PHYSICS-BASED SITE-AMPLIFICATION PREDICTION EQUATIONS: A DREAM AT REACH ?

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ABSTRACT

Previous ESG blind tests and symposia, together with the advances in computation capabilities, allowed to significantly improve the reliability of numerical simulation for site response estimates. In parallel, the considerable progress in instrumentation has made available numerous high quality data sets, which allowed impressive developments in empirical ground motion prediction tools (GMPEs). Yet a number of important site amplification components are not, or incompletely, accounted for in such GMPEs, because of too poor site metadata or missing recordings, given the complexity of site amplification physics. One might dream that present-day numerical simulation tools, large data sets, and machine learning could be merged to establish more physics-based, statistically meaningful site terms providing a better (i.e., more accurate and less scattered) prediction of site amplification. This paper aims at discussing the maturity of such dreams for different components of site amplification, i.e., 1D linear site response, non-linear modifications, effects associated with surface topography, and aggravation factors in valleys and basins.

Keywords: Site response – proxies – non-linearity – aggravation factor – surface topography – machine learning – Ground motion prediction equations

INTRODUCTION

In line with the initial incentive in the late 80's, one of the peculiarities of ESG1-6 symposia has been to emphasize the benchmarking of both State-of-the-Art and State-of-Practice scientific and engineering methods and tools to blindly predict the actual ground motion in a variety of real, or at least realistic, cases, with a focus on site amplification issues. Up to now, i.e., despite 30 years of impressive improvements in the performance of simulation tools, ground motion data acquisition and field survey techniques, there still exist a large epistemic uncertainty in blind site response prediction, even for sites with well-known underground structure. The E2VP benchmark focusing on 3D, linear effects (Maufroy et al., 2015, 2016, 2017) indicated a prediction-to-prediction variability generally ranging between 10 and 25% after iteration, and a prediction-to-observation distance ranging from 40 to 100% including source uncertainties, but reduced to 20-30% when only site response is considered. The PRENOLIN benchmark comparing various 1D, non-linear site response concluded at numbers spanning a wide range (30 - 100 %) for the code-to-code variability under strong shaking (0.5 g), and 60-120% for the prediction-to-observations distance (Régnier et al., 2016b, 2018). Despite these limitations, numerical simulation is extremely precious in providing in-depth information on the physics details and on the sensitivity to the relevant parameters.

In parallel, ground motion prediction equations underwent considerable developments over the last decades. They are now based on much larger strong (and weak) motion data sets (including sometimes simulation results for filling some data gaps): for instance the Kotha et al., 2020 European GMPE has been trained on the ESM2018 data set with 18222 recordings, while the previous version (Kotha et al., 2016) used the RESORCE 2014 one consisting of only 1251 recordings (Akkar et al., 2014a). Beside a trend for more and more complex functional forms, there are also trends for either using artificial intelligence (AI) tools leading to highly complex mathematical expressions without any direct physical meaning (although the retrieved trends are completely data-driven and do exhibit the physics of ground motion), or for simple functional forms for fix ed effects and more and more random effects terms (Kotha et al., 2020). Whatever the increasing complexity, the corresponding site terms remain usually based on only few (one or two at most) site proxies (V_{S30} and Z_{VREF} or f_0), and are thus able to capture only a limited part of the multifold physics of site effects. They essentially focus on impedance-related amplification, with some (limited) non-linear modulation, but let aside resonant-type effects, and neglect all effects related to surface or subsurface geometry. Moreover, as mentioned by several authors (e.g., Kotha et al., 2016; Loviknes et al., 2021) and as for all Generalized Inversion techniques, there exist a possibility of trade-off between the various GMPE components (source, path, site) on one side, and of a regional dependence of the sensitivity of site amplification to too simple proxies such as V_{S30} on the other: For instance, the dependence on V_{S30} may not be the same for deep deposits of the Los Angeles basin, the Mississipi embayment, the Kanto area, Italian intra mountain basins or alpine valleys. As a consequence, no site term of any existing GMPE can be considered as intrinsic, nor be exported to another GMPE without any adaptation.

The dream would therefore be to merge a sound physical description of the site term, as provided by numerical simulation or by very specific data sets obtained in test-sites and dedicated to particular components of site amplification, and the classical GMPE approach, which offers the "comfort" of simplicity, provided the site proxies used for the prediction of the various components of site effects are available. This concept may be summarized by the following equation:

$$ln(GMIM) = f_{rock}(M, R) + SAPE(site\ proxies;\ GM_{rock}) \tag{1}$$

where GMIM is the ground intensity measure to be predicted at the site, f_{rock}(M, R) stands for the prediction of the same GMIM on "standard rock" on the basis of magnitude M and distance R (only generic notations are used here, corresponding to all the specific magnitude and distance metrics used in present GMPEs). SAPE stands for "Site Amplification Prediction Equation", which should be "universal", i.e., only physics-based and region independent, so as to offer the possibility to be added to any rock GMPE (the latter can definitely have a strong regional dependence to optimally characterize the regional source and crustal propagation features). The explanatory variables of such SAPEs may be any site condition proxy (e.g. V_{S30} or f_0 or Z_1 or frequency scaled curvature or basin thickness/width shape ratio) considered as relevant for one particular component of site term, and also some ground motion parameter on rock (GM_{rock}) to be used for the scaling of non-linear site response.

Such SAPEs do not exist yet, except for the classical site term, which cannot be considered as fully "physics-based" and thus exportable from one region to another. The present paper is simply intended first to present shortly the concept of such an approach, how it fits in the present landscape of ground motion prediction, and then how those "SAPEs" could be derived for various components of site response. Four such components are successively considered: 1D linear site response, non-linear behavior, surface topography and underground geometry (valleys or basins). For each of them, a short overview of the present state-of-knowledge is provided together with a discussion on the corresponding proxies, the kind of data or simulation that are needed to reach satisfactorily constraints on the corresponding relationship between site proxies and amplification components, and the resulting maturity level of such an approach. The possibility of coupling and feedback between these different terms is also shortly discussed. The paper ends with some comments on the corollaries of this "SAPE" approach, such as the need to associate much richer site metadata to ground motion databases, and the need to complement them with easily accessible repositories for accumulating results of comprehensive simulations in a standardized way.

BASIC CONCEPT AND SITE TERM COMPONENTS

The trend in recent GMPEs is to derive the site-term as proposed in Kotha et al. (2020). With the increasing sensitivity of strong motion sensors and/or the incorporation in ground motion databases of recordings from broad-band sensors, more and more recordings are available from each single station and for each single event as well, so that it it becomes possible to obtain both a site specific residual $\delta S2S_s$ (and an event specific residual δB_e) according to the following generic equations:

$$ln\,(GMIM_{es}) \;=\; ln\,(GMIM_{rock,fixed}) \;+\; \dots \;+\; \delta B_e \;+ \delta S2S_s \;+\; \dots + \varepsilon_0 \tag{2}$$

$$ln\,(GMIM_{rock,fixed}) \;=\; a_1 \;+\; f_M(M) \;+\; f_{R,g}\,(M,R) \;\;+\; f_{R,a}\,(R) \tag{3}$$

where $GMIM_{es}$ is one ground motion intensity measure for event e and site s, expressed as the sum on one "fixed effect" term corresponding to the deterministic prediction of "average" rock motion $GMIM_{rock,fixed}$ taking into account the magnitude scaling $f_M(M)$, the magnitude and distance dependent geometrical spreading $f_{R,g}\,(M,R)$, and the anelastic attenuation $f_{R,\mathrm{a}}\,(R)$. The functional forms of these terms – which vary from one GMPE to another - are established from an a priori grasp of the physics of source and crustal path effects, but their coefficients are tuned to the data set under consideration. The other terms are "random-effects" terms, which include at least an event term δB_e and a site term $\delta S2S_s$, estimated from the residuals with respect to the fixed effect dependence. Some authors (e.g., Kotha et al., 2020) also include some other random effects, related to regional "stress" or attenuation peculiarities.

As far as site terms are concerned, the next step is to establish the relationship between the site residual $\delta S2S_s$ and the site proxies considered as relevant. The present practice is most often to consider only those which are available in the strong motion databases, i.e., most often V_{S30} and Z_{VREF}, which may be either measured or inferred. These relationships are generally expressed as follows:

$$\delta S2S_s \;=\; F_{lin}(V_{S30}, Z_{VREF}) \;+ F_{NL}(V_{S30}, GM_{rock}) +\; \varphi_{S2S} \tag{4}$$

$$F_{lin}(V_{S30}, Z_{VREF}) \;=\; \alpha_0 +\; \alpha_1\,ln\,\frac{V_{S30}}{V_{REF}} \;+\; \alpha_2\,(ln\,\frac{V_{S30}}{V_{REF}})^2 \;\;+\; g(Z_{VREF}) \tag{5}$$

$$F_{NL}(V_{S30}, GM_{rock}) \;=\; h_1(V_{S30}) \times\; h_2(GM_{rock}) \tag{6}$$

where F_{lin} is a linear term generally increasing with decreasing stiffness (V_{S30}) and increasing thickness (Z_{VREF}), while F_{NL} corresponds to the modifications linked to the non-linear site response. It is most often a reduction coefficient (thus negative), the absolute value of which is increasing with decreasing V_{S30} and increasing reference rock motion GM_{rock}. The functional forms for h_1 and h_2 vary from on GMPE to another; they generally involve some pivotal values for V_{S30} (beyond which NL effects are considered negligible), and GM_{rock} (below which NL effects are also considered negligible), and involve several coefficients which are tuned either from data, or from numerical, 1D site response simulations (Waling et al., 2008; Kamai et al., 2014; Seyhan & Stewart, 2014).

The basic idea here is to replace these expressions for the site $\delta S2S_s$ by other terms, accounting for a enlarged set of site condition proxies SCPs, and differentiating different site effect components which could be independently determined on the basis of either dedicated data sets, or dedicated sets of numerical simulations. The present paper addresses the possibilities of changing Equation (4) into equation (7):

$$\delta S2S_s = F_{1D,lin}(SCP_{1D}) + F_{NL}(SCP_{NL}, Loading_{NL}) + TAF(SCP_{topo}) + AGF(SCP_{v,b}) +\; \varphi'_{S2S} \tag{7}$$

in which the fist term corresponds to 1D, linear site amplification, the second one to non-linear modifications, the third one to amplification factor related to surface topography (often "topographic amplification factor"), and the fourth one to "aggravation factors" (AGF) due to the underground geometry in valleys and basins (which could be shallow or deep). In such a formulation, the core element is considered be the linear, 1D site response, while the three other terms are mainly "corrections" to this base effect. Each of these terms is related to a set of specific site condition proxies, denoted SCP_{1D}, SCP_{NL}, SCP_{topo}, and $SCP_{v,b}$, respectively. Some of these SCPs might be common to several components, some other may be very specific to one component. It is considered here, at least as a first approximation, that only the NL term should include a dependency on the loading level. In principle, with such a formulation, the standard deviation of φ'_{S2S} residuals should be lower than Φ_{S2S}.

The following sections detail each of these 4 terms in light of recent investigations involving either instrumental data or numerical simulation (or sometimes both), the corresponding proxies, and the associated functional forms or the way to derive them in case of complex, multivariate dependence. The chosen formulation implicitly implies an absence of coupling between the four different terms. Neglecting all possible coupling is certainly convenient in a preliminary step, but may not be always physically sound: these issues are also discussed in the following sections, especially regarding the decoupling of valley and NL terms, and the decoupling of surface topography and 1D or 2D-3D effects linked to subsurface heterogeneities.

1D LINEAR SITE TERMS

"Historical" site terms and proxies

The site terms were initially introduced in GMPEs as simple scalar correction coefficients modifying the ground motion depending on the site category (soil or rock, for instance). Such coefficients vary from one GMIM parameter to the other, and are therefore frequency dependent when considering the response spectra SA(f) at different frequencies. They were progressively improved to take into account continuous (rather than discrete) site descriptors, such as the harmonic average of S wave velocity over he top 30 meters, V_{S30} , introduced in the early nineties by Borcherdt (1992, 1994) and Boore et al. (1994), and a non-linear dependence on the level of reference rock motion. Given the limitation of V_{S30} to shallow velocity structure only, some GMPEs added the accounting of the depth Z_{VREF} at which the S-wave velocity exceeds a given threshold velocity V_{REF} (varying from one study to another, from 800 m/s to 2.5 km/s: Ancheta et al., 2014), while some others considered the fundamental site frequency f_0 or the "dominant" frequency f_d either for site classification (Zaré et al., 1996; Zhao et al 2006; Cadet et al., 2010) or as a additional, continuous site parameter (Cadet et al., 2012; Derras et al., 2017). Because of its early proposal, V_{S30} has been the first non-discrete site parameter to be included in strong motion databases for their subsequent use in GMPEs, and, even though some databases also now include the f_0 (or f_d) or Z_{VREF} information, it has become the dominant site proxy in almost all GMPEs. Nevertheless, one single scalar parameter cannot characterize alone the whole site response. For instance Bergamo et al. (2020) report that two sets of Swiss and Japanese sites within the same V_{S30} range but with significantly different depth-to-bedrock, exhibit different site amplification patterns. As the resonant behavior of a soil column is controlled by both the velocity and thickness of deposits, the consideration of V_{S30} only will merge sites with very different resonant frequencies, and therefore smooth and broaden the amplification peaks. Similarly, the consideration of the fundamental frequency only would merge together sites with very different impedance contrasts and therefore amplification levels, and result in average spectral amplification with large scatter.

Newly proposed site condition proxies and assessment of their respective performance

That is why efforts have been made to look for additional, complementary descriptors to optimally summarize the site geophysical and geotechnical structure with a few indicators which be both relevant for site response and rather easy to obtain (e.g., Castellaro et al., 2008; Luzi et al., 2011; Cadet et al., 2012; Zhu et al., 2020, see Cultrera etal., 2021 for a comprehensive list). Specific 1D simulations and borehole data can be used in that aim. A few recent studies compared the relative performances of various site proxies so proposed to predict the mainly 1D, linear site response. Boudghène-Stambouli et al. (2017) investigate the predictability of 1D linear amplification factors predicted for more than 800 real velocity profiles with various usual site proxies, Derras et al. (2017) analyze the performance of 4 different site proxies through the dependence of within-event variability of GMPEs obtained for a subset of KiK-net data, while Bergamo et al. (2020) extract the experimental site response from a large set of Swiss and Japanese recordings and compare the performance of a large number of proxies, including "vector quantities". Their respective results are summarized in Table 1. Only results addressing the performance of quantitative proxies direcly related to site response are considered here: performance of "indirect" parameters such as local slope or terrain-based site maps (see Yong et al 2012 or Yong 2016) is left aside as they are only "proxy to proxies" and usually lead to a much larger spread in predictions residuals.

Only the first of these studies is strictly related to 1D linear site response since the prediction targets are estimated with a 1D linear code. The two other are based on real recordings which might include, at some sites, some contribution from 2D or 3D effects, or from NL site response; however the core of those data correspond to only moderate motion, and the selection procedure amongst the whole set of KiKnet stations is likely to lower the proportion of significant 2D/3D effects.

Table 1: Overview of proxy performance investigations by Boudghène-Stambouli et al. (2017), Derras et al. (2017) and Bergamo et al. (2020)

Study	Boudghène-Stambouli et al. (2017)	Derras et al. (2017)	Bergamo et al. (2020)
Data	858 real velocity profiles	KiKnet subset 977 recordings, 199 sites	Swiss (84 sites) and KiK-net (276 sites) subsets
Prediction target	1D linear amplification factor (AF(f), short period average F_a, intermediate period average F_v, numerically derived)	Response spcctra SA(f)	Instrumental 1D Fourier transfer functions
Predictors (proxies)	V_{S30}, V_{SH}, f_0, H or Z_{800}, $V_{Sbedrock}$, $C_V = V_{Sbedrock}/V_{Smin}$	V_{S30}, f_{0HV}, Z_{800} (+ slope)	V_{S10}, V_{S20}, V_{S30}, Z_{800}, V_{SZ800}, C_V, C_{V10}, $V_S^{QWL}(f), I_C^{QWL}(f)$ f_{0HV}, A_{0HV}, H/V(f)
Prediction Method	NN (Radial Basis Function)	NN (Perceptron)	NN
Performance evaluation	Variance reduction with / without site proxies	Variance reduction with / without site proxies	Deviation from true value + single parameter correlation
Best single scalar proxy	Velocity contrast C_V	f > 1.5 Hz : V_{S30} f < 1.5 Hz : f_{0HV}	< 1.5 Hz : Z_{800} 1.5-5 Hz : V_{S30}, and / or f_{0HV} 5-10 Hz : C_{V10}
Best pair of scalar proxies	{C_V, f_{0HV}}	T < 0.3 s : {V_{S30}, Z_{800}} T > 0.3 s : {V_{S30}, f_{0HV}}	{V_{S30}, f_{0HV}} ?
Preferred set of scalar proxies	{V_{S30}, f_{0HV}}	(V_{S30}, f_{0HV}}	{V_{S10}, V_{S20}, V_{S30}, Z_{800}, C_{V10} , f_{0HV}}
Best vector proxy	-	-	$V_S^{QWL}(f)$
Preferred proxy set	{V_{S30}, f_{0HV}}	(V_{S30}, f_{0HV}}	$\{V_S^{QWL}(f),\ I_C^{QWL}(f)\}$

The two first studies consider only a limited set of proxies, related to the velocity profile (V_{S30}, Velocity contrast C_V between the deep bedrock velocity $V_{Sbedrock}$ and the layer with the minimum velocity V_{Smin}), the average velocities down to the deep bedrock V_{SH} or to the 800 m/s velocity horizon V_{SZ800}, together with the corresponding depths H and Z_{800}), or to the site fundamental frequency, derived directly from the velocity profile (f_0), or from the earthquake H/V ratios ($f_{0H/V}$). Bergamo et al. (2020) consider a much larger set of proxies, also related to the velocity profile, or t the H/V signature. They also consider a pair of specific vector proxies, the quarter wavelength velocity $V_S^{QWL}(f)$ and the corresponding impedance contrast $I_C^{QWL}(f)$: the first one is the travel-time averaged S-wave velocity V_{SZ} down to a depth z equal to one fourth of the corresponding wavelength, with a depth-frequency relationship given by $f = V_{SZ}(z) / 4z$; the second one is the corresponding velocity contrast at that depth. The determination of those vector proxies requires the availability of the whole velocity profile (or of broad-band dispersion curves), which is also required for a number of other scalar proxies such as H, Z_{800}, $V_{Sbedrock}$, C_V, C_{V10}. As expected, the best performance (Table 1 and Figure 1) is obtained with the richest description of site characteristics, i.e., the vector proxies, which is actually a very strong incentive to include the whole velocity profile in site metadata. Similarly, Boudghène-Stambouli et al. (2017) find the best single proxy performance for the velocity contrast parameter C_v, as it partly controls the amplification level. Nevertheless, obtaining reliable estimates of this series of parameters involving the whole velocity profile has a significant cost, especially for thick deposits, even when using non-invasive techniques. It is therefore also useful to check the performance of other simpler, scalar parameters such as V_{S10}, V_{S20}, V_{S30} or f_0 / f_{0HV}, because of their attractive availability easiness from shallow active or passive seismics, or single point noise measurements.

The correlation coefficients displayed in Figure 1 indicate the rather satisfactory performance of shallow velocity values, especially for Swiss data, and of the fundamental frequency for the Japanese data. When considering pairs of scalar proxies, all studies indicate a) improved performances with respect to one single proxy, and b) the satisfactory performance of the pair (V_{S30}, f_0), which carry information on both the shallow stiffness – likely to be related to amplification – and a combination of the average stiffness and thickness of resonating deposits.

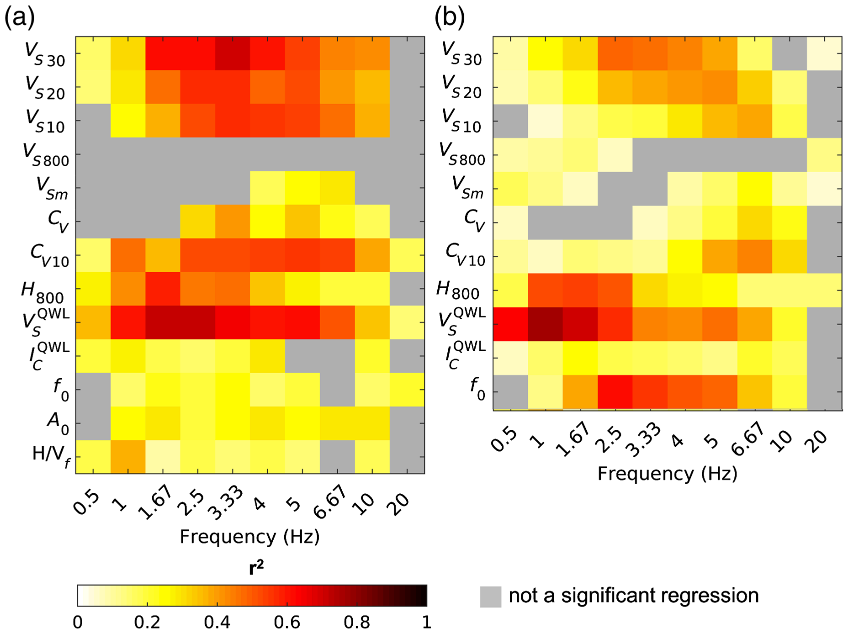

Figure 1 (reproduced from Bergamo et al., 2020). Quality of the regressions obtained between (frequency-dependent) Fourier amplification factors and each individual proxy. Note that the values of V_S^{QWL}, I_C^{QWL} and H/V_f change with frequency. The color code corresponds to the value of the coefficient of determination R^2. Panel (a) refers Swiss data and panel (b) to Japanese data.

Another specific topic is worth being mentioned concerning 1D site response issues. A special attention has been brought over the last two decades on the changes in ground motion between "standard rock" (characterized by V_{S30} = 800 m/s), usually considered as the default reference, and harder rock with much higher S-wave velocities (up to 3 km/s and beyond). For such adjustments, the standard practice has long been the "Vs-κ" approach (e.g., Campbell 2003; Al Atik et al., 2014) based on values of V_{S30} and of "κ_0" characterizing the high-frequency decay of ground motion at the site (Anderson and Hough 1984). Nevertheless, κ measurements are uneasy, and caution is needed in their interpretation in terms of shallow attenuation (Perron et al., 2017). It is therefore not routinely included in strong motion databases, and was not considered in the performance studies mentioned above. Moreover, as shown in Laurendeau et al. (2018) and Bard et al. (2020), there exist other alternative approaches avoiding the use of κ for such rock to hard-rock adjustments, for which the parameters analyzed in Figure 1 are likely to be sufficient.

Community recommended site proxies

Cultrera et al. (2021) offer a completely different and complementary perspective, by reporting the results of a questionnaire survey about the importance of a large number (24) of site indicators *as perceived* by a wide range of scientists or engineers, producing or using the site metadata provided with strong motion recordings. The survey also asked respondents for information about the cost and difficulty/ feasibility to get reliable values for a given indicator. The list of indicators is provided in Table 2, further details on the exact definition of each parameter can be found in Cultrera et al., 2021. The importance was to be ranked by each respondent according to a 4-degree scale: mandatory, recommended, optional, unknown. A similar 4-degree scaling was proposed for the cost (< 1 k€, 1-5 k€, 5-20 k€, unknown) and the feasibility (easy, intermediate, difficult, unknown), from which it was possible to define an overall "cost index" and an overall "difficulty index". The results of this survey are summarized in Figure 2, showing the perceived importance (proportion of respondents considering one given site indicator as "mandatory" for a good site characterization) in the cost index versus difficulty index plane. It turns out that a total of seven indicators (f_0, V_S, V_{S30}, H_{seis_bed}, H_{eng_bed}, geology and soil class, in decreasing ranking order) are considered as "mandatory" by a majority (> 50%) of respondents The associated cost and difficulty index show that these seven recommended indicators span a representative range of cost and difficulty: the most difficult and expensive to get are the velocity profile and the engineering and seismological bedrock, while geology, fundamental frequency f_0, soil class and V_{S30} are considered as more affordable. It is interesting to notice that the site indicators promoted by this survey are those which are found to present the best physical relevancy in the above-mentioned technical studies, which is a strong incentive to promote the use of these site parameters in strong motion databases.

Table 2: Site condition indicators considered in the questionnaire survey by Cultrera et al. (2021)

Indicators [short name]	Description
f_0	Fundamental resonance frequency of the site
f_1 f_2 ... f_n [f123]	Frequency peaks of *n* higher modes
A_0, A_1, A_n [A0123]	Amplitude of the HV spectral peaks at resonance frequencies fi
STF	Fourier site transfer function
Direction	Predominant direction of ground motion
k_0	κ0 - High-frequency / near-surface attenuation parameter
FDA	Frequency dependent near-surface attenuation
$V_S(z)$ [V_s]	shear-wave velocity profile(V_S) as a function of the depth (z)
$V_P(z)$ [V_p]	P-wave velocity profile
V_{S30}	Travel-time averaged velocity V_S down to 30 m depth
Vsz	Travel-time averaged V_S down to depth z
Vs_seis_bed	V_S of the "seismological bedrock" controlling f_0
H_{seis_bed}	Depth of the seismological bedrock
H_{eng_bed}	Depth of the "engineering bedrock" corresponding to the first exceedance of a conventional V_S value (often 800 m/s or 1.5 km/s)
Disp_curve	Surface-wave dispersion curve (vector, Rayleigh or Love)
RW_ellipticity	Rayleigh wave ellipticity curve
Soil_class	Building code Site Class
AF	Aggravation factor for basin or topography (2D or 3D / 1D ratio)
Geology	Geological/lithological information at the site
Topo_class	Building code topographic class (if any)
geostrat_log	geo-stratigraphic 1D log of soil column
H_wt	Depth of the water table
NL_curve	Non-linear degradation curves
geotech_par	Profile of geotechnical parameters

These "perception" results may however vary from one continent to another and from one community to another: the number of informed respondents (71/ 280 invitations) and their origin (mainly Europe - 69%- and northern America - 11% -, although it was distributed also widely in Asia and Latin America) suggests that it provide a reliable picture of essentially the "European" perspective. Nevertheless, the consistency between the outcomes of the survey and the scientific assessment of the parameter performance, indicates the resulting recommendations might be considered as valid also outside Europe.

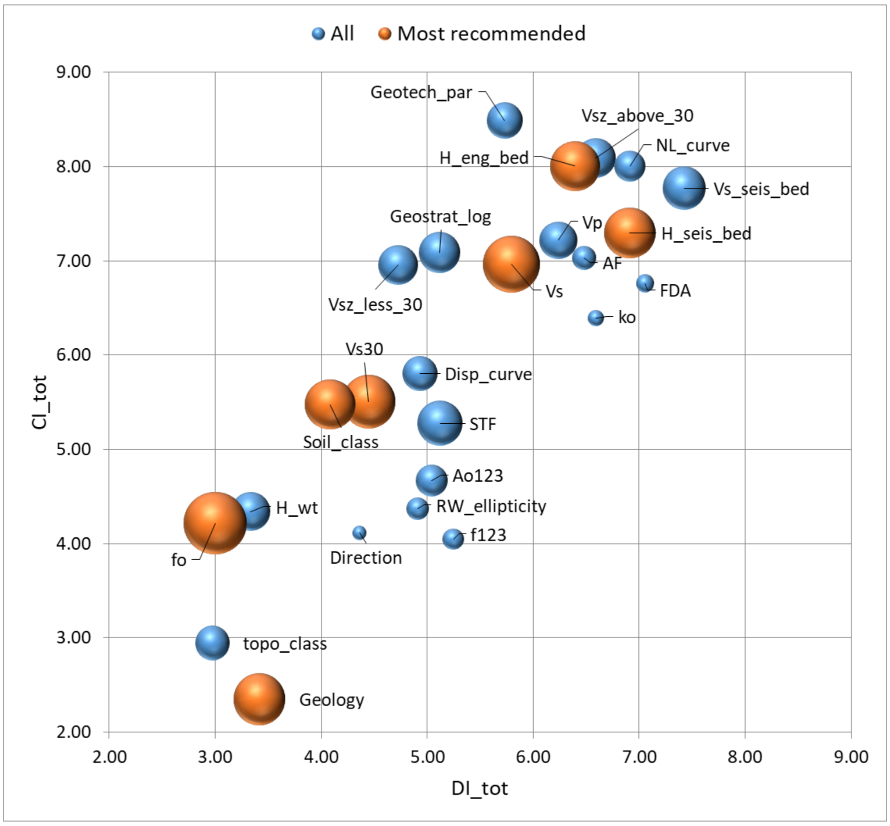

Figure 2 (reproduced from Cultrera et al., 20021): Perceived importance of each site indicator (see the list in Table 2) and location in the overall Cost index (CItot) versus Overall Difficulty index (DItot). The colors distinguish the most recommended indicators (in orange) from the others (in blue). The symbol size is proportional to the percentage of respondents considering the indicator as “mandatory”.

Last but not least, no specific functional form is provided to explicit the dependence of the site amplification on the selected parameters. This is actually relatively easy when only one parameter is accounted for, but becomes more complex when a larger number is considered. Actually, most of the multi-parameter predictions mentioned in this section use a machine-learning approach based on neural-networks, which are now more and more common and allow obtaining a fully data-driven prediction without any a-priori on the functional form. It is true however that the corresponding equations are quite complex, and that only a graphical display of their results allows to capture the physical dependence of one given site response parameter on the site parameters.

NON-LINEAR TERM

NL effects were explicitly introduced in GMPEs site-terms for the first time by Abrahamson and Silva (1997), on the basis of an earlier model by Youngs (1993). In such early models, the description of site conditions was discrete and even binary (soil/rock), and the non-linear part was a correction depending on the predicted rock pga. After the introduction of V_{S30} as a continuous site-descriptor by Boore et al.

(1997), the non-linear part of site terms became V_{S30}-dependent as proposed by Choi & Stewart (2005) and implemented later in the NGA suite of GMPEs (Power et al. 2008). It implies a significant increase in the number of GMPE site-term parameters to be regressed from the strong motion data sets, with actually limited constraints since only relatively only few recordings correspond to the very strong motion range where NL effects are pervasive. Thus, up to recently, there were relatively few GMPEs for which the non-linear part of site terms was exclusively based on recorded data (e.g., Sandıkkaya et al., 2013; Derras et al., 2017), while for most of them the NL site term is actually constrained by a set of complementary 1D simulations, as described in Walling et al., 2008 for the NGA models, Kamai et al. (2014) and Seyhan & Stewart, 2014 for the NGA West 2 models, or by Zhao et al. (2015) for KiK-net stations. NL site terms were therefore the first for which the tuning of coefficients was based on numerical simulation. It does not mean, however, that this kind of NL SAPE is already mature and needs only marginal improvements, as several questions remain to be answered:

- Is V_{S30}, if not the best, at least a relevant and sufficient proxy for NL effects ?
- Are PGA_{rock}, or alternatively $Sa_{rock}(T)$, relevant parameters for characterizing the loading ?
- Are the NL behavior models and parameters used for numerical simulations consistent with the observations ?
- Are there other functional forms, or other approaches for modulating the linear response as a function of the loading ?

Optimal Site Condition Proxies (SCP_{NL}) for NL site response

Early NL site terms used either a discrete description of site conditions (soil / rock), or the continuous V_{S30} parameter, simply because it was the only information available in strong motion databases. From a theoretical viewpoint, given the experimental results in laboratory tests (e.g., Vucetic & Dobry, 1991; Darendeli, 2001), the plasticity index PI should also be taken into account in addition to the soil stiffness or strength. This is supported by several recent investigations on various data sets. Wang et al. (2019) investigate 8 KikNet stations with numerous recordings, and conclude that the acceleration threshold corresponding to the onset of NL behavior seems to be primarily controlled by both the soil stiffness and its plasticity index. This is consistent with the outcomes of two other studies on large data sets. Guéguen et al. (2019) compare non-linear terms of a few recent GMPEs with the actual observations of four large data sets: KiK-net (the subset used in Régnier et al., 2016a), K-Net (1996-2016 recordings with pga exceeding 10 cm/s^2), NGA-West2 (Ancheta et al., 2014), and an early version (Luzi et al., 2016) of the European ESM database: they find some significant mismatch which they interpret as potentially due to the use of V_{S30} as site proxy. The same conclusion is reached by Loviknes et al. (2021) after analyzing the site-to-site variability of site response on a larger KiK-net data set as compiled by Bahrampouri et al. (2020): they similarly conclude that the conventional V_{S30} site proxy is not sufficient for characterizing the non-linear site response. Consistently, the analysis of κ values for strong motion recordings at 20 KiK-net sites performed by Ji et al. (2021) points the importance of velocity gradient and/or velocity contrasts (site characteristics which both are not mapped in V_{S30}) in controlling the degree of strain and thus of non-linearity in strong motion site response. Finally, Derras et al. (2020) compare the performances of V_{S30} and various other SCPs in predicting the non-linear site response of the KiK-net subset used in Régnier et al (2016a). The other proxies they consider are related either to the velocity profile (the minimum velocity V_{Smin} and the velocity gradient characterized by B_{30}, as defined in Régnier et al., 2013), or to the H/V site signature (the fundamental frequency f_{0HV} and the corresponding H/V amplitude A_{0HV}, both derived from earthquake recordings); unfortunately they could not consider any parameter directly related to the geotechnical characteristics (especially the plasticity index), as they are not available for KiK-net stations. They conclude that the fundamental frequency slightly outperforms V_{S30}, when only one SCP is accounted for, while the consideration of two SCPs leads to more or less equivalent performances of all pairs except those using the minimum velocity, which amazingly appears to be the worst SCP. They finally recommend the pair (V_{S30}, f_{0HV}).

One may mention also that, despite the recognized importance of soil strength in NL site response models (Shi and Assimaki, 2017), this parameter has not yet been taken into account because of its unavailability in strong motion databases, and also because of the need to translate the whole strength profile into a single scalar value.

Optimal loading parameter

From a mechanical viewpoint, the "best" loading parameter to be used should be the shear strain. That is why numerous studies, following Idriss (2011), make use of the ratio "PGV/V_{S30}", or any other estimate of the peak particle velocity divided by a local shear wave velocity, considered as a reliable strain proxy on the basis of non-dispersive plane wave propagation theory. Actually this is now a "must" for almost all studies attempting either to characterize the non-linear site response, or to retrieve the in-situ soil dynamic parameters from strong-motion recordings: see for instance Chandra et al. (2015, 2016), Guéguen (2016), Guéguen et al. (2019), Wang et al. (2019), Ji et al. (2021), Kuo et al. (2021), among others. Depending on the kind of used data (borehole recordings with sensors at different depths, or single surface recordings), the peak particle velocity is estimated from absolute or relative motion, and the shear wave velocity from V_{S30} or interval velocity.

Therefore, in their efforts to compare the performance of various sets of input parameters for predicting the observed non-linear site-response, Derras et al. (2020) considered various GMIM (Ground Motion Intensity Measures), spanning from the classical peak values PGA and PGV and the strain proxy PGV/V_{S30}, to some "energy" indicators such as cumulative absolute velocity CAV, or Arias Intensity I_A and the associated "root-mean square acceleration" a_{rms} and Trifunac-Brady strong motion duration D_{TB} (Trifunac & Brady, 1975). The peak values, i.e., PGA, PGV and PGV/V_{S30}, are found to perform better in predicting the non-linear modulation of site amplification than the four other, with only slight differences between them 3.

Agreement between simulations and observations

Two directions have been explored to compare observations and simulations. The most straightforward way is to compare the impact of the non-linear components of site terms as implemented in various GMPEs, and the actual observations from a collection of site, as done for example by Loviknes et al. (2021). They propose a framework for testing non-linear versus linear site amplification models, and find that below a pga of 0.2 g, nonlinearity has a too small impact on site response to really justify the consideration of nonlinear site terms in GMPEs; this must be balanced however by the fact that the KiK-net sites they consider generally correspond to rather stiff sites – even if as discussed before, the presence of large velocity gradients or impedance contrast prevails on the V_{S30} value alone for the strain values and the onset of non-linear behavior.

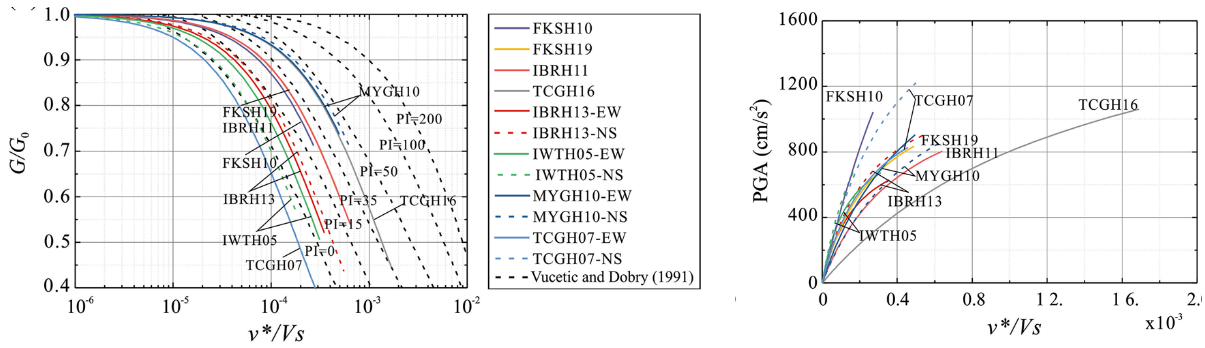

Figure 3 (reproduced from Wang et al., 2019): Instrumentally derived relationships between shear strain and shear modulus ratio (left), compared with laboratory G–γ measurements by Vucetic and Dobry (1991), and between shear strain proxy and peak ground acceleration (right).

The other direction is to compare the "in-situ" soil dynamic parameters (i.e., those derived from strong motion recordings), to those used in the forward simulation models. Using pga as a stress proxy and the velocity ratio as a strain proxy, Wang et al. (2019) retrieve the parameters of the classical hyperbolic models considered for non-linear behavior, and find that nonlinearity starts at rather low strain levels (around 10^{-5}), and becomes significant for trains beyond 10^{-4}. Such threshold strains are in good agreement with usual NL soil models. Nevertheless, for very large motion (up to 0.8 g), the shear modulus reductions remain generally limited (less than 40%) except for the few sites with lowest V_{S30} and PI (see Figure 3).

This comparison is however limited to very few, rather stiff sites. Guéguen et al. (2019) performed a similar comparison in a statistical way for the four large databases mentioned previously. basically compare the NL signature on observed peak ground acceleration as a function of proxy interpreted in terms of shear modulus reduction, to the signature associated to four GMPEs including non-linear terms. They do observe a non-linearity in the databases, limited, seems larger than what is accounted for in the considered GMPEs, and can be rather stiff soils with high V_{S30} (
Figure 4). The latter result is consistent with the findings by Régnier et al. (2016a) and Derras et al. (2020) who indicate significant nonlinear effects for stiff sites with rather high fundamental frequencies, corresponding to thin soft soils over much stiffer soil or rock. Such results indicate that the NL part of GMPE site terms could be improved by accounting for more parameters

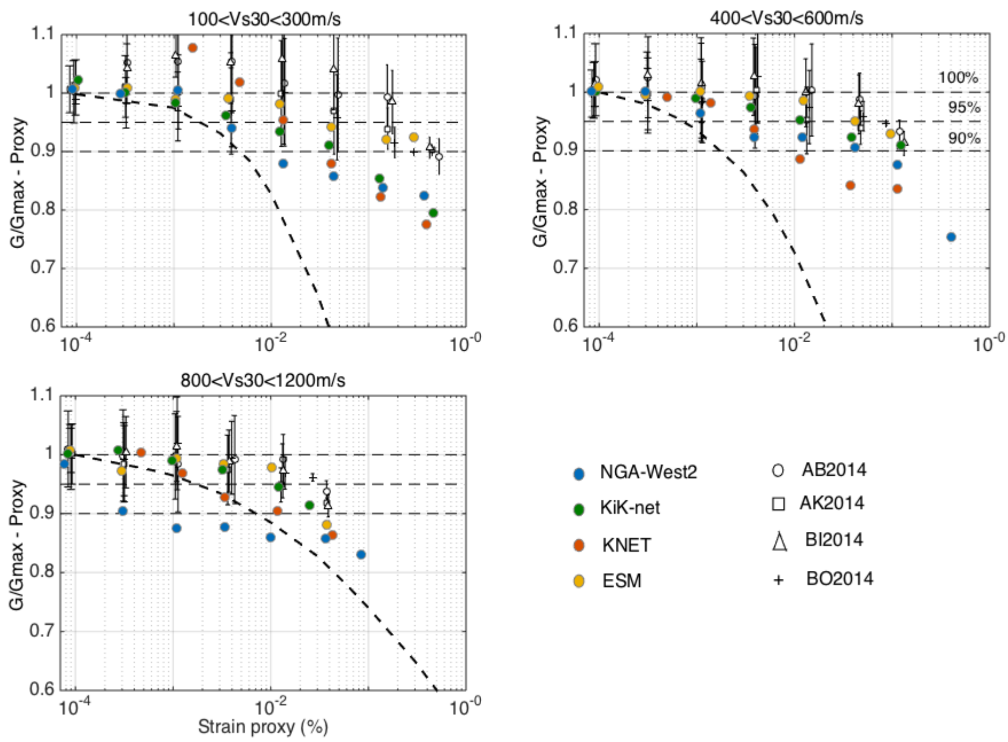

Figure 4 (reproduced from Guéguen et al., 2019): Comparison of predicted and observed nonlineariies in terms of the shear modulus reduction G/G_{max} (estimated from PGA to strain proxy ratios in different strain intervals) as a function of the strain proxy (PGV/V_{S30}). Open symbols correspond to estimates according to four GMPEs (AB2014: Abrahamson et al., 2014; AK2014: Akkar et al., 2014b; BI2014: Bindi et al., 2014; BO2014: Boore et al., 2014). Filled, colored circles correspond to average values from the four databases for three site classes, for strain proxies larger than 10-4 %. Thin horizontal dashed lines correspond to 100%, 95% and 90% of the G/Gmax values. Bold dashed lines for each VS30 class, are standard G-γ curves for clay (PI=15%), sand and rock-like soil from Zhao et al. (2015), respectively.

Another interesting piece of comparison is provided by Kuo et al. (2021), who revisit the old set of SMART1 data to investigate the impact of non-linearity on damping, under the assumption of frequency-dependent damping which is rather unusual in geotechnical engineering and classical in seismology. Their results indicate a large increase of quality factor with increasing frequency (median $Q = 15\ f^{0.9}$) at shallow depth, and a trend for a slight damping increase with strain increase (40 to 50% increase for strain proxy in the range $10^{-4} - 10^{-3}$. The comparison of these values with usual damping degradation curves indicate however a significant discrepancy, with much higher damping values for the latter (see their Figure 9).

Other approaches and functional forms

The approach initially proposed by Youngs (1993) and Abrahamson & Silva (1997), has been implemented in later GMPEs with only marginal changes in the functional forms h_1 and h_2 of Equation (6). Two other approaches have been proposed later. Régnier et al. (2013, 2016a) define a "non-linear modulation" function $RSR_{NL\text{-}L}(f)$, defined as the ratio between the Fourier transfer function under strong shaking to the average Fourier transfer function obtained for weak motion (i.e., below some pga or strain proxy threshold). More recently, Derras et al. (2020) go one step further in proposing a set a predicting models providing the dependence of $RSR_{NL\text{-}L}$ as a function of some loading level parameter and some site condition proxies: their optimal model makes use of the strain proxy PGV/V_{S30}, V_{S30} and f_{0HV}, with a rather complex functional form obtained with a neural network approach. Example results are illustrated in Figure 5. Castro-Cruz et al. (2020) take advantage of the low-frequency shift induced by the shear modulus reduction to propose applying a loading-dependent frequency shift to the linear transfer function, keeping however the same amplitude whatever the loading. Both approaches were used for the Kumamoto site in the ESG6 blind prediction exercise as explained in Régnier et al. (2021), which will allow to tell whether they are worth further investigations and improvements.

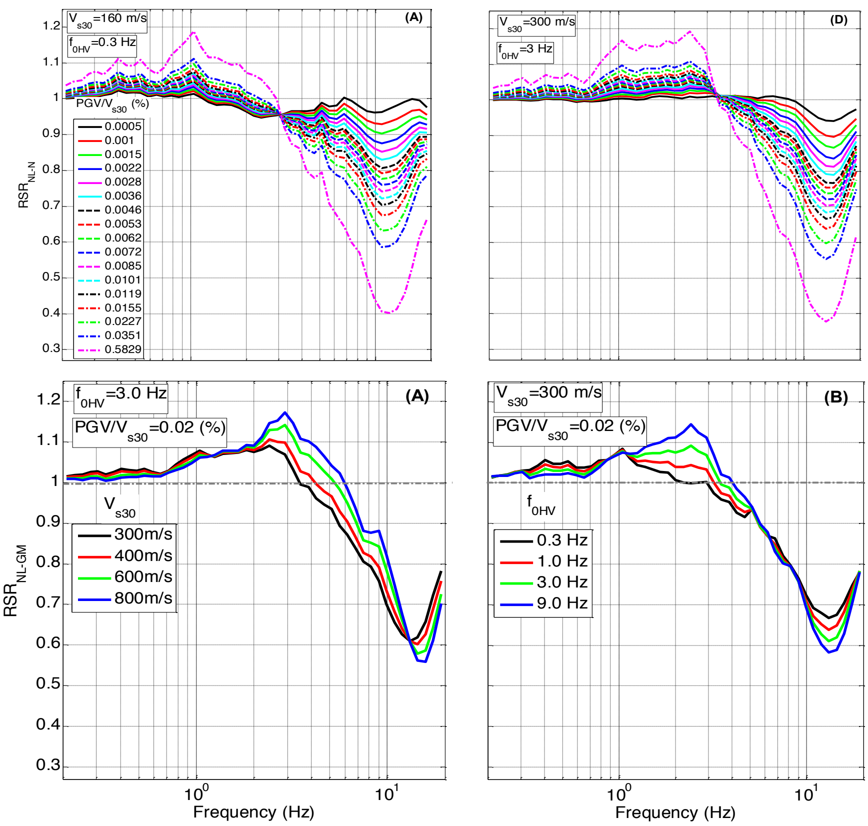

Figure 5 (reproduced from Derras et al., 2020): Variation of $RSR_{NL\text{-}L}(f;\ PGV/V_{S30};\ V_{S30},\ f_{0HV})$ predicted for increasing values of PGV/V_{s30} and fixed values of V_{S30} and f_{0HV} (top row), or for fixed strain and f_{0HV} values and different V_{S30} values (300, 400, 600, 800 m/s, bottom left), or for fixed strain and V_{S30} values and different f_{0HV} values (0.3, 1.0, 3.0, 9.0 Hz, bottom right). The values of PGV/V_{s30} (in %), V_{S30} and f_{0HV} are provided in each frame,.

To conclude this NL section, the significant progress in data-driven models should be emphasized, based on the numerous, strong shaking, borehole recordings and the increasing use of in-situ strain proxies, which leads to rather encouraging comparisons between "in-situ" and laboratory measurements of non-linear properties. Strong motion databases however still lack important geotechnical parameters such as the plasticity index or strength, which prevents to establish fully satisfactory data-driven models.

SURFACE TOPOGRAPHY: TOPOGRAPHIC AGGRAVATION FACTOR

Recent attempts: a mixed success

Amplification effects related to surface topography have been noticed, and studied, for many decades. Yet, unlike the effects of soft surface deposits, even though numerous recording sites are located on non-flat topographies. it has never been formally introduced in GMPEs, while it is actually included – in a very rough and physically unsatisfactory way - in some building codes such as EC8 in Europe. These apparent inconsistencies could be partly related with the fact that GMPEs were first developed mainly on the US West Coast, where most human settings are located in flat areas, to the contrary of the Euro-Mediterranean area where many villages or towns were settled long ago on topographic highs for security reasons, and are more prone to "promontory effects" (Maufroy et al., 2018).

This apparent lack in GMPEs has been noticed for at least one decade, and there have been several attempts to lay the ground for specific surface topographic terms in GMPEs, starting with Cauzzi et al. (2010, 2012) in Europe, or Rai et al (2016, 2017) in USA. Nevertheless, despite several proposals, it did not yet succeed in formulating specific "topographic" terms having a solid enough physical basis to be widely accepted and routinely incorporated in GMPEs. This failure has various origins. Up to one-two decades ago, there were not enough recordings with consolidated metadata about topographic characteristics to ground a statistical analysis. This is however no longer the case with the availability of world-scale DEM with relevant resolution, and terrain-based classification schemes (Yong et al., 2012). Some attempts have thus been made to correlate GMPE site residuals with some topography-related characteristic, as in Rai et al. (2012, 2016, 2017) for Californian or NGA-West2 data, or Burjanek et al. (2014) for a set of Swiss and Japanese data. Despite a significant scatter, the former were quite confident in proposing some median numbers for short period amplification in elevated areas (up to 1.13), and long period deamplification (down to 0.75) in topographic lows. The latter were much more cautious: they did observe some significant amplification on some of the elevated sites they considered (and most often with a pronounced directionality of both earthquake recordings and ambient noise measurements), but they did not find any clear correlation between the observed amplification and the local topography characteristics, which led them to conclude that these observed amplifications are more likely to be primarily controlled by the local subsurface shear velocity structure, than by the surface geometry itself.

These contrasting conclusions are indeed witnessing what is likely to be the main origin of the failure of a routine implementation of topographic effects in GMPEs, i.e., the divergence of interpretations. This could be summarized by the co-existence of two main schools, one looking for "genuine topographic effects" linked only to the surface topography, and another one considering that most of the significant amplifications observed on topographic highs, from either post-seismic damage surveys or instrumental recordings – or sometimes both -, are indeed due to a coupling between local subsurface peculiarities and surface geometry. For the former school, it is thus possible to propose some topographic factor directly from extensive numerical simulations, while for the latter, the lack of detailed knowledge on underground structure, and the multiplicity and complexity of possible coupling mechanisms, makes it impossible, or at least premature, to classify all possible situations, to identify the corresponding relevant proxies, and to associate amplifications values. The next subsections propose a quick overview of the present state-of-knowledge (actually through references to comprehensive, recent reviews), and of the proposed site proxies.

Origins of topography effects: a controversial issue

The above mentioned issues are addressed in a series of two companion papers by Massa et al. (2014) and Barani et al. (2014). The first one presents an extensive review of the literature over several decades, addressing both numerical simulation and observational studies, and adds a few specific studies for five Italian instrumented sites with numerous recordings. Although numerical simulations and instrumental observations agree on a number of qualitative items, as listed in Table 3, they still disagree as to the amount of amplification (see Figure 6), and the importance of directionality effects (i.e., azimuth-dependent amplification, very often much larger in observations than predicted, even though models usually predict a larger effect on the orthogonal-to-ridge component). They conclude with a warning on the complexity of the so called "topography effects" often corresponding to "complex site amplification effects", as topographic irregularities are most often associated to various structural inhomogeneities and tectonic discontinuities, in addition to surface weathering. The poor knowledge of the underground structure thus leads to be cautious on the capability of numerical simulation to provide accurate enough, quantitative predictions of the actual site response. The companion paper (Barani et al. 2014) sets a framework for adding a surface topography term in GMPEs, but cannot propose any specific formula given the variety of situations and multiplicity of parameters. They simply recommend, for a purely empirical approach, to classify seismic stations into different topographic categories based on their geometry, and probably also on their fundamental frequency for coupling effects. They also consider the numerical modeling approach as an alternative approach, to be used only in the absence of instrumental data, and keeping in mind it is likely to provide lower bound estimates of "true" amplifications (Figure 7)

Table 3:: Summary of results from numerical simulations and instrumental observations on surface topography effects (from Massa et al., 2014 and Géli et al., 1988)

<table>
<tr><th></th><th></th><th>Numerical simulation</th><th>Instrumental observations</th><th>Agreement / Disagreement</th></tr>
<tr><td rowspan="4">Crest/base effects</td><td rowspan="2">Spatial distribution</td><td>Amplification on convex parts, reduction on concave parts</td><td>Amplification on elevated sites</td><td>A</td></tr>
<tr><td colspan="2">Difficulty to select an appropriate "reference" for comparison</td><td></td></tr>
<tr><td rowspan="2">Frequency dependence</td><td>max effects for λ comparable to width w</td><td>Sometimes but not always</td><td>Partial agreement</td></tr>
<tr><td>HF oscillations on slopes (constructive / destructive interferences</td><td>Often negligible effects on slopes</td><td>D</td></tr>
<tr><td rowspan="5">Top Amplification</td><td>Level</td><td>Moderate</td><td>Highly variable, may exceed 10</td><td>D</td></tr>
<tr><td>Sensitivity to shape ratio h/w</td><td>Increases with h/w</td><td>Increases with h/w</td><td>A</td></tr>
<tr><td>Component-to-component variability</td><td>Moderate But largest effects on T component, smallest on V component</td><td>Often large T/L differences , lowest on V</td><td>Qualitative agreement only</td></tr>
<tr><td rowspan="2">Sensitivity to incident wavefield</td><td>Largest for S waves, lowest for P waves</td><td rowspan="2">Largest on outward slopes</td><td rowspan="2">-</td></tr>
<tr><td>Largest for vertical incidence</td></tr>
</table>

Grelle et al. (2016, 2018a,b, 2020) propose a way to account simultaneously for both kinds of effects with the SiSeRHMap ("Simulation of Seismic Response by using a Hybrid Model") computerized methodology based on a hybrid, litho-morphometric model combining 1D site response approach and a specific topographic module. The latter provides a "topographic amplification factor" on the basis of the DEM and available results for homogeneous and sometimes heterogeneous topographies (Géli et al., 1988; Assimaki et al., 2005). However, it does not take into account the specific coupling between both kind of effects (the physics of which is not yet fully understood), nor the effects of tectonic or structural discontinuities.

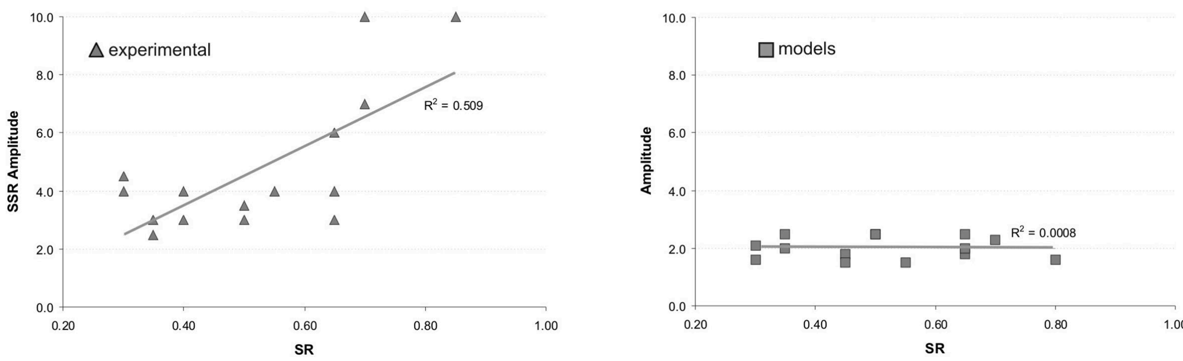

Figure 6 (reproduced from Massa et al (2014): Relationships between topographic shape ratio h/w and SSR (Standard Spectral Ratio) amplitude as obtained from experimental (left-hand panel) and numerical (right-hand panel) data.. (Data collected from published, noteworthy studies, grey triangles correspond to instrumental observations (left-hand side), grey squares to numerical simulation (right-hand side, grey lines to simple regressions.

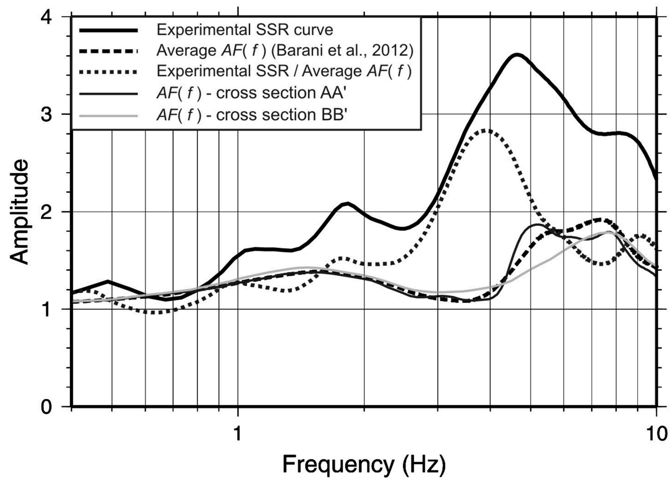

Figure 7 (reproduced from Barani et al 2014): Comparison between the numerical amplification functions AF(f) for two cross-sections (AA' and BB') and the experimental AF(f) obtained by Massa et al. (2010) at the Narni ridge (central Italy).

Topographic Proxies and associated amplification

The literature survey mentioned in the above-mentioned papers allows to list a number of parameters and formulas proposed by several authors for closed-from estimates of the topographic amplification factors. It must be clear however that such factors correspond only to simple geometrical effects, and not to "complex amplification effects on heterogeneous, elevated sites".

Cauzzi et al. (2010, 2012) proposed a simple multivariate linear formula accounting for the geometry of the relief (for the amplitude) and its average mechanical properties (for the frequency scaling). The proposed explanatory variables are derived from the topographic height (the real one or some alternative estimates), length and width at the base corresponding to low slope values, the crest width, the local elevation and slope for any point on the topography, and the average shear wave velocity. Almost all of them but the last can be derived from DEM.

Maufroy et al. (2015) used extensive 3D modeling with highly complex surface topography and multiple point sources presented in Maufroy et al. (2012) to constrain a prediction model based on the "frequency scaled curvature" (FSC) derived from the second derivative of the elevation map, with a frequency-dependent smoothing related to the S-wave wavelength, which can be easily derived from DEMs. The most robust predictions are found for topographic highs and lows, while the highest variability is found on slopes, in relation to azimuthal and source depth effects,. They propose simple linear relationships between FSC and (purely) topographic amplification, as illustrated in Figure 8, which also displays the wide scatter in the original numerical results.

Rai et al. (2016, 2017) investigated several topographic parameters to explain the observed station residuals: the relative elevation (i.e., the local elevation difference with respect to the average elevation over a given surface around the site, typically over a circular area with a radius around 1 km), the smoothed curvature proposed by Maufroy et al. (2015), and the smoothed slope. They find statistically significant results for the first two. The median topographic factors they propose exhibit a linear ramp like functional form, with however a large scatter with standard deviations much larger than the median corrections, which is likely to witness the contribution of many other unknown factors.

These relationships and their coefficients are based on numerical simulation considering pure surface topography effects in homogeneous half-spaces. They thus involve only moderate topographic amplification factors, which may strongly underestimate some observations. Nevertheless, as they are based on simple geometrical parameters readily available from already existing DEM, network operators and GMPE developers should be strongly encouraged to incorporate them in site metadata: it should lead to a slight reduction of the within-event variability, and it would help to identify elevated sites exhibiting an anomalous behavior and deserving further investigations. In parallel, performing systematic directional H/V processing on earthquake recordings and, when available, ambient noise measurements, would be very useful in identifying all sites with highly polarized motion, which constitutes a frequent characteristic of elevated sites with "complex seismic amplification" (Burjanek et al., 2014; Massa et al., 2014).

One may finally notice that, amongst the various specific site response topics mentioned here, surface topography issues are the only ones which up to now have not been the focus of any ESG blind test. This could actually be useful to think about it for ESG7, as it would also be an opportunity to raise the attention of a broader community, including engineers and building code writers who seem satisfied with either the non-physical provisions presently in use in EC8, or their absence in most others.

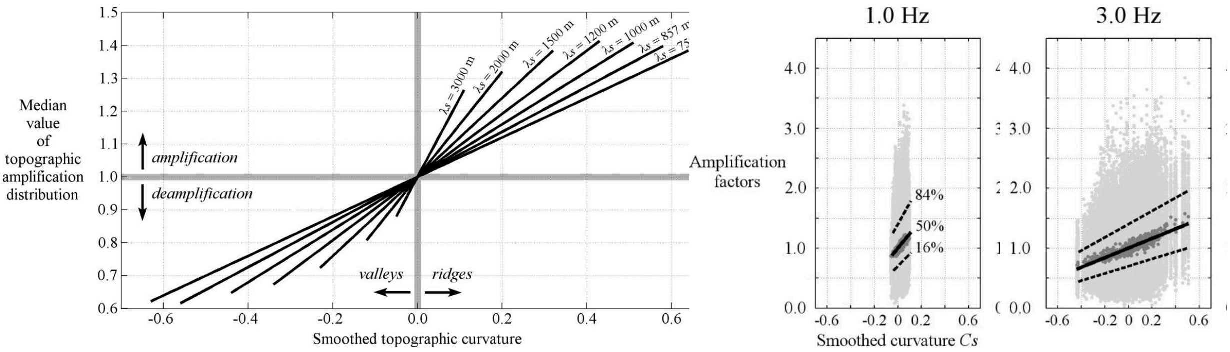

Figure 8 (reproduced from Maufroy et al., 2015): (Left) Median linear relations established between the smoothed topographic curvature and the median value of the topographic amplification, for different S-wavelengths in the range 750-3000 m. (Right) Example dispersion of all numerical results (light gray dots) around the best-fitting curves shown on the left for 1 and 3 Hz (solid black lines: median curves, dashed black lines; 16% and 84% percentiles).

UNDERGROUND GEOMETRY: AGGRAVATION FACTORS IN VALLEY AND BASINS

Quick overview of past studies

There exist numerous observations of the importance of enhanced wave trapping in valleys or basins, as for instance, among many others, the basin-edge effects during the Kobe (1995) event (Kawase, 1996). As mentioned above, the site terms currently considered in most GMPEs are related only to the parameters of the soil column (V_{S30}, f_0, Z_1 or $Z_{2.5}$), and therefore implicitly to 1D site response. When those site terms are derived exclusively from ground motion recordings, they may however include some effects related to the lateral variations of surface deposits thickness, in an aleatory way however since none of the considered site parameters describes any feature of such lateral variations. Even what is called "basin effect" in some recent GMPEs (e.g., Campbell and Bozorgnia 2014) is indeed mainly a low-frequency effect related to the thickness of deposits, that cannot be captured by shallow velocity V_{S30}: it might be biased by the amount of recordings from California deep basins (Los Angeles area in particular) and thus include some amount of "overamplification" related to basin geometry, but cannot be extrapolated to any other basin without some specific, and presently unknown, tuning.

As indicated in Boudghène-Stambouli et al. (2018) or Zhu et al. (2020), lateral thickness variations in alluvial valleys or basins have been shown to induce peculiar wave propagation phenomena (diffraction of surface waves, body wave focusing, lateral reverberations) leading to a more efficient energy trapping and complex interference schemes, and therefore to potentially significant differences with respect to the case of horizontally stratified layers ("1D soil columns"): the ground motion duration is generally increased, its amplitude as well - although it is sometimes reduced -, and the geometry-induced modulations exhibit a significant frequency and spatial variability.

Bard (1986) proposed to use "2D modifiers" to the 1D site response to account for such valley effects, and Chavez-Garcia & Faccioli (2000) and Chevez-Garcia (2007) formulated them as "aggravation factors" (AGF), the term which is now commonly used to describe the ratio between 2D (or 3D) and 1D amplifications for any relevant ground motion parameters. This "AGF" approach has been developed in numerous later studies, all based on numerical simulations. Some of them consider only linear 2D or 3D response: Makra et al. (2001, 2005) for the Euroseistest site (Mygdonian basin, Greece), Paolucci and Morstabilini (2006) for a collection of hypothetical basin edges (walls or wedges), Kumar and Narayan (2008) and Narayan and Richharia (2008) for strong, step-like lateral discontinuities, Riga et al. (2016) for trapezoidal valleys, Zhu et al. (2016, 2017, 2018a,b, 2020) for shallow trapezoidal, or deep, "alpine-like" valleys, or Moczo et al. (2018) for a set of real 2D or 3D basins. The same AGF concept was also applied with the consideration of non-linear soil behaviour by Hasal and Iyisan (2012), Gelagoti et al. (2012), Vessia and Russo (2013), and Ozaslan et al. (2020) for hypothetical or real basins (using fully non-linear or linear equivalent approaches).

Main findings

All these studies provided first estimates of the range of values for AGF, and some included sensitivity studies indicating their dependence on a number of site or valley parameters in a semi-quantitative / semi-qualitative way, as summarized below

- The 2D/1D AGFs are component dependent (Boudghene-Stambouli et al., 2018; Moczo et al., 2018). They are found systematically the largest for the vertical component, and the smallest for the in-plane component as a consequence of the edge-induced Rayleigh and Love waves, and to a lesser extent S-P and P-S conversions. This extreme sensitivity of amplification of vertical ground motion to the 2D (or 3D) underground structure results in an increased contribution of geometrical effects for vertical ground motion.
- The values of amplification and aggravation factors depend on the considered GMIM (Boudghene-Stambouli et al., 2018; Moczo et al., 2018; Brissaud et al., 2020). Largest values are found for the Arias intensity I_A and peak spectral amplification (up to 3-4 for horizontal components and 8-10 for the vertical component), and to a lesser extent for the cumulative absolute velocity CAV (around 2-2.5 and 3.5-4 for horizontal and vertical components, respectively), while lowest values are found for root mean square acceleration. For GMIMs commonly used in engineering design (short period and long period spectral values, PGA, PGV), AGF values remain most often lower than 2 for horizontal components, and 3 for vertical components. As to ground motion duration, it may be significantly prolongated within 2D valleys, up to 10 to 15 seconds for deep and embanked low-frequency deposits.

- As expected, the aggravation factor is found to be tightly related to the valley geometrical characteristics (Gelagoti et al., 2012; Riga et al., 2016; Boudghene-Stambouli et al., 2018; Moczo et al., 2018), but the effects also depend on the location inside the valley. At valley center, the aggravation factor increases as expected with the shape ratio (i.e., the ratio of maximum valley thickness to its width). On the contrary, at valley edges, deamplification effects with AGFs lower than 1, are more and more pronounced as slope angle becomes steeper, but they are localized in narrower and narrower areas close to the rock/valley border. In addition, even relatively shallow valleys (shape ratios as low as 0.05) can lead to significant aggravation factors in case of relatively wide edges because of the efficiency of surface wave generation on long, gently sloping interfaces. Not only the overall shape ratio is important, but also the overall geometry of the sediment-bedrock interface, in particular the sloping angles on valley edges.
- The impedance characteristics between sediments and rock, which are the main controlling factor for the 1D amplification level, also impact significantly the AGF values: for a given geometry, the larger the impedance contrast, the larger the aggravation factor, in relation with the increased efficiency of lateral wave trapping (Riga et al., 2016; Boudghene-Stambouli et al., 2018; Moczo et al., 2018).
- The sediment material damping impacts in the same way the amplification and aggravation factors: larger attenuation results in smaller amplification and aggravation factors, especially for the vertical component and for high-frequency ground-motion intensity measures (Boudghene-Stambouli et al., 2018; Moczo et al., 2018).
- Finally, even if only very few papers investigated the coupled effects of valley geometry and non-linear behavior, the available results (Gelagoti et al., 2016) confirm the common-sense expectations according which geometrical effects decrease with increasing non-linearity (in relation with increased damping): they tend to become localized only close to the valley edges for shallow basins, and to reduce the AGF at the center of embanked valleys.

Next steps for deriving operational AGF SAPEs

Despite these consistent and physically intelligible numerical results, only very few studies have proposed quantitative relationships between AGF and site characteristics: sensitivity studies indicate general trends for the dependence on one site parameter, but only very few propose a full prediction of AGF based on a set of relevant proxies, which is the next step for deriving mature and reliable SAPEs for effects of 2D/3D underground geometry. Two issues should be solved for such a goal: What are the valley parameters to be used as predictors ? What are the corresponding functional forms ?

Most of the above mentioned studies agree on the few key-parameters that control the aggravation factor

- The site location within the valley. While Zhu et al. (2018b, 2020) indicate that site location is not a key issue for deep valleys prone to global 2D resonance, they agree with most recent other studies emphasizing the differences between valley edges and centers for shallow or wide valleys. Site location is thus introduced through either a dimensionless ratio x/w (Narayan & Riccharia, 2008; Gelagoti et al., 2012; Paolucci & Morstabilini, 2006, etc.) where x is the distance form edge and w is the valley width, or a differentiation of different zones within the valley (Riga et al., 2016; Stambouli et al., 2018, see Figure 9), with outer edge, inner edge, and central part, or simply the area close to the edges up to a distance equal to about 1.5 times the basin depth (Zhu et al., 2017).
- A few geometrical parameters characterizing the gross geometrical shape of the valley: the shape ratio h/w (thickness over width), and the average slope angles on each edge, α_1 and α_2.
- A few mechanical parameters characterizing the recording site: V_{S30} and f_0, or alternatively the rock / sediment impedance contrast and the basin depth (Brissaud et al., 2020). From a physical viewpoint, the damping should also be accounted for, but it is presently so rarely available that it is not accounted for in 1D site terms…

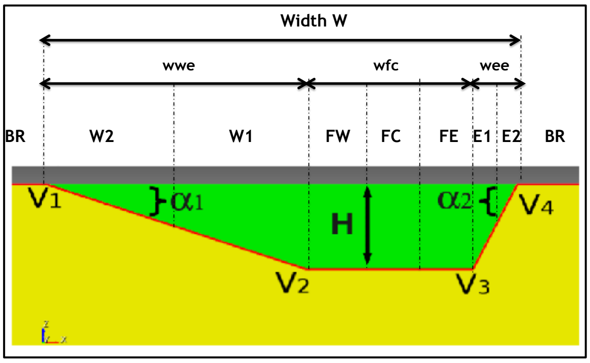

Figure 9: Definition of valley zones in Boudghène Stambouli et al (2018). The total valley width W is separated in seven zones. Four correspond to the edges above the sloping interface: the extreme edges (W2 and E2), the "inner edges" (W1 and E1). In case of trapezoidal shape, the central, flat part is divided in three equal width parts, FW and FE correspond to the parts closer to the edges ("outer central part"), FC correspond to the central part

Table 4: Input parameter values considered for cases displayed in Figure 10

Plot name	Shape	Zone	H/w	α_1	α_2	V_{S30} (m/s)	f_0 (Hz)
A	Triangular	W1UE1	x-axis	15°	15°	124, 198, 331, 498	0.5
B	Triangular	W1UE1	x-axis	10°, 20°, 45°, 65°	15°	240	0.5
C	Trapezoidal	FC	x-axis	45°	45°	124, 198, 331, 498	0.4
D	Trapezoidal	FC	x-axis	10°, 20°, 45°, 65°	45°	220	0.4

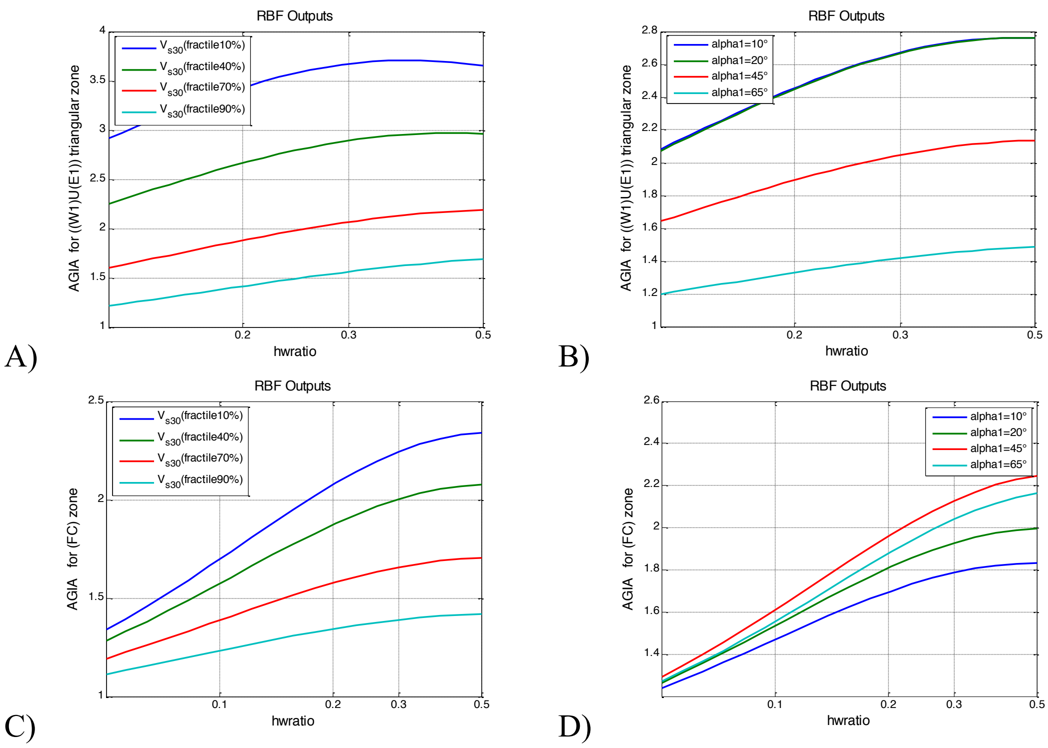

Figure 10: Example predictions for the Arias Intensity, for the W1UE1 zone in triangular valleys (cases A and B on top), and for the central falt part FC of trapezoidal valleys (cases C and D on bottom). The different cases considered are listed in Table 4

Apart from the original, limited proposal by Bard (1986) considering only the peak Fourier amplification at the fundamental frequency and at valley center, with a dependence on the shape ratio, the impedance contrast and the sediment damping, there is only one study – to my knowledge – attempting to propose a set of equations predicting the AGF value. Boudghène-Stambouli et al. (2018) use a comprehensive set of 2D numerical simulations consisting of 131 trapezoidal and 18 triangular valley shapes, with six different gradient velocity profiles corresponding to V_{S30} values from 125 m/s to 500 m/s, and a RBF (radial basis function) neural network approach to describe the dependency of AGF on the above-mentioned site and valley parameters. They consider six different zones (4 for trapezoidal valleys, and 2 for triangular valleys), and 7 different GMIM (PGA, PGV, Arias Intensity IA, peak spectral amplification, Cumulative Absolute Velocity CAV, short and intermediate amplification factors Fa and Fv). Example results are shown in Figure 10 for Arias Intensity the inner part of triangular valleys and the central part of trapezoidal valleys, as a function of the shape ratio h/w and for different values of the edge angle and the velocity contrast (cases A and C), and for fixed values of the other parameters as listed in Table 4. Such examples illustrate that the dependence on some parameters (such as the edge slope angle α_1 are not simple, and that the functional form of multivariate dependence cannot be considered as simple and intuitive: machine learning approaches should be used to obtain data-driven results, at least for now.

CONCLUDING COMMENTS

The title of this paper ends with a question mark: is it possible to answer it at the end of this overview? In other words, is it realistic to hope having more physics-based site terms, that could be added without any modification to any regional rock GMPEs, in a near future? The issue can actually be splitted in several sub-questions:

a) is the present knowledge sufficient to identify the relevant site proxies for a given type of site amplification component?
b) Are these proxies available in the site metadata of existing ground motion databases to ground fully data-driven SAPEs?
c) Are present numerical simulation tools able to be an alternative for establishing numerical results compensating the missing or incomplete instrumental data?
d) What are the tools to derive predicting equations for each individual site amplification component?

My personal, certainly subjective, answers to those questions are listed in Table 5. In short, I have the feeling that our present understanding of linear site amplification due to sedimentary fillings in 1D, 2D and 3D situations is mature enough to allow the possibility to use extensive numerical modeling to propose operational, physics-based prediction equations. The latter are likely, however, to be too complex to be summarized in simple functional forms, and to require artificial intelligence tools to optimally capture multivariate dependencies. Nevertheless, the existing structuration of site metadata in most ground motion databases is not suited for deriving fully data-driven relationships. Dedicated test-sites with detailed geophysical information and dense, sensitive instrumentation, are thus needed to validate the accuracy of such numerically-based site terms.

Table 5: Tentative answers to summary questions for each site amplification component

Question	Site terms				
	1D, linear	NL	Surface topography: Homogeneous half-space	Surface topography: Underground heterogeneities	Valleys / Basins, linear domain
a)	Yes	Only partly	Yes	No	Mostly yes
b)	Generally not	Incompletely	No, but easy	No	No
c)	Yes	Incompletely	Yes	No	Yes
d)	AI	?	Simple	-	AI

Regarding surface topography effects, my feeling is that the situation is mature only when considering the purely geometrical effects associated to irregular topographies at the surface of a homogeneous half-space. For such relatively simple effects, it is relatively to include the required topographic information in the ground motion databases from available DEM, and to propose relatively simple prediction equations from numerical results. It is likely however that the comparison between informed observations and such simple numerical predictions will be characterized by a large scatter and an underestimation bias, due to the frequent association of surface topography with weathering, fracturing, or sharp mechanical discontinuities leading to presently insufficiently understood coupling effects. The inclusion in site metadata of H/V directionality properties (from either noise or earthquake recordings), will greatly help in understanding the discrepancies, and could offer a path to operational prediction even without complete in-depth understanding of the pysics of these coupling effects.

Finally, concerning non-linear effects, the situation is contrasted between highly sophisticated, multi-parameter non-linear mechanical models calibrated with laboratory experiments, and the general absence of geotechnical site metadata in strong motion databases: even the simple plasticity index, which is identified as an important parameter in controlling the non-linear degradation, is almost never provided. Some knowledge is also still missing for the actual non-linear properties of deep soils, i.e. under large confining pressure uneasy to be reproduced in the lab. So, even if the increasing amount of borehole recordings (in particular from the KiK-net array) has already provided numerous, strong enough recordings to allow purely empirical appraisals of the impact of non-linear site response, testing and validating predictions of NL models for a wide variety of soil conditions (thickness, softness, strength, plasticity) still requires gathering data from dedicated test sites with rich geotechnical information.

As a conclusion, even though all answers are not positive, I do think the available data and numerical studies are very useful in allowing to identify promising research directions. Concerning ground motion databases, it seems feasible in the short to medium term to enrich them with additional site metadata which offer a very good benefit / cost ratio given their performance to explain instrumental or numerical site response, the reliability of the existing measurement techniques, and their affordable cost : fundamental site frequency, H/V directionality, DEM-derived topographic proxies, velocity profiles and associated quantities, dispersion curves. Concerning numerical simulation results, it would certainly be highly beneficial to build open repository platforms where results from diverse teams could be progressively accumulated in a standardized way, which would in turn offer the possibility to build and tes new result-driven models as in presently done with strong motion flat-files. Organizing such platforms is not straightforward, and will require a lot of IT investments, which should however be framed by the objectives of building new models and testing them against instrumental data, which implies a smart structuration with all potential metadata, as well as ways to check the reliability of the numerical results. I hope the present overview paper will motivate young, smart scientists and engineers to commit themselves in such long-term endeavors, although they look tedious and unattractive.

Such perspectives might be proved soon to be completely outdated with the (exponential ?) multiplication of low cost sensors and "big data" analysis tools: there would no longer exist any need for physics-based models, as the quantity and density of recordings would do a better predicting job than a smaller number of recordings with high-quality metadata (though already much larger than simply 3 decades ago at the beginning of the ESG series). My old-fashioned bias is however to consider that physical understanding is always useful.

ACKNOWLEDGMENTS

Some of the results mentioned here were obtained within the framework of various projects: CASHIMA-E2VP, NERA, SERA, SIGMA, SINAPS@. The complete references of these projects are acknowledged in the quoted publications. Similarly, many of these results were obtained in close cooperation with many colleagues from France and other Euro-Mediterranean teams: it is impossible to mention them all here, but their appearance in many quoted publications should be considered as grateful acknowledgements to the benefits of working and discussing with them. I want to specially acknowledge also the priceless benefits, for the whole site effect community, of the huge set of high quality Japanese strong motion recordings and site metadata, and express my sincere thanks to all people who spend much time and energy in installing and maintaining the instrumentation networks, and making their data freely available to the whole world.

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