SITE-SPECIFIC PSHA: COMBINED EFFECTS OF SINGLE STATION SIGMA, HOST-TO-TARGET ADJUSTMENTS AND NON-LINEAR BEHAVIOR

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Abstract

Several recent dramatic events drew the attention on the need to carefully reassess the very rare, high-impact, seismic hazard for large urban centers and critical facilities. Following this aim, the present trend all over the world is to more and more rely on probabilistic approaches to estimate seismic hazard, and determine annual exceedance probabilities for various ground-motion levels (down to very low probability levels). Most developments regarding the probabilistic seismic hazard assessment ("PSHA") methods have been concentrated on rock sites, although many cities are located on soft soil sites, which can significantly affect the shaking. In most PSHA studies, the amplification of the soil at the site is taken into account in a crude way, where hazard estimates can be both under-estimated (e.g. resonance effects are ignored) or over-estimated (nonlinear effects are ignored). Critical facilities designed neglecting local site effects within the framework of PSHA may thus have unknown safety margins, with the possibility of under-design. This work contributes to provide recommendations for the incorporation of site response in PSHA estimates. We present a methodology on how to account for site-specific characterization, single station sigma, host-to-target adjustments and non-linear behavior of a soil column. In this study, we estimate the soil hazard for a 5000 years return period at the middle of the EUROSEISTEST valley, using different methods to account for site effects. We perform single station sigma hazard calculations, we apply host to target adjustments when required, we implement 1D linear and non-linear ground motion wave propagation, to finally describe the epistemic uncertainties related to the selected site-specific approach, and its impact on a probabilistic seismic hazard estimates.

Keywords: Site Effects, Epistemic Uncertainty, PSHA, Single Station Sigma, Host to Target Adjustments, Nonlinear Effects.

1. Introduction

Several recent research works have pointed out the importance to improve the methodologies of site-specific seismic hazard analysis, as many cities and critical facilities are located on areas with specific site conditions, which significantly modify the characteristics of ground motion. Within the general framework of probabilistic hazard assessment ("PSHA"), the seismic hazard is traditionally performed for rock conditions [1], and, whenever needed, site-amplification is added later by using amplification factors such as the ones specified in several seismic design codes or the site factors used in GMPEs. Such an approach however is not fully satisfactory as it combines probabilistic and deterministic estimates, and various improvements have been proposed recently ([2][3][4]). The purpose of the present paper is to illustrate the impact of such recent propositions on one example case study, the EUROSEISTEST site, where these various approaches can be applied and tested. This site is located about 30 km east of Thessaloniki (Greece) and has been the target site of detailed geophysical and geotechnical surveys, a dedicated instrumentation, and extensive numerical simulation benchmarking exercises ([5-12]).

In order to be able to correctly perform a Site Specific PSHA, a significant amount of data from the site is required. The ideal site should present:

- Preexisting geological, geophysical and geotechnical characterization in order to produce a realistic model of the soil column;
- Significant amount of instrumental earthquake recordings to be able to derive a partially non-ergodic PSHA.

Such information is required to describe in the most accurate way the soil models or site amplification functions for each site-specific method. The EUROSEISTEST was thus selected as a suitable place to apply this comparison exercise, because of the availability of extensive geological, geotechnical and seismological surveys.

Once defined the site of application, the various methods to account for site effects in a probabilistic framework will be first shortly presented, from the simplest to the more complex ones, and the corresponding results will then be compared and discussed. All these approaches intend to better describe the physical phenomena of wave propagation from rock through a soil structure. The aim of this work is to apply all methods at the same site, to discuss the epistemic uncertainties related to each approach and their impact on the probabilistic seismic hazard estimates.

2. Study Area and Data

The EUROSEISTEST is located in the Mygdonian basin in North-Eastern Greece, 30 km ENE of Thessaloniki (Fig. 1), at the epicentral area of the magnitude 6.5 event that occurred in 1978.

The Mygdonian basin has been extensively investigated first within the framework of various European projects (Euroseistest, Euroseismod, Euroseisrisk, Ismod : [5], [7]) and later in view of benchmarking exercises ([10], [11], [12], [13]). The basin is currently densely instrumented with surface accelerometers, as well as a vertical array with 6 sensors over 200 m depth at the central TST site, which are jointly maintained by ITSAK and AUTH. The corresponding recordings have been gathered and made available in a specific database [8].

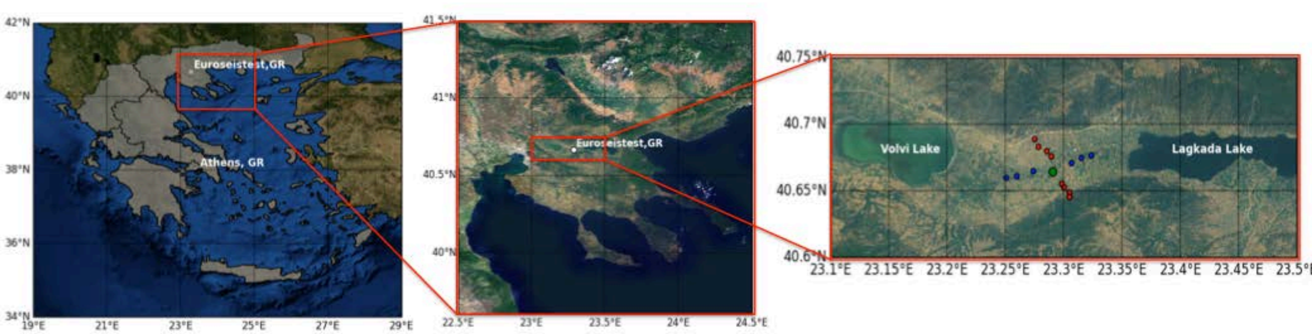

Fig. 1 – Location of the Euroseistest and the Mygdonian basin in North Eastern Greece.

The velocity model of the site has been published by several authors ([5], [7]), and was used to define 1D linear and nonlinear soil columns for the present comparison exercise. Degradation curves were also provided to characterize each soil layer [13], as well as instrumental amplification functions with respect to various rock sensors (surface or downhole), among other kinds of information that will be mentioned along this study and will support the robustness of our results.

The target sites considered here are the "TST0" and "TST196" stations, located in the very center of the graben (Fig. 2) at the surface and at the bottom, respectively.

2.1. Soil Site Characterization

To perform a site-specific hazard assessment, the geological, geophysical and geotechnical data at the site of interest need to be gathered. Previous studies at EUROSEISTEST provide a detailed soil profile, the geometry of the basin, the shear-wave velocity at the bedrock and at the surface, which allow to properly characterize the soil properties.

As shown in the shear-wave velocity profile in Fig. 2, the EUROSEISTEST basin is described by a soft soil at the top of the basin, with an average shear wave velocity in the first 30 m of 186 m/s and a large impedance contrast between sediments and bedrock since the latter has a shear wave velocity of 2600 m/s. This high velocity contrast makes this particular location a very good example of significant site-specific effects, and one of the reasons why it was selected to be instrumented besides its relatively active seismicity.

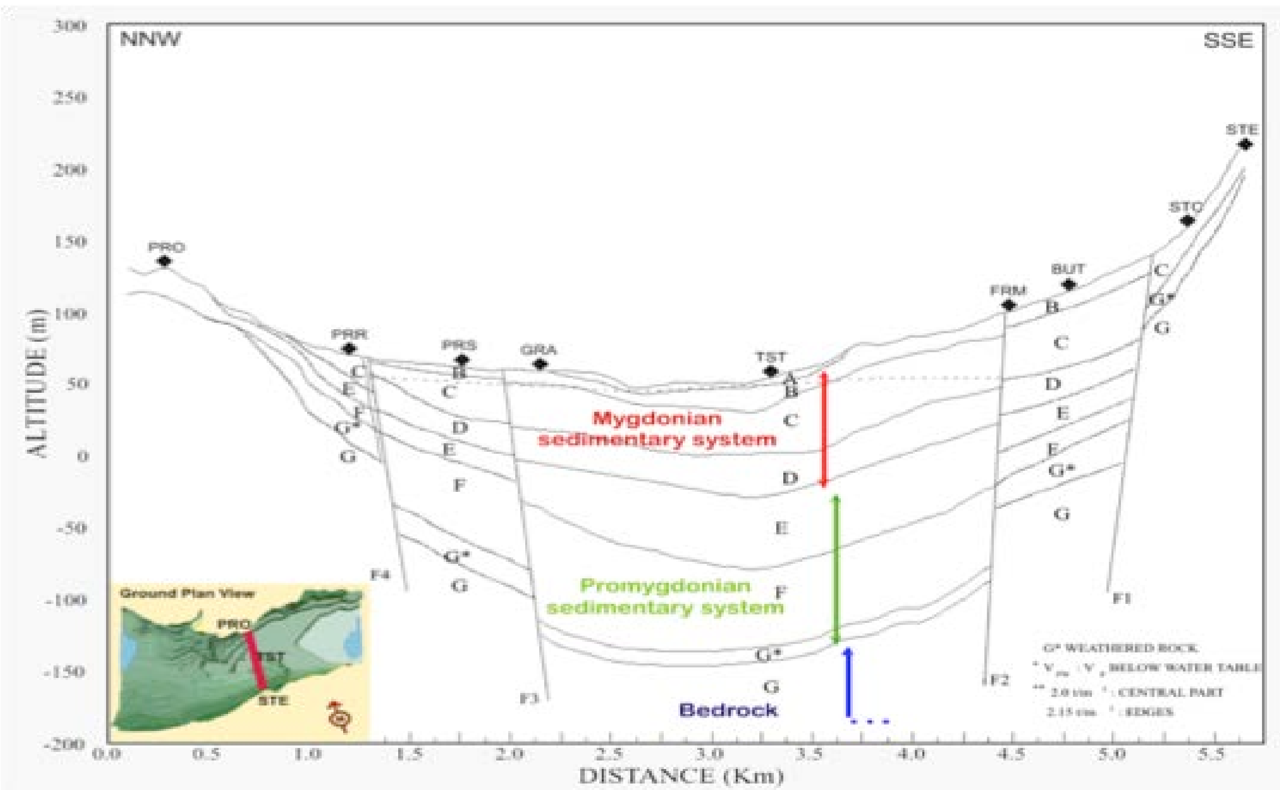

Fig. 2 –2D N-S soil model [10]. Line F1 coincides with the seismogenic fault of the 1978, M6.5 earthquake.

Several studies performed at the Euroseistest, both instrumental and numerical, have shown a fundamental frequency f_0 of the TST site around 0.6 - 0.7 Hz ([6], [7], [10], [11], [12]). The harmonic average shear wave velocity over the top z meters indicated in Table 1 are derived from the velocity profile provided in Fig. 2 right. With these parameters, the 1D simulations predict a fundamental frequency similar to what is actually measured.

Table 1 –Euroseistest average shear wave velocity up to top z meters and its fundamental frequency.

$V_{S,5}$ (m/s)	$V_{S,10}$ (m/s)	$V_{S,20}$ (m/s)	$V_{S,30}$ (m/s)	f_0 (Hz)
144	153	170	186	0.6 - 0.7

3. Overview of the used methods

This section presents a short outline of the various approaches that are used here to account for site effects in a probabilistic assessment framework, with an increasing level of detail and complexity : They are therefore labeled from level 0 to level 2, also including some sub-classification as described below. A more extensive description of these methodologies can be found in Aristizábal et al. 2016 [14].

3.1 Generic or partially site-specific approaches

These methods consider site effects in an average and approximate way through one or several site proxies, and are based on simplified approaches.

3.1.1 Level 0 - Site effect by proxy in GMPEs

The simplest (and widely used) approach consists in assuming that the actual amplification at the site of interest can be approximated by the site terms of the GMPEs used for the hazard estimation. In other words, the site response is assumed to be correctly captured by the average site amplification of all the stations of the GMPE strong motion database exhibiting similar values of the site proxy. Therefore, the hazard spectra (deterministic or probabilistic) estimated with these GMPEs with the corresponding value of the site proxy, already account, in a simplified and generic way, for site effects through an "averaged" site factor. It should be noted that this approach ignores virtually almost all the site-specific information (except for the value of the considered site-proxy). It therefore produces only a relatively imprecise, generic assessment of the hazard corresponding to a global average over many sites with similar values of the site proxy, and is associated to a relatively large site-to-site variability.

The most common proxies used to describe site conditions in GMPES are the shear wave velocity of the top 30 meters (V_{S30}, by far the most frequent), the fundamental frequency f_0 (very rarely used as a continuous parameter), the site class (based on V_{S30} and/or f_0 ranges), and the depth at which the shear wave velocity first exceeds a given threshold, for instance 1.0 km/sec or 2.5 km/s ($Z_{1.0}$ and $Z_{2.5}$, respectively). Some GMPEs use a combination of two proxies (e.g., V_{S30} and $Z_{1.0}$) in view of capturing different characteristics of the site amplification. The depth proxies ($Z_{1.0}$, $Z_{2.5}$) are usually not considered as single site proxy in a GMPE, but they are used complementarily with V_{S30} in order to account for the site amplification due to deep sediments in general – also improperly called "basin effects".

In the present example case study, we used one single GMPE, Akkar et al. 2014 [15]. The site proxy used in this GMPE is V_{S30} (with a value of 186 m/s at station TST_0).

3.1.2 Level 0.5 – a posteriori modification of the site term using a "SAPE"

This approach requires a further methodological step with respect to the previous one (Level 0). It is assumed that the simple site amplification from the GMPEs is a first-order model for the target site response, but that some site-specificity can be included in order to provide a better description of the site response. A correction factor can be developed and applied, as a post-processing to the hazard spectrum. In other words, the idea is to separate the site term, to be handled through specific "SAPEs" (Site Amplification Prediction Equations), and use the GMPEs only to estimate the hazard on rock. This allows to take into account some additional site information, and in principle, in the long run, could allow to account for effects of the surface or subsurface geometry (topography or basin effects), or non-linear effects, in a more physical, though still simplified way than what is proposed even in the most recent (and increasingly complex…) GMPEs.

The term "site amplification prediction equation" (SAPE) was first introduced in Cadet et al. (2011a,b) ([16], [17]), and this particular example follows the approach proposed in their work. Amplification factors with respect to a standard rock were computed for a large number of KiK-net sites and correlated with site parameters to define as "stand-alone" site terms. Several proxies were considered (travel-time average S-wave velocities over the top z meters, V_{SZ}, with z from 5 to 30 m, fundamental frequency f_0) both individually and by pairs, i.e. considering the (f_0, V_{SZ}) couples [actually, the correlation between amplification factors and V_{SZ} was performed in the dimensionless frequency (f/f_0) domain]. The best performance in predicting site amplification was obtained by the twin parameters (V_{S30} - f_0), while the best single parameter proved to be f_0, in agreement with other studies (Luzi et al., 2011) [18].

The application of this approach requires the knowledge of the f_0 and V_{SZ} of the site in order to derive the amplification function. The "standard rock" hazard spectrum is then multiplied by this amplification function "SAPE" according to Eq. (1), where the various subscripts of "SAPE" correspond to the different expression SAPEs that. Care must be taken when combining the hazard spectrum and the amplification function in order not to double count the site effect in both GMPEs and SAPE.

$$UHS_{soil} = UHS_{(800\,m/s)} \cdot SAPE_{(f_0),\ (V_{S5},f_0),\ (V_{S10},f_0),\ (V_{S20},f_0),\ (V_{30},f_0)} \qquad (1)$$

3.2 Site-specific approaches

The "site-specific" term means that the actual site amplification is considered on the basis of more refined, instrumental or numerical analysis, based on a much more detailed description of the site conditions (velocity profile, NL parameters, 2D or 3D underground structure, ...). This allows to reduce the aleatory uncertainty on the GMPEs, through the use of "single-site sigma" values, since there is no longer the "site-to-site" variability component for all sites having the same proxy value (say, V_{S30} value). Two main levels of complexity have been introduced in [14], depending on whether the site response is considered linear (i.e., independent of the rock hazard level: Level 1), or non-linear (Level 2).

In addition to a detailed site characterization, these approaches (Levels 1 and Level 2) also need, most often, host-to-target (HTT) adjustments, since the actual reference rock with respect to which the site amplification is estimated, can only very rarely be assimilated to the “standard rock” used for standard PSHA estimates. Very often, the bedrock velocity is much larger than the standard value of 800 m/s, and presently existing GMPEs cannot predict the motion for much harder bedrock (i.e., with velocities from 1.5 to 3.5 km/s). There exists however, even in the case of a very hard bedrock, a fully instrumental way to avoid HTT adjustment, which requires careful site monitoring and data analysis (Level 1a presented below).

3.2.1 Level 1a – Using site specific residual (δS2s,s from GMPEs)

When a large enough number of ground motion recordings are available at the site of interest, S, it is possible to estimate more precisely the site–specific effects by analysing the site-specific residuals, classically characterized by their average value δ_{S2Ss}, and standard deviation $\phi_{ss,s}$, with respect to the various GMPEs used for the PSHA estimates. Such a site-specific bias (δ_{S2Ss},) may then be used to correct the GMPE predictions for the site under consideration.

As mentioned above, the specificity of the site term allows to replace the total within-event residual standard deviation (ϕ) of the GMPE by the single-station within-event variability $\phi_{ss,s}$ of the site. It is important however to notice that not all the GMPEs have their standard deviation separated into between-event and within-event components. Therefore, some of them cannot be used for this approach unless a separation of its standard deviation is previously done.

To implement this approach in the present case, we used the work by Ktenidou et al. (2015) [19] to estimate the site specific residuals in the basin (both TST_0 and TST_{196} station), and followed the methodologies proposed by Rodriguez-Marek et al. (2013, 2014)) [20][21] and Al Atik et al. (2010 [22] for the partially non-ergodic PSHA.

3.2.2 Level 1b - Site response analysis with instrumental linear amplification function

The site-specific amplification can be estimated in a purely empirical way on the basis of a dedicated instrumentation. Many site response studies have been performed at the site, since the EUROSEISTEST has been instrumented in 1993. Strong motions recorded by the permanent network are available online (http://euroseisdb.civil.auth.gr) for visualization and/or downloading through the "Database Search" page ([8]).

Two types of (linear) instrumental site response analysis have been obtained with this approach:

- Standard spectral ratios based on the accelerometric data set recorded on the Euroseistest array (e.g. Raptakis et al. 1998) [23].

- Amplification function calculated using the *δS2S* approach (Ktenidou et al. 2015) [19].

These instrumental results provide the site amplification with respect to a reference site, which may be either a "standard rock" or a "hard-rock", and where the motion may be either "outcropping motion" or "within motion". One important issue is therefore to correctly estimate the hazard at the corresponding reference site.

- The simplest case is when the reference site is an outcropping standard rock: this is the case when the amplification function is either provided by the GMPE site-specific residual *δS2S* (in the present case $\delta S2S_{TST0}$ with respect to the Akkar et al. 2014 [15] GMPE), or measured by the SSR technique (site-to-reference spectral ratio) with respect to an outcropping, standard rock, as done in [23] where the reference site is the northern rock site (PRO). In such cases, the only requirement for the rock hazard is to estimate it with the classical PSHA procedure with reduced aleatory uncertainty (single-site sigma).
- A more complex correction, the "host-to-target" adjustment, is required when the reference site is a very hard rock. As most existing GMPEs – including the one used here [15] - can be applied only for V_{S30} values in the range [100, 1000 m/s] at most, a specific procedure must be applied to estimate the hard rock motion. This is the case here when the reference site is the TST_{196} sensor, for which the S-wave velocity is about 2600 m/s. We thus used here the Vs-kappa correction procedure detailed in [24]; there is not enough space here to delve into this rather complex and time-consuming methodology; a broader explanation can be found in [14]. This correction significantly impacts the hazard estimates, as shown in the results section.
- Finally, in the present case, another correction has to be introduced since the reference site TST_{196} is located at depth, and the recorded motion is not outcropping motion but within motion. Two alternative correction procedures were considered here. The first one uses the "depth correction factors" (DCF hereafter) proposed in [16] on the basis of KiK-net down-hole recordings, and the second one simply uses the site specific residual $\delta S2S_{TST196}$, which automatically includes both the hard-rock correction, and the within motion correction.

The uniform hazard spectrum at soil surface can then be obtained by convolving the uniform hazard spectra on rock (corrected if needed as mentioned for the two latter cases), and the linear amplification function (e.g. SSR or *δS2S* based).

3.2.3 Level 1c – Site response analysis with numerical linear amplification function

The amplification function can be also estimated numerically, the main difference with respect to the previous approach (Level 1b) is the way the amplification functions from rock to soil are calculated. In the previous case, the amplification function was derived using instrumental data, while in this case it has been calculated numerically. For this example case study, we only considered the 1D response, but the same approach could be used with 2D or 3D simulation codes (as done in [10], [11], [12] for instance). The linear 1D response has been computed here with the linear part of the NOAH code (Nonlinear Anelastic Hysteretic finite difference code – Bonilla 2000 [25]) and with the velocity profile indicated in Fig. 2. The corrections to be applied for the hazard at the reference hard rock site are the same as in the previous case (Level 1b)

3.2.4 Level 2a – Site response analysis with numerical nonlinear amplification function

Similarly to the linear transfer function obtained in Level 1c, a non-linear response can be calculated using the same soil profile and a set of strong motion accelerograms selected to fit the target (corrected) uniform hazard spectra at the reference rock, in this case, the 5000 years return period at TST_{196} station. The non-linear parameters for the whole column have to be been defined in the NOAH code through the strength profile, characterized by the friction angle ϕ and cohesion values: the latter were derived from the known G/Gmax degradation curves. The non-linear site response has been computed with respect outcropping hard rock conditions, so that the only correction required for reference hazard is the host-to-target adjustment. More details on the NL computations can be found in [14].

As the site response is in this case dependent on the input motion, the surface spectra resulting from the uniform hazard spectrum at the reference site and the NL-site response computations can no longer be considered to represent the uniform hazard spectra for soil site, while it was so for the linear response case. This terminology with however be kept in the following, for sake of simplicity.

4. Results

An overview of the results obtained at Euroseistest site with the different methods is presented in this section. The Uniform Hazard Spectra (UHS) on soil obtained from generic or partially site-specific approaches (Level 0 and 0.5) are shown, as well as for the site-specific approaches (Level 1a, 1b, 1c and 2a). Some specific comparisons are detailed in Fig. 3 through Fig. 5. For an easier understanding. Fig. 3 presents results obtained at levels 0 and 0.5, Fig. 4 displays results at Levels 1 and 2, and Fig. 5 compares all spectra, for the reference rock (left) and for TST_0 soft soil site (right).

The first comparison plot displayed in Fig. 3 focuses on the Level 0 and Level 0.5 "generic" approaches, the only ones where full aleatory variability is considered for the derivation of rock and/or soil UHS. Level 0.5 considers a SAPE accounting for both f_0 and V_{S30} proxies at TST_0, which leads to a significantly larger hazard than the one predicted by Akkar et al. (2014) [15] using V_{S30} as a proxy (Level 0). These differences are especially large around the fundamental frequency f_0. The reason for this higher estimate is two-fold: a) the absence of nonlinear behavior in the considered SAPE, while the GMPE in [15] does take it into account (this is the main reason for the short period differences); b) low values of f_0 and V_{S30} proxies lead to larger (linear) amplification than simply low V_{S30} (this explains the differences at long period, where nonlinear effects are not expected to be significant).

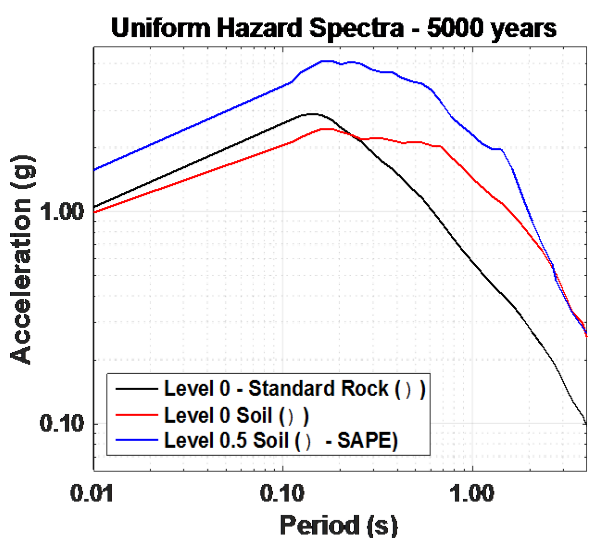

Fig. 3 – **Left:** Akkar et al. 2014 Uniform Hazard Spectrum for 5000 years return period. Generic or partially site specific Approaches. Level 0 – Standard Rock (ϕ) (black), Level 0 – Soil (ϕ) (red), Level 0.5 - Soil ($\phi, SAPE$) (blue).

Before commenting the results obtained at levels 1 and 2, it is very instructive to compare the corresponding rock spectra (Fig. 5 left) obtained with different values of the within-event variability (full or single-station sigma), with or without host-to-target adjustments (standard rock or hard rock/less attenuating rock), with or without depth correction factors (outcropping motion at surface or within motion at depth). At short period, a large hazard reduction (close to a factor of 2) is noticeable: it is associated with the reduction of the within-event variability ("single-site-sigma" effect – Level 1a standard rock) and to the "within" motion effect (to be used only when the site-specific amplification is measured or computed with respect to the motion at depth). For this example, at short periods, the impact of the “within” effect (very hard rock) implies larger reduction effect than the single station sigma effect.

On the other hand, at long periods (say, $T \geq 1$ s), the hazard reduction due to both corrections has smaller impact than at short periods. This time, inversely to the short period case, the within-event variability effect has more impact than the within motion effect, which however is not small enough to be neglected.

It is also worth mentioning that the host-to-target adjustments have only limited effects despite the high shear wave velocity at depth, this, mainly because of the κ correction, which "boosts" the short periods. There are some indications that this peculiar effect is deeply correlated with the current "V_{S30} - κ" host-to-target approach and the underlying assumptions (stochastic modeling with Vs effects accounted through impedance effects only, possible bias in κ measurements). Other approaches using GMPEs specifically established for hard-rock sites

(Laurendeau et al, 2015)[26], would lead to larger reductions than the exposed cases, in particular at short periods, suggesting that the presently used host-to-target adjustment techniques are likely to be significantly conservative.

Results obtained with site-specific estimates of the site linear response (Level 1), together with the corresponding reference rock spectra (single site sigma estimates, with or without host-to-target adjustments, outcropping or within motion), are all displayed in Fig. 4 (Left).

The variability of the soil results, is somehow limited in the short period range (around a factor of 2), but is larger (up to factor of 4) at intermediate and long periods, especially close to the site fundamental period (1.5 s). The origin of this intermediate to long period variability is two-fold: a) The way the reference motion is defined (with or without host-to-target outcropping or within) and b) The way the linear site amplification was estimated: numerical or instrumental. One should also keep in mind that some variability is associated to instrumental or numerical estimates (mainly aleatory in the first case, and mainly epistemic in the second). For this study, this uncertainty was not taken into account, but the literature shows it corresponds at least to a factor ± 50%.

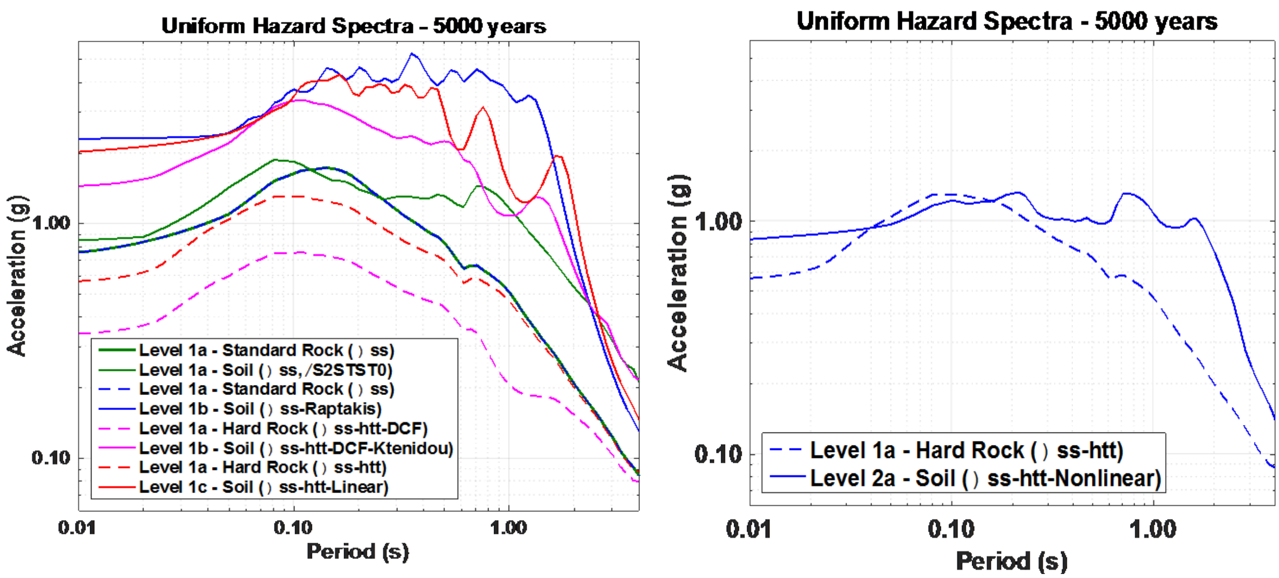

Fig. 4 **:** Uniform Hazard Spectrum for 5000 years return period at TST_0 and for the corresponding reference rock for Level 1 (Left) and Level 2 (right), site-specific approaches. Level 1a – Standard Rock (ϕ_{ss}) (dark green dashed), Level 1a – Soil ($\phi_{ss}, \delta S2S\ TST_0$) (dark green continuous), Level 1a – Standard Rock (ϕ_{ss}): (blue dashed), Level 1b – Soil ($\phi_{ss}, Raptakis$): (blue continuous), Level 1a – Hard Rock (ϕ_{ss}, htt, DCF) (magenta dashed), Level 1b – Soil ($\phi ss, htt, DCF, Ktenidou$) (magenta continuous), Level 1a – Hard Rock (ϕ_{ss}, htt): (red dashed), Level 1c – Soil ($\phi_{ss}, htt, Linear\ NOAH$): (red continuous). Level 2: Level 1a –Level 2ª - Soil (ϕss,htt,Nonlinear) (blue continuous). The corresponding rock spectrum is the same as for level 1a (ϕss,htt), (blue dashed).

The results of Level 2 approach (non-linear site response) displayed on Fig. 4 (Right) and Fig. 5 as well, exhibit significantly lower surface spectra than the linear cases, especially at short periods. This reduction is typically the effect of non-linear site response. However, as repeatedly shown in the benchmarking exercises of recent years (e.g., [27], [28], [29]), numerical estimates of non-linear site response are associated with a significant amount of epistemic uncertainty, which increases with the input motion level.

Fig. 5 compares all the results (Levels 0, 1 and 2) in terms of reference rock (left) and soil surface (right) spectra. Even without taking into account the aleatory or epistemic variability associated with the estimation of site-specific response, the overall variability of the site spectra reaches extreme values around 3 at short periods (pga values from 0.8 to 2.4 g), 4 to 5 at intermediate periods, and decreases to a factor of 2 at long periods. In the present case where a rather thick and soft soil deposit is considered, linear site-specific response estimates exhibit larger values than the standard level 0 approaches, despite the consideration of single-site sigma that significantly lowers the rock hazard estimates.

The site amplification is significantly larger than the average accounted in the Akkar et al. 2014 GMPE (Level 0), using V_{S30} as generic proxy. Only the joint consideration of single-site sigma and non-linear site response (Level 2a) and the case where single-site sigma and the $\delta S2S$ approach (Level 1a), leads to a reduced hazard. However, this result showing a reduction of the hazard due to nonlinear effects should not be generalized to all possible real situations, since the present example corresponds to a rather high seismicity area, and thick and soft soils, with a prominent reduction effect of non-linear soil behavior.

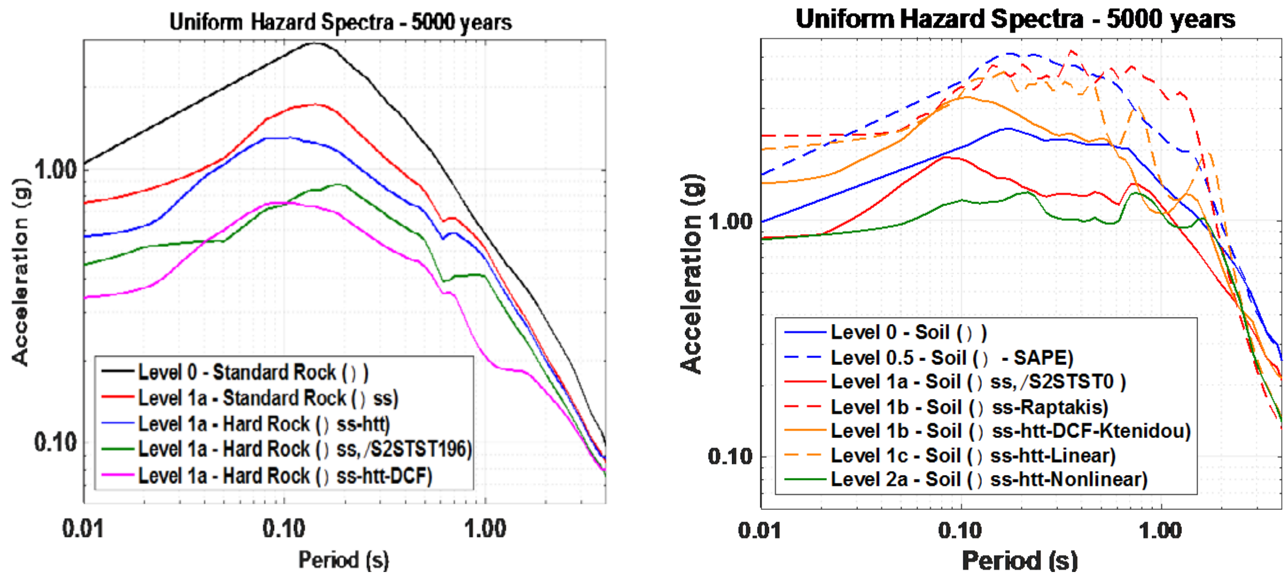

Fig. 5 – Overview of UHS for reference rock (left) and site surface (right) for a 5000 years return period. **Left : Rock hazard** Level 0 – Standard Rock (ϕ) (black), Level 1a – Rock (ϕ_{ss}) (red), Level 1a – Hard Rock (ϕ_{ss}, htt), (blue), Level 1a – Hard Rock ($\phi_{ss}, \delta S2S\, TST\_196$), (dark green), Level 1a – Hard Rock (ϕ_{ss}, htt, DCF), (magenta). **Right : Soil Hazard** Level 0 – Soil (ϕ), (blue), Level 0.5 - Soil ($\phi, SAPE$), (blue dashed), Level 1a – Soil ($\phi_{ss}, \delta_{S2S}\, TST_0$), (red), Level 1b – Soil ($\phi_{ss}, Raptakis$), (red dashed), Level 1b – Soil ($\phi ss, htt, DCF, Ktenidou$), (yellow), Level 1c – Soil ($\phi_{ss}, htt, Linear$), (yellow dashed), Level 2a – Soil ($\phi_{ss}, htt, nonlinear$), (dark green.

5. Conclusions

Site-specific hazard calculations aim to provide improved hazard estimates at well-characterized sites. Several authors have shown that nonlinearities in site response and the associated uncertainties are important in estimating site-specific hazard ([30], [31]). However, classical PSHA does not capture properly these phenomena, and only the most recent ground-motion prediction equations (such as the NGA-West2) are able to take into account nonlinear behavior, though in a very generic and approximate way.

Several approaches are possible to merge site-specific estimates of site response and rock hazard, corresponding to different sophistication levels and different kinds of epistemic uncertainties. The aim was to illustrate the application of the various methods at one site, discuss the associated issues, and to compare their results, in order to better appreciate the gains against the required costs and efforts when performing this type of analysis. There are certainly numerous limitations in this single example of application, which prevent from drawing too general conclusions and recommendations (see Aristizábal et al. 2016). However, several relatively robust conclusions can be drawn from the panel of results obtained at the EUROSEISTEST.

One of the characteristics of the selected example site is the existence of a large amplification over a broad frequency range, due to a combination of several factors (the large velocity contrast at depth, the low velocity at surface, and the graben structure leading to additional "valley effects"), which leads to a site amplification significantly larger than the generic, average amplification accounted for in GMPEs. Basically, site-specific hazard estimates are thus larger than "generic" Level 0 estimates for low acceleration levels / short return periods, and lower at long return periods / large acceleration levels because of the impact of nonlinear effects in thick, soft sediments.

With respect to Level 0, when the panel of selected GMPEs includes both linear and non-linear site terms, the epistemic variability of Level 0 hazard estimates on soil sites is significantly larger than the corresponding estimates on rock site. One may also highlight that recent GMPEs have very complex functional forms, and it is safer to use already written and validated implementations such as the Openquake engine.

Concerning Level 0.5, it has been found for Euroseistest that: a) The twin accounting for V_{S30} and f_0 leads to higher amplification compared to the site term in the GMPEs, even when only the linear part of the site term is considered in the latter. This increased amplification is more consistent with the actual observations and measurements for the considered site, for the reasons already mentioned above. b) The limitation of the considered SAPE to the linear domain leads to an overestimation of the site response for high rock hazard levels: critical infrastructures should be designed for large return periods (i.e., 5000 years or more), leading to ground motion levels where nonlinearity is expected. For this reason, further research on developing SAPE, including nonlinear effects is encouraged according to what is suggested in [32].

Site-specific approaches (Levels 1 and 2) present the major advantage of allowing a reduction of the within-event variability, which leads, at long return periods at the Euroseistest, to a significantly reduced rock hazard. However, it should be very clearly stated that performing a site-specific hazard analysis does not necessarily imply a reduction of the hazard but only of the aleatory uncertainty. The site response may indeed be significantly different, and thus in some cases larger, than the "average", "generic" effects accounted for in a very simplified and crude way in GMPEs.

In addition, if the site-specific knowledge is severely limited, use of single-station sigma should be accompanied with the accounting for a significant epistemic uncertainty ([24], which may partly or totally compensate for the reduction of the aleatory variability.

The linear response analysis corresponding to Level 0.5 (ϕ, SAPE), Level 1a (ϕ_{SS},$\delta S2S$ TST_0), Level 1b (ϕ_{SS}, Raptakis), Level 1b (ϕ_{SS}, htt, Linear NOAH)) lead to spectras significantly higher than the Level 0 (ϕ, Vs_{30}) for this particular example. This illustrates the huge impact of soil non-linearity (included in the AA14 GMPE) compared to linear response, and therefore the practical interest to include soil non-linearity in hazard estimates. However, this should be done very carefully, with the use of several independent GMPEs, or with dedicated SAPEs, to be sure that the linear part of the site response is not severely underestimated (as it is the case for Euroseistest).

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7. Copyrights

8. References

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