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► **To cite this version:**

Pierre-Yves Bard, S Singh Bora, F. Hollender, A. Laurendeau, P. Traversa. ARE THE STANDARD VS 30 -KAPPA HOST-TO-TARGET ADJUSTMENTS THE BEST WAY TO GET CONSISTENT HARD- ROCK GROUND MOTION PREDICTION?. Best Practices in Physics-based Fault Rupture Models for Seismic Hazard Assessment of Nuclear Installations: issues and challenges towards full Seismic Risk Analysis , CEA - AIEA, May 2018, Cadarache France. hal-01826648

HAL Id: hal-01826648

<https://hal.science/hal-01826648>

Submitted on 29 Jun 2018

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ARE THE STANDARD V_{S30} -KAPPA HOST-TO-TARGET ADJUSTMENTS THE BEST WAY TO GET CONSISTENT HARD-ROCK GROUND MOTION PREDICTION?

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Abstract. Site-specific seismic hazard studies involving detailed account of the site response require the prior estimate of the hazard at the local reference bedrock level. As the actual characteristics of such local bedrock often correspond to "hard-rock" differing significantly from "standard rock" conditions, standard rock PSHA estimates should be adjusted accordingly. The present practice is based on V_s (S-wave velocity) and " κ_0 " (site specific, high-frequency attenuation parameter) values, and generally predicts larger high-frequency motion on hard rock compared to standard rock. However, it also proves to be associated (Biro and Renault, 2012; Al Atik et al., 2014) with a large uncertainty level, related to (i) the measurement of host and target parameters, and (ii) the forward and inverse passage from the response spectrum domain to the Fourier domain to apply the V_s and κ_0 adjustments. Moreover, recent studies (Ktenidou and Abrahamson, 2016) demonstrate that "first generation" V_{S30}/κ_0 correlation relations are not robust, so that the significant amplification of high frequency content for hard-rock with respect to standard-rock seems questionable. This paper discusses the key aspects of a few, recently proposed, alternative approaches. The calibration of GMPEs directly in the Fourier domain rather than in the response spectrum domain is one example (Bora et al., 2015; Bora et al., 2017). Another example is the derivation of GMPEs, which be valid also for hard-rock conditions (e.g. Laurendeau et al., 2017). In this case the host site response is first removed using theoretical site response analyses (and site velocity profile), or generalized inversions techniques. Finally, when a sufficient amount of records are available at a given site, generic GMPE predictions can be scaled to the site-specific ground motion using empirical site residual ($\delta S2S_S$). Such alternative approaches present the advantage of a significant simplification with respect to the present practice (with thus a reduced number of uncertainty sources); their generalization calls however for high-quality recordings (including high-quality site metadata) for both host regions and target sites, especially for small to moderate magnitude events. Our answer to the question in the title is thus "No, alternative approaches exist and are promising; though, their routine implementation requires additional work regarding systematic site characterization (host) and high-quality site instrumentation (target)".

Key Words: Hard rock – kappa – host-to-target adjustment -.

1 INTRODUCTION

Taking into account the local site response within a seismic hazard assessment study can be achieved following different approaches. The simplest generic methods use GMPE where site conditions are characterized only by simple, single site proxies such as V_{S30} values or soil classes. Such methods cannot capture the whole features of local conditions and may be either

over- or un-conservative. The most advanced, fully site-specific, methods explicitly account for the local site amplification and are preferable for the design of critical facilities, even though they are more complex and may have to cope with additional sources of uncertainties. They need two fundamental elements. First, they need of course an accurate estimation of the local amplification. Second, they need a reliable “reference” ground motion as the input motion on the specific bedrock beneath the considered site: the latter issue is the focus of the present paper.

In site-specific seismic hazard studies it is thus common practice to first assess the ground motion at reference bedrock using Ground Motion Prediction Equations (GMPEs) and then to perform site response analyses to obtain the free field ground motion at the considered site. Provided that the soil column lying above the reference bedrock is well described in terms of dynamic behaviour, this approach has the potential advantage of accounting for more realistic estimates of site amplification than when using generic GMPE site terms. Nevertheless, the characteristics of the bedrock beneath the considered site can significantly differ from those involved in the derivation of the used GMPE. The latter are most often – almost always indeed - representative of “standard” rock conditions with S-wave velocities around 800 m/s, while the reference bedrock for the sites under study often consists of “hard-rock” with S-wave velocities much higher than 1 km/s. The standard practice (e.g., Campbell 2003, Al Atik et al., 2014) recommends performing “host-to-target” adjustments in order to remove the effects of the average rock characteristics of strong motion databases and to replace them by the effect of the bedrock characteristics of the site. These adjustments are presently based on shear-wave velocity V_s and the site attenuation “ κ_0 ” parameter, characterizing the part of the high-frequency decay which is “site-specific”: they are indeed an important source of uncertainty which significantly contribute to the global uncertainties of the SHA, as shown for instance in Biro and Renault (2012). These uncertainties are related to two main uneasy steps: (i) the measurement of host and target parameters; (ii) the forward and inverse passage from the response spectrum domain to the Fourier domain to apply the V_s and kappa adjustments. Concerning the first one for instance, recent studies demonstrated that a) “first generation” V_s30/κ correlation relations are not robust (Ktenidou and Abrahamson, 2016), and that b) the measurement of κ may be significantly biased by site amplification (Parolai and Bindi, 2004, Perron et al., 2017). The consequence is that the amplification of high frequency content for hard-rock with respect to standard-rock obtained with the current practice, does not seem to be relevant anymore.

Alternative approaches to this practice have recently been proposed with the aim of both reducing the uncertainties mentioned above and avoiding to double-count site effects. The present paper intends to highlight the principle and the pros and cons of some of these alternative approaches. After a short overview of the present “ $V_s30- \kappa$ ” adjustment practice, it will address successively the derivation and calibration of GMPEs directly in the Fourier domain rather than in the response spectrum domain (Bora et al., 2015; Bora et al., 2017), the direct derivation of GMPEs for hard-rock reference motion (e.g. Laurendeau et al., 2017), and the use of site-specific, hard-rock residuals ($\delta S2S_S$), to correct the existing GMPEs. The first approach presents the interest to remove the uncertainties associated to the second, uneasy step (ii) above while still using the two site proxies V_s30 and κ , the second one allows to skip all κ -related issues (and thus difficulties linked to steps (i) and (ii) mentioned above) by using only the site velocity proxy, while the third one – which could also be combined with the first two – does not need any site proxy – but requires a large enough number of local instrumental recordings. The conclusion section will highlight the various advantages of these alternative approaches, among which their simplicity with respect to the present practice.

2 PRESENT STATE-OF-THE-PRACTICE

The definition of the “reference” hard-rock ground motion is indeed a critical part of the fully site-specific seismic hazard study. This issue is faced in particular in the (relatively frequent) case of an installation located on a thick alluvial or sedimentary cover (a few tens to a few hundred meters): the amplification phenomena are indeed controlled to the first order by the velocity contrast at the sediment / bedrock interface, and when the latter is deep enough for the bedrock to be un-weathered, its S wave velocity can largely exceed 2000 m/s. Such a situation is encountered for instance in the ILL research neutron reactor in Grenoble, the major part of the Rhône Valley in France where the Messinian crisis led to deep indentation of the bedrock, now filled with sediments, or even in the Cadarache area characterized by relatively stiff soils overlying high velocity limestone (Garofalo et al., 2016; Hollender et al., 2018).

The current Ground Motion Prediction Equations (GMPEs) are poorly constrained for hard-rock site conditions due to the lack of accelerometric stations installed on such geological conditions (even those on "standard rock" are not so frequent, and too often lack detailed geophysical characterization).

2.1 V_{S30} -kappa adjustment

The current standard procedure to adjust the ground motion predicted for "standard-rock" to "hard-rock" has received the name of 'host-to-target adjustment' (HTTA in the following). It has been applied for example for the re-evaluation of seismic hazard for Swiss nuclear power plants (PEGASOS and PRP projects, Biro and Renault, 2012) and for the 'Thyspunt Nuclear Siting' project in South Africa (Rodriguez-Marek et al., 2014).

The basic principle (Campbell, 2003, Cotton et al., 2006, Al Atik et al., 2014) is to (try to) take into account any possible differences in source, propagation, and site conditions between the host area and the target site using physics-based models. These adjustments thus require, in principle, a good understanding of the physical phenomena controlling ground motion, as well as a well-defined procedure for adjusting the corresponding GMPE terms or the resulting hazard values. However, the corresponding adjustments to the source (e.g., stress drop) and crustal propagation terms (e.g., quality factor, Moho depth) are generally only minimally constrained for "host" regions, and the main correction is limited to a theoretical adjustment factor based only on two types of corrections, one corresponding to an impedance effect linked to the V_{S30} proxy, and another one linked to the site specific attenuation at shallow depth, characterized by the high-frequency decay parameter κ_0 . The present standard HTTA procedure is thus called V_S - κ adjustment. In short, the physics based adjustments are made in the Fourier domain and transposed in the traditional domain of response spectra via random vibration theory (Campbell, 2003, Al Atik et al., 2014), via two correction factors:

- The first correspond to the crustal amplification factor, and is based on the impedance effects modeled by the 'quarter-wavelength' approach (QWL in the following) initially proposed by Joyner et al. (1981). As shown by Boore (2003), the crustal amplification estimate is derived from the S-wave velocity profile down to the very deep bedrock, and exhibits a smooth and monotonous increase with frequency, with a maximum high frequency value of the order of the square root of the ratio ($V_{S_surface} / V_{S_deepbedrock}$). The resonance effects related to possible superficial or deep contrasts are neglected in this impedance correction. Moreover, its application requires the knowledge of the 'average' velocity profile (down to several kms depth) of both the host region and target site. As the former is most often unknown in practice – if not the latter...-, the workaround strategy is

to use a family of 'standard profiles' that are anchored on the available, shallow velocity values (V_{S30} , cf. Boore and Joyner 1997 and Cotton et al. 2006).

- The second one is related to the difference of the site-specific attenuation (characterized by the high-frequency decay parameter κ_0) between the host region and the target site, and introduces a modification of the high frequencies: if the target site attenuates less than the rocky sites of the host region ($\kappa_{0_target} < \kappa_{0_host}$), ground motion on hard rock is thus enriched at high frequency.

It has indeed been commonly accepted over the last two decades that the parameter κ_0 decreases when stiffness increases. The combined effect of impedance (QWL) and attenuation κ_0 thus generally leads to a slight decrease in low frequency motion (impedance effect), and a high frequency increase (attenuation effect), for 'hard' rock compared to 'standard' rock. The latter result, though accepted in the engineering community over the last two decades, is however considered counterintuitive by some seismologists, and is worth a careful analysis and discussion.

2.2 Practical limitations

Applying such an HTTA procedure requires the knowledge of V_{S30} and κ_0 values (and of the associated uncertainties) for the host region, and their measurement for the target site. The latter requires numerous enough, high-quality, on site instrumental recordings, and careful processing, while for the host region(s), this a priori knowledge seems reasonable for V_{S30} , but very optimistic for κ_0 , the estimate of which must generally be made a posteriori. The practice of the procedures proposed by (Campbell, 2003, Al Atik et al., 2014) prove to be rather heavy and sometimes subjective. This HTT approach is thus affected by a rather high level of epistemic uncertainty related to several factors, detailed below, which may strongly impact the hazard and risk estimates at long return periods. These uncertainties are of four types: the first one is related to the physics behind the so-called " κ_0 " parameter, the second one is associated with the host region, the third one with the target region, and the last one is associated with the method for defining the adjustment factor.

- The physics underlying the use of the κ / κ_0 parameters is assumed to be the attenuation features beneath the studied site. Low attenuation (assumed to be associated to hard rock) results in a rich high frequency content and a low κ_0 parameter. This is indeed a fact that most rigid sites statistically produce recordings with the higher amount of high frequency content. However, this feature can be explained not only by a "lack" of attenuation (the only invoked phenomenon within the usual κ_0 interpretation), but also by local amplifications generated by less rigid, thin surface layers that cause high-frequency resonance. The latter phenomenon is actually very common for free-field "rock" stations because of the presence of weathered layers. FIG 1 shows example amplifications for three accelerometric stations on rocky sites from the RAP (French accelerometric network) (Hollender et al., 2017). The significant high frequency amplifications are due to local amplification of shallow, weathered layers. This feature questions the accuracy of κ parameter for such situations that are very common in strong motion databases. There are also other phenomena that may bias the high frequency content of recordings, and therefore the κ_0 estimate and its interpretation in attenuation only, such as local instrumental setup choice or the installation depth of sensors, are illustrated in Hollender et al. (2018)
- In general, on the 'host' side, the S-wave velocity profile (involving not only V_{S30} , but also its shape down to several kilometers depth) and κ_0 are, at best, poorly known, and, in

general, are not constrained at all, which leads to the use of generic velocity profiles (Boore and Joyner, 1997, Cotton et al., 2006), and κ_0 values derived from statistical correlations $V_{S30}-\kappa_0$, such as those proposed by Silva and al. (1998), Chandler et al. (2006), Douglas et al. (2010), Drouet et al. (2010), Edwards et al. (2011), Van Houtte et al. (2011) or Kottke (2017). Their analysis reveals a large variability in average trends from one study to another, as well as a huge dispersion of raw data. Most recent studies indicate that the low κ_0 values proposed in the late 90's - 2000's for hard rock on the basis of very few data and too quick estimates could be affected by significant biases or measurement problems. In particular, Ktenidou and Abrahamson (2016) analyzed a set of records corresponding to sites with (inferred) $V_{S30} \geq 1500$ m/s (especially in the Eastern United States) from which reliable κ_0 measurements could be performed: they report both significantly higher κ_0 values (around 0.02 s) than expected from the usual correlations, and observed hard rock motion comparable or smaller than standard rock motion, over the entire frequency range, including high frequency.

- On the target side, even if the same type of "correlation" approach as for the host region can be used when there is no site-specific κ_0 measurement, it seems highly preferable (and consistent with a site-specific study) to derive site-specific values from an ad-hoc instrumentation, allowing the velocity profile and the κ_0 value to be much more precisely constrained. Even in the latter case, the measurement can still be affected by several biases, as illustrated in FIG 1 and Parolai and Bindi (2004), which can explain the dispersion of $V_{S30}-\kappa_0$ correlations, depending on the care taken to measure κ_0 .
- Finally, two main sources of methodological uncertainties can be identified in the current HTT approaches. First, the use of the impedance-only approach (or "quarter wave length" - QWL) to estimate the amplification functions related to the rock velocity profile, neglects the effects of resonance and can not therefore account for high-frequency amplification peaks at many rocky sites (Steidl et al., 1996, Cadet et al., 2012). Then, the necessary back-and-forth conversions between the two spectral domains (Fourier and response spectra) via random vibration theory (RVT and IRVT, see Al Atik et al., 2014, Bora et al., 2015), introduce uncertainties because this process is highly nonlinear and non-unique, especially in the high-free-quency range (Bora et al., 2016). It can be noted that most of these uncertainties come from the lack of knowledge of the rock velocity profiles and of the exact values of κ_0 for the host regions.

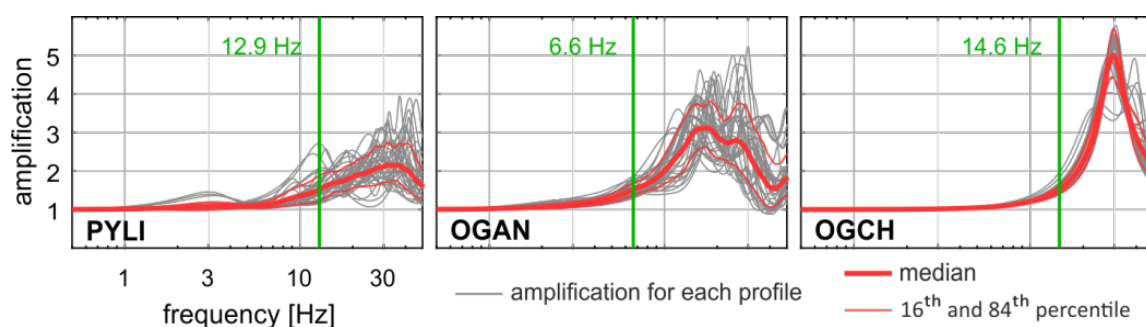


FIG 1: Example of 1D transfer functions computed using the V_S profiles inferred from surface-wave inversion for 3 RAP (French accelerometric network) rock sites. For each station, 33 1D Transfer Functions were computed using 33 different profiles to account for V_S profile uncertainties (grey lines), as well as their mean and standard deviation (red lines). All stations exhibit high-frequency amplification due to shallow weathered layers. The frequency identified by the green vertical line is the one above which amplification > 1.5 . From Hollender et al. (2017).

3 ALTERNATIVE APPROACHES

3.1 Fourier domain GMPEs

A first alternative approach consists in removing the variability associated with the back-and-forth passages from the response spectra to the Fourier domains, by working primarily in the Fourier domain. This may be done in two ways:

- Using generalized inversion techniques to identify the respective contributions of the source, path and site terms in the Fourier domain with some a priori models such as the Brune model for the source (characterized by its moment M_0 and stress-drop $\Delta\sigma$), a given, parametric geometrical spreading functional form $G(R)$, an anelastic attenuation term (" κ "), combining the crustal (Q) and site (" κ_0 ") contributions, and a frequency dependent site term. Such an approach, which is closely related with forward stochastic modelling using point sources as proposed by Boore (1983), has been implemented with the present scope in Bora et al. 2015, 2017, following a long list of studies using generalized inversion studies aiming at retrieving source, path or site terms (e.g., Drouet et al. 2008, 2010).
- Deriving "GMPEs" in the same way for Fourier spectra as for oscillator response spectra, i.e., in a purely empirical way where a priori functional forms with unknown coefficients are driven by the underlying physics (Bora et al., 2015)

In both approaches, there is still however one passage from Fourier to response spectra (the less problematic one), which is performed using forward RVT and assumptions or empirical models about duration (Bora et al 2015)

Such approaches offer the advantages a) to provide a means to estimate directly the "host" κ_0 value in a somehow physical – though indirect – way, and b) to allow an easy correction of crustal amplification and attenuation terms directly in the Fourier domain. For instance, the recent application to the European RESORCE data set (Bora et al., 2017) led to κ_0 values for nearly one hundred stations (FIG 2), with several interesting observations: a large event-to-event variability for a given site, the absence of obvious correlation between κ_0 values and either V_{S30} , or site class, the class-to-class changes remaining much smaller than the event-to-event variability.

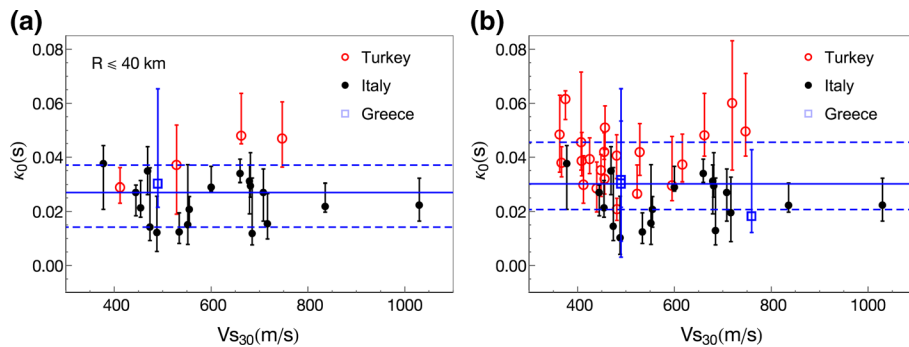
There still exist however several limitations which hamper the generalization of such results:

- The very small number of rock stations with measured V_{S30} values (TAB. 1)
- The significant trade-off between the geometrical spreading term $G(R)$, the crustal attenuation term (Q_0 – with or without frequency dependence) and the site-specific attenuation term (κ_0), as illustrated in FIG 3, so that those approaches cannot provide an "absolute" estimate of the site κ_0 value. The set of obtained values for $G(R)$, $Q_0(f)$ and κ_0 , can however be used together in forward modelling. So that HTT adjustments remain possible though requiring much care about the consistency of the three terms
- The use of a "generic" crustal velocity profile imported from elsewhere (California) to estimate the "reference rock" crustal amplification, together with the use of the quarter wave-length approach to estimate the associated amplification, which thus leads to

neglect possible high-frequency resonance effects and may induce some bias in κ_0 estimates.

TAB. 1: Site class median κ_0 values together with the 16-84% percentile range for Italy, Turkey and other European areas, together with the estimates of average, frequency independent crustal quality factors (From Bora et al., 2017). For each site class in each region, N_R indicates the number of recordings from which the 16, 50 and 84th percentiles are derived.

Area	Soft soil ($V_{S30} \leq 180$ m/s)		Usual soil (180 - 360 m/s)		Stiff soil (360 - 750 m/s)		"Rock" ($V_{S30} > 750$ m/s)		Crustal quality factor Q_0
	N_R	Median value, (16-84 % percentile range)	N_R	Median value, (16-84 % percentile range)	N_R	Median value, (16-84 % percentile range)	N_R	Median value, (16-84 % percentile range)	
Italy	32	0.029 (0.019 – 0.062)	83	0.0271 (0.017 – 0.044)	219	0.0224 (0.010 – 0.039)	38	0.0212 (0.008 – 0.032)	601
Turkey	14	0.0395 (0.027 – 0.047)	330	0.0433 (0.027 – 0.068)	315	0.0416 (0.028 – 0.061)	8	0.0495 (0.032 – 0.066)	1462
Other	-	-	43	0.0267 (0.011 – 0.047)	96	0.0271 (0.012 – 0.043)	22	0.0232 (0.005 – 0.045)	780



The generalization of such approaches would thus benefit from a larger number of rock stations, and from more sensitive instruments to increase the number of records for each station, and as much as possible to reduce the site event-to-event variability in κ_0 estimates.

FIG 2: κ_0 estimates obtained for European stations located on stiff sites ($V_{S30} > 360$ m/s) and having more than 10 recordings, plotted as a function of the corresponding V_{S30} values. On the left, only small distance recordings are used ($R < 40$ km), while the right plot accounts for all recordings for each station. Markers (empty circles, disks and empty squares indicate the median, while vertical bars indicate the range of 16-to-84 percentile of each station, i.e., the event-to-event variability. The horizontal solid line indicates the median value of all stations, while the two dashed lines indicate the corresponding 16 and 84 percentiles of all station median values, i.e., the between-station variability (From Bora et al., 2017)

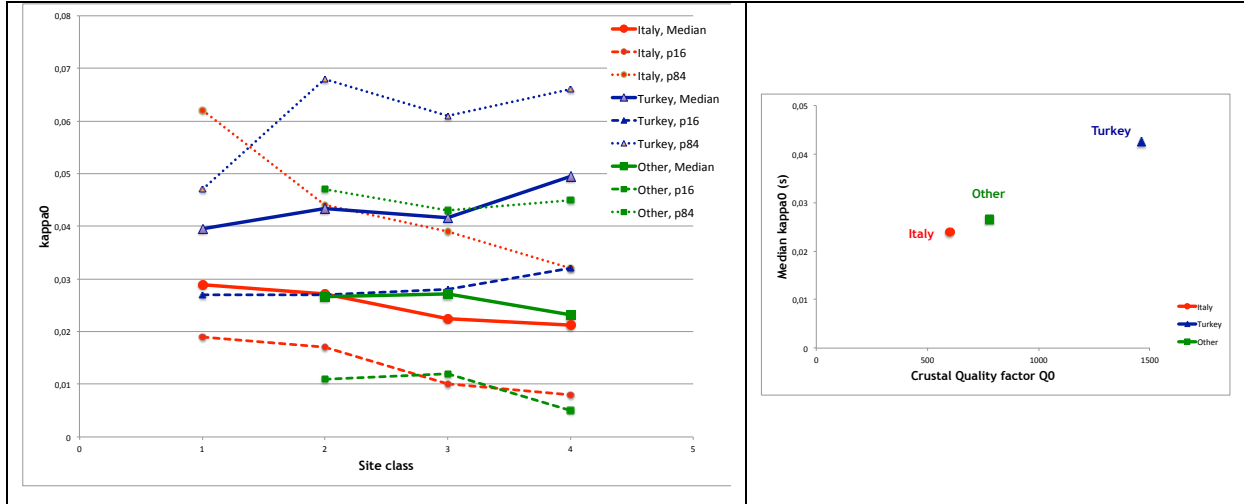


FIG 3: Variability of the site-class specific κ_0 values derived from the RESORCE data base (Bora et al., 2017). Left: variation of κ_0 values with site class (from soft soil ("1") to rock ("4")) for Italy (red), Turkey (blue) and Other European areas (green). Solid line= median values, dashed line = 16% percentile, dotted line = 84% percentile. Right = variation of median regional κ_0 values with the inverted average, frequency independent quality factor.

3.2 Hard-rock GMPEs

The basic idea is to avoid all κ_0 related issues by establishing GMPEs directly for rock motion, which be related only to the rock stiffness, i.e., the V_{S30} value. However, at present, the only available rock recordings which combine a large enough number with reliable, measured site metadata, are the deep sensor recordings of the KiKnet network. This direction was first explored by Cotton et al. (2008) or Rodriguez-Marek et al. (2011) who proposed GMPEs established directly from these deep recordings; their models are however not used in SHA studies because of the reluctance of many scientists or engineers to use depth recordings that are contaminated by a 'within motion' effect, and are therefore smaller than outcrop motion – even with the same rock velocity.

The first explored approach was therefore to simply correct these deep sensor recordings using the depth-correction function proposed by Cadet et al. (2012). In short, the within-motion modulation induced in depth by interference between upgoing and surface-reflected downgoing waves, is characterized, in the Fourier domain, by a maximum reduction at a frequency f_{dest} controlled by the depth Z of the sensor and the average speed V_{SZ} between the surface and the sensor ($f_{dest} = V_{SZ} / 4Z$), possibly with smaller reductions at higher harmonics. At low frequency ($f \ll f_{dest}$), the wavelength is much greater than the depth of the sensor, and the motion at depth is therefore identical to the outcropping surface motion, while at high frequencies ($f \gg f_{dest}$), the interference effect leads to an average decrease close to a factor of 2, corresponding to the free surface effect. Cadet et al. (2012) proposed a correction function to be applied on the response spectra, therefore corresponding to a smoothed version of the Fourier domain modulation: the surface / depth ratio (oucrop / within motion) varies from 1 at low frequency to a maximum of about 2.5 for $f = f_{dest}$, stabilizing around 1.8 for $f > 5 f_{dest}$, according to the following expression:

$$DCF(f) = C_1(f) * C_2(f),$$

$$\text{with } C_1(f) = 1 + 1.6 \frac{\text{atan}(f/f_{dest})}{\pi} \text{ and } C_2(f) = 1 + 0.8e^{-\{(f/f_{dest} - 1)^2 / 0.09\}}$$

Its application therefore only requires the knowledge of the value of the fundamental frequency of destructive interference f_{dest} , which can be obtained in two different ways: from the (known) velocity profile $V_S(z)$ between 0 and Z , and also from the average H/V ratio of deep recordings (which exhibit a minimum around f_{dest}): these two approaches are possible for deep KiKnet recordings, and have been found to produce comparable estimates of f_{dest} .

Nevertheless, as the availability of deep recordings together with bedrock velocity is only exceptional, Laurendeau et al. (2017) also explores another approach which can be applicable to surface data from other networks. It consists in taking advantage of the knowledge of the velocity profile between 0 and Z to deconvolve the surface motion of the corresponding theoretical transfer function, calculated with the reflectivity method for vertically incident S waves. In addition to a strong implicit assumption of only 1D surface effects, this approach also requires additional assumptions about the profile, regarding especially the quality factor or attenuation profile. In the absence of direct measurements, the current approximation of proportionality $Q_S(z) = V_S(z) / X_Q$ with $X_Q = 10$ was selected, but a sensitivity study was conducted using X_Q values ranging from 5 to 50. Moreover, the 1D hypothesis was tested by comparing the digital transfer functions with direct observations (surface / depth ratios), and retaining only the sites for which this comparison is satisfactory according to the correlation criteria proposed by Thompson et al. (2012). Here again, a sensitivity study was conducted to evaluate the robustness of the results with regard to the correlation threshold selected for the selection of 1D sites.

These two approaches were applied by Laurendeau et al. (2017) to the KiKnet data subset, using data obtained between 1999 and 2009 on stiff sites with $V_{S30} \geq 500$ m/s and V_{SDH} depth velocity ≥ 1000 m/s, corresponding to crustal earthquakes with magnitudes ≥ 3.5 and depth ≤ 25 km. Such selection criteria resulted in a set of 2086 recordings, corresponding to 272 events and 164 sites. The data distribution in terms of V_{SDH} is almost uniform between 1000 and 3000 m/s, which allows, if the procedures are correct, to achieve the desired goal.

Once these two independent estimates of hard-rock outcropping motion are obtained, the last step is then to establish GMPEs according to the standard procedures in order to be able to quantify the dependence of ground motion on rock stiffness using the "c₁" site coefficient in the following, simple, GMPE functional form:

$$\ln(SA(T))_{es} = a_1(T) + a_2(T) \cdot M_w + a_3(T) \cdot M_w^2 + b_1(T) \cdot R_{RUP} - \ln(R_{RUP}) + c_1(T) \cdot \ln(V_S/1000) + \delta B_e(T) + \delta W_{es}(T)$$

(Where $SA(T)$ is the spectral acceleration for the oscillator period T , M_w is the moment magnitude, R_{RUP} the distance to rupture, V_S the rock velocity (V_{S30} at surface or V_{SDH} for corrected surface or down-hole recordings), and δB_e and δW_{es} are the between- and within-event residuals, respectively).

Such relationships offer the advantage of not requiring any other site characteristic than the V_S value; in other words, any possible correlation between V_S and κ_0 is "hidden" behind the V_S dependence, but implicitly accounted for. They have been established for several datasets:

- The original set of surface recordings (DATA_surf) and deep recordings (DATA_dh), the validity range of which correspond to 500-1000 m/s and 1000-3000 m/s, respectively.
- the corrected estimates SURFcor and DHcor (whose range of validity spans the range of down-hole velocities, i.e 1000-3000 m/s)
- Hybrid sets combining these last two sets with DATA_surf (whose validity range in V_S thus extends from 500 to 3000 m/s).

The main result of this work is summarized in FIG 4, which represents the ratio between the estimates on standard rock motion ($V_{S30} = 800$ m/s), and on a "very hard" rock ($V_{S30} \approx V_{SDH} = 2400$ m/s) for the HTT approach implemented in a traditional way with the correlation relationships from Van Houtte et al. (2011), and for the alternative approaches discussed in the present section. It shows a good agreement at low frequency until about 2-3 Hz, where the impedance effect results in a slight (20 to 30%) increase, and a strong disagreement at high frequency (beyond 5 Hz). The average correlation between V_{S30} and κ_0 used in Van Houtte et al. (2011) leads to κ_0 values around 0.008 s for hard-rock, so that the effects of very small attenuation dominate those of higher impedance at high frequency: HTT approach predicts a larger hard-rock motion (compared to standard rock) beyond 7-8 Hz, with an amplification up to a factor 2 at 20-30 Hz. All other estimates obtained by Laurendeau et al. (2017), whatever the initial data set and the correction procedure, indicate that the impedance effect is also dominant at high frequency, with reduction factors 2 to 3 compared to the standard rock for frequencies above 8 Hz. The resulting difference between hard-rock motion predictions thus reaches a ratio about 4 at high frequency between the usual HTTA approach involving the usual $V_{S30} - \kappa_0$ correlations, and alternative approaches based on hard-rock GMPEs built from KiKnet data.

The magnitude of these high frequency differences obviously depends on the rock stiffness: they become negligible for rocks having S-wave velocities below 1200 m/s, but are even larger for very hard rock such as the one present underneath the Grenoble basin, with VS close to 2.8 km/s).

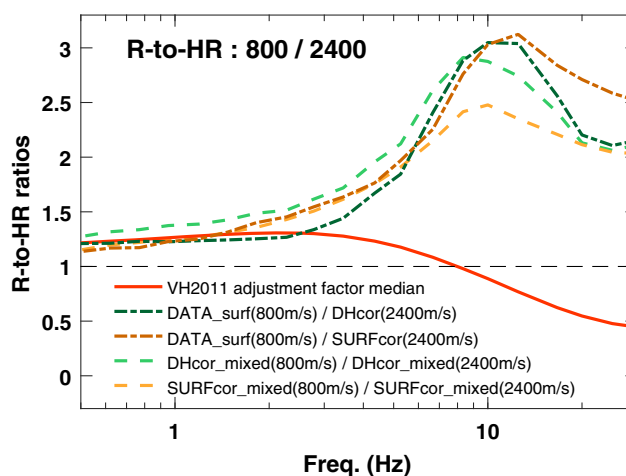


FIG 4: Comparison of the ratios between standard rock ($V_{S30} = 800$ m/s) and hard-rock ($V_{S30} = 2400$ m/s) obtained with the GMPEs derived by Laurendeau et al. (2017) (dashed lines), and those predicted with the HTT approach and the $V_{S30}-\kappa_0$ correlation of Van Houtte et al. (2011). The specific scenario considered here is ($M_w = 6.5$; $R_{RUP} = 20$ km). From Laurendeau et al. (2017).

The robustness of the median results obtained with the two correction approaches (SURF_cor and DH_cor, see FIG 4) supports the questions about bias in the HTT approach, and their possible origin as discussed above in section 2.2. As stated in the discussion section of Laurendeau et al. (2017), the high-frequency amplifications observed at the surface of KiKnet sites are underestimated in the HTT approach using generic profiles, and are likely to strongly bias the instrumental estimation of the high frequency attenuation coefficient κ , with an overestimation trend for "standard" rock (measure of κ in a frequency band beyond the peak

amplification), and an underestimation trend for “hard” rock (measurement of κ in the frequency band below the amplification peak). This interpretation is supported by the latest, higher quality κ_0 measurements on hard-rock sites by Ktenidou and Abrahamson (2016) and Perron et al. (2017). It should be noted, however, that the hard-rock to standard-rock ground motion ratios obtained by the former are closer to unity than those of FIG 4, especially at high frequency, but that only a few of the hard-rock sites they consider have measured V_{S30} values. The final answer of the current questions will undoubtedly come from high quality rock recordings for which both V_{S30} and κ_0 values are carefully measured.

3.3 Site-specific residuals

The idea, which is implemented for instance in Kotha et al. (2017), is simply to take advantage of the recordings available at a given site to evaluate, for each GMPE of interest, the site-specific residual term $\delta_{S2S}(T)$ (average of $\delta W_{es}(T)$ over all recordings) so as to tune each of them to the specific site under study. An example is given for instance in Ktenidou et al. (2017) for the Euroseistest site, from which is extracted FIG 5.

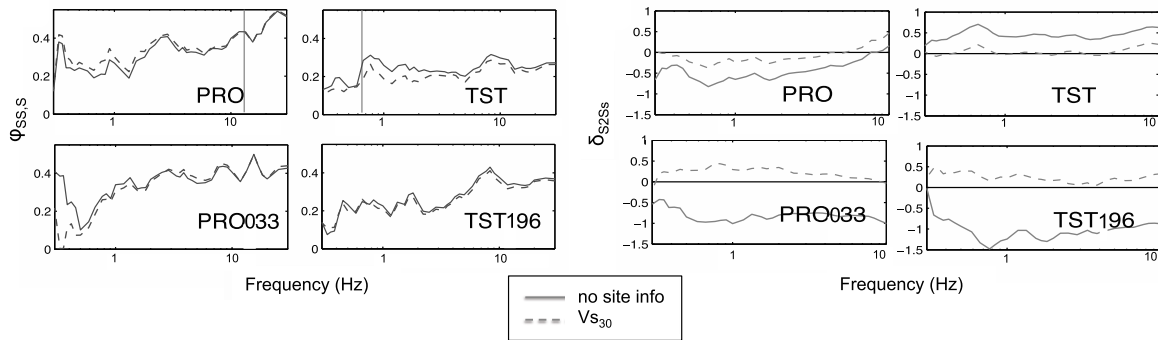


FIG 5: Period-dependence of site term residuals $\delta_{S2S}(T)$ (right) and of the associated variability $\phi_{S2S}(T)$ (left) for 4 recording sites of the Euroseistest array. PRO is an outcropping rock site with a V_{S30} around 600 m/s, PRO33 and TST196 are down-hole rock sites with VS around 1400 and 1900 m/s, respectively, while TST is a surface, soft site ($V_{S30} = 186$ m/s). The solid line correspond to the case where no site term is included in the GMPE, while the dashed line corresponds to the case where the GMPE includes a site term related to the site proxy V_{S30} . (From Ktenidou et al., 2017).

This approach is very appealing, as it combines the site-specificity from the available local recordings and the robustness of GMPEs derived on much larger and diverse data sets, and it should definitely be encouraged whenever possible. It should however be emphasized that such a local-global combination is possible if and only if a) the available local recordings have a good enough quality to offer an acceptable SNR ratio over a broad frequency range, and are sufficiently numerous and diverse to prevent such residuals to be present a single-path bias (see Maufroy et al., 2017), and b) they fall fully in the (magnitude – distance) range of validity of the considered GMPEs: if the latter condition is not fulfilled, the δ_{S2S} site residual estimates are likely to be significantly biased by errors in magnitude or distance scaling, and cannot thus be applied to other sets of magnitude – distance than those corresponding to the available recordings.

FIG 6 compares the distribution of available recordings for three European sites located in different seismicity contexts: the Provence site (top left, Perron et al., 2017) is located in a low-to-moderate seismicity context; the Argostoli site (top right, Perron, 2017), is located in Argostoli in Cephalonia Island (Greece), one of the most active areas in Europe; Euroseistest

(bottom, Ktenidou et al., 2017) is located in the Mygdonian graben east of Thessaloniki, in a relatively active area. The first set of data consists of 774 recordings obtained over a 15 year long period by accelerometers operated on a triggered mode (2000-2011, 237 recordings) and mid-band, continuously recording velocimeters (07/2012-07/2014, 537 recordings). The second one has been mainly obtained on sensitive, continuously recording accelerometers during a 16 month post-seismic campaign following a sequence of 2 magnitude 6 events (Theodoulidis et al., 2016) temporary and gathers over 6000 events, mainly from aftershock activity. The third one has been gathered over a 20-year period on a dedicated accelerometric instrumentation (Pitilakis et al., 2013).

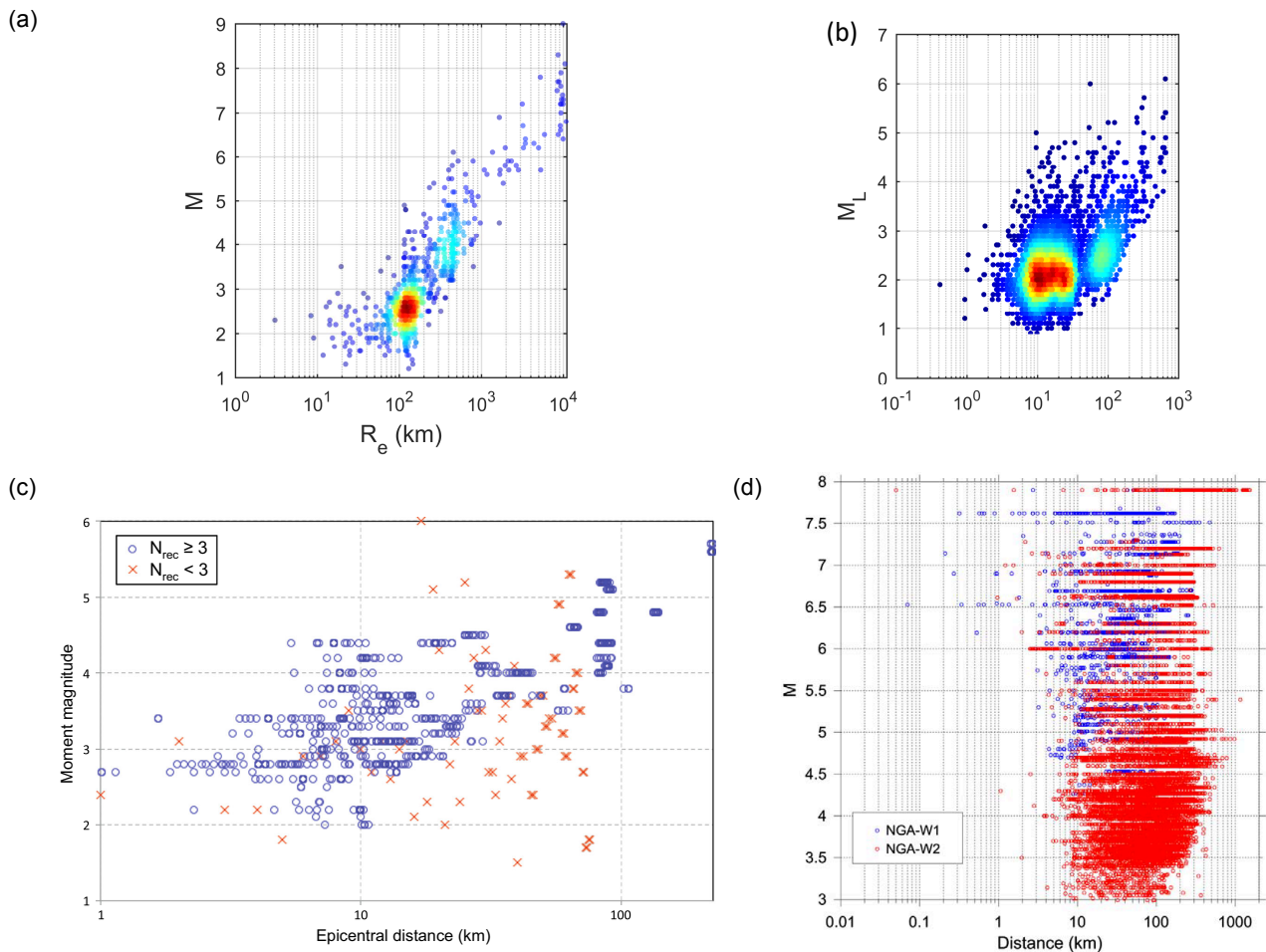


FIG 6: Example magnitude-distance distributions of site-specific data recorded at three sites in different seismicity contexts: a) top left: Provence (Southeastern France), from Perron et al., 2017. b) Top right: Argostoli (Cephalonia Island, Greece) from Perron (2017); c) bottom left: Euroseistest (Mygdonian basin, Greece), from Ktenidou et al., (2017). On bottom right is shown for comparison the similar magnitude-distance distribution for the NGA-W1 (blue) and NGA-W2 (red) databases (Ancheta et al., 2017)

It thus turns out that whatever the site, over a limited period of time (from a few years to two decades), the heart of the recorded data does not suit the validity range of most existing GMPEs: is this especially true in low to moderate seismicity areas (Provence) where moderate to large magnitude recordings ($M \geq 4$) correspond only to distant events ($R \geq 100$ km), and shorter distance recordings mostly correspond to magnitude 2-3. Even at a site

instrumented for 2 decades in a relatively active area (Euroseistest), most of available recordings correspond to magnitudes between 2 and 4. Today, there exist only very few GMPEs, which are valid down to magnitude 2 at distances of several tens of kilometres: for instance the NGA (Chiou et al., 2008), and RESORCE (Akkar et al., 2014) are valid only for magnitude above 4. The NGA-West2 project (Ancheta et al., 2014) made a huge effort to include recordings from events down to magnitude 3 (see FIG 6d), and the next challenge ahead of the engineering seismology community is to build consistent, homogeneous data bases, with rich enough metadata, so as to develop GMPEs which be valid from magnitude 2 to over 7, and for distances from a few kilometres to a few hundred kilometres. This implies not only to structure the coordination between network operators (as is done for instance in Europe with the NERA, SERA and EPOS projects), but also a significant amount of additional funding for network operators for building the required metadata (precise source location, homogeneous magnitude scales, measured site conditions). In particular, it was concluded both by Ktenidou et al. (2017) and Maufroy et al. (2017) with two different approaches, that the between-event variability τ is, as expected, very sensitive to the quality of the hypocentre location. This result emphasizes the need for dense seismological networks in moderate seismicity areas, so as to have a location precision less than 2 km.

Seismic motion recordings (weak and strong) are thus an indispensable contribution to the understanding and prediction of seismic hazard. So, besides this challenging issue regarding the GMPEs database and validity range, another important item deals with the type of instruments to be used in order to optimize the amount and use of local instrumental recordings. Traditionally, empirical seismic hazard estimates are obtained with accelerometers because they do not clip in case of strong events. These instruments are therefore traditionally recommended in instrumenting critical infrastructures and recording local events of significant magnitude; their limited sensitivity prevents them from recording weaker motions. In areas of low to moderate seismicity, the occurrence of moderate to large events is however rare, and good quality recordings with good signal-to-noise ratio (SNR) over a broad enough frequency range are unlikely to be obtained with such instruments within a "reasonable" time.

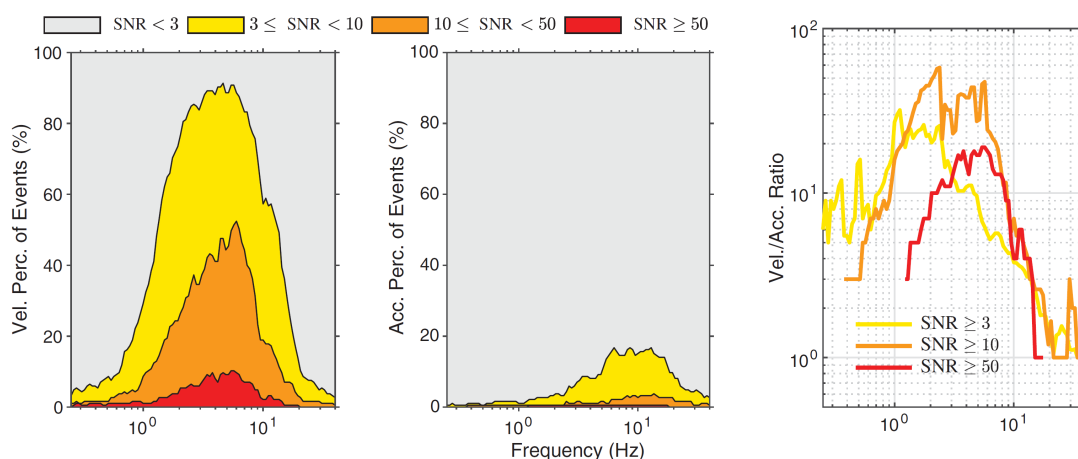


FIG 7: Comparisons between the number of good quality recordings obtained in a moderate seismicity site in Provence (France) on velocimetric and accelerometric instruments over the same period of time. A total of 185 events were considered. Left: percentage of velocimeter recordings satisfying four different ranges of signal-to-noise ratios (SNRs) as a function of frequency. Middle: same thing for accelerometric recordings. Right: ratio between the number of velocimeter and accelerometer recordings that satisfy the same SNR criteria. From Perron et al. (2017).



Perron (2017) thus addressed the issue of the quality and quantity of recordings that can be acquired in a low seismicity area over what is considered as a reasonable time, i.e. a few years. He compared, in the industrial site in Provence, France, for which the local noise level is rather low, the number of good quality recordings obtained with classical accelerometers and mid band velocimeters within a two and a half year period. The conclusion is that the latter provide 30 to 50 times more recordings with $\text{SNR} \geq 3$ at low and medium frequency, than the former (FIG 7). Of course, this low seismicity database is not comparable in terms of quantity and quality of recordings to a strong motion database, but it is sufficient to provide very useful, quantitative site-specific information such as site amplification in the linear domain, site residual δ_{S2S} (T) without any "single-path" bias, κ_0 measurements... An important recommendation for critical facilities in low to moderate seismicity areas where seismic hazard has to be accounted for, is therefore to promote the use of mid-band velocimeters operating on a continuous recording mode. As they provide more rapidly higher quality recordings, they do help in constraining the local hazard estimate.

4 CONCLUSIONS AND RECOMMENDATIONS

We consider the work achieved over the last years and reminded above did lead to significant progress on the "reference motion" issue. Up to recently, only very few methods for GMPE adjustments ("host-to-target" adjustment HTT) were available, and thus widely used for large industrial projects, despite rather fundamental questions as to their physical basis, and several practical issues in their actual implementation (especially on the parameter κ_0). The developments by Bora et al. (2015, 2017), Laurendeau et al. (2017), Perron et al. (2017) and Ktenidou et al. (2017) showed that alternative approaches are possible for a more satisfactory tuning of ground motion predictions for specific hard rock sites, without adding new sources of epistemic or aleatory uncertainties. So our to the title question is clearly "no!", as there exist consistent, robust evidence that conventional HTT approaches are very likely to overpredict hard rock motion, at least at high frequency.

Nevertheless, the implementation of the alternative approaches listed here involves, for all of them, to invest in in-situ, instrumental measurements for both the host regions and target sites: approaches still using κ_0 values (Bora et al., 2015, 2017) require high-quality instrumental recordings to avoid trade-off effects with other attenuation parameters, those aiming at deriving directly hard-rock GMPEs require systematic site surveys at each recording site to allow deconvolving the surface recordings from the site response, and those based on the use of site residual imply high-quality recordings at the target site, and an extension of GMPEs to small magnitude events.

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