equivalent-linear and nonlinear soil response site-specific spectra are substantially lower (up to 40-50 %) than the generic ones at all spectral periods. Amplification factors derived using equivalent-linear and purely nonlinear approaches are in good agreement.

In the following we highlight several points for discussion:

- The GMPEs logic tree weights were assigned before the host-to-target Vs-kappa adjustment. In our opinion the weights should also take into consideration the Vs-kappa adjustment process (and its uncertainties) that may be different for each GMPE. The weighting process should consider, for example, the fact that the kappa host values estimated for the Cauzzi et al. (2014) GMPE are less variable with respect to magnitude and distance than for other GMPEs. As another example, the fact that the host Vs profile is more uncertain for the Ameri (2014), due to the use of EC8 site class A, should also be considered in the weighting process.

- The application of the adjustment factors derived by Bora (2014) to other GMPEs needs further investigations. In this study (for one adjustment approach) we consider the hypothesis that the host characteristics of Ameri (2014), Boore et al. (2014) and Cauzzi et al. (2014) may be similar to the Bora (2014) ones. However this may not be the case and the average kappa-host values may be quite different, especially for the Cauzzi et al. (2014) and the Boore et al. (2014) models because the underlying datasets are remarkably different with respect to the one used by Bora (2014). Further studies should be performed in order to verify the applicability of the adjustment factors proposed by Bora (2014) to the other GMPEs.

- The Vs-kappa adjustment contains several uncertainties that were not addressed in the SIGMA IE due to the short time-frame and to the restricted scope of work. The estimation of kappa host based on the IRVT approach is a source of uncertainties and the resulting kappa scaling may be affected by the selected frequency range. For example, the magnitude-dependence of the kappa host values obtained for two GMPEs may be partially related to the variable frequency band with magnitude and in particular to the fact that the starting frequency may contain source effects (being close to the peak of the spectrum). On the other hand, the choice of the variable frequency band is supported by the fact that the corner frequency, and thus the peak of the IRVT-derived FAS, varies with magnitude. In any case the frequency range selection for kappa determination is a relevant issue also considering standard approaches to estimate kappa based on FAS of records (Ktenidou et al. 2014).

  The choice of the host Vs profile also carries uncertainties. The proposed approach is quite simple and yet it is the most widely used in PSHA practice. It is based on the assumption that the generic rock profiles for Western U.S of Boore and Joyner (1997) are representative of the average characteristics of rock stations in the datasets used to derive the considered GMPEs. It would be interesting to perform additional studies to investigate the appropriateness of such assumption.

  Finally no uncertainties were assumed in the target Vs and kappa values. Since large variability may be associated to kappa estimation for rock sites (e.g., Ktenidou et al. 2013) it would be desirable in future studies to account for such variability in target kappa by using different values as alternative branches in the logic tree.

- Uncertainties in the site response analysis are considered only in terms of motion-to-motion variability. Uncertainties related to the definition of the Vs profile and to the selection of the model parameters for the site response analyses are not considered in the scope of work. These are important elements to define the variability of the site term that could contribute to the total uncertainties at the surface. In the SIGMA IE we were mostly interested in the comparison of site-specific and generic mean spectra at the surface and for this reason we restricted our analyses to derive best estimate amplification factors. In this respect, we noticed that the use of the two sets of acceleration time histories (scaled or spectrally-matched) selected by two different teams provide consistent results in terms of mean amplification factors, with only minor differences at long periods.

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