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TOWARDS THE DEFINITION OF REFERENCE MOTIONS (1000<VS<3000 M/S): ANALYSIS OF THE KIK-NET DATA AND CORRECTION OF THE LOCAL SITE EFFECTS

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Abstract

A key scientific component in Seismic Hazards Analysis (SHA) is the assessment of a local hazard for hard rock sites ($1000 < V_{S30} < 3000$ m/s), either for applications to installations built on this site category, or as a reference motion for site effect computation. Within the context of SHA, empirical ground motion prediction equations (GMPEs) are the traditional basis for estimating shaking intensities and V_{S30}, the time-averaged shear-wave velocity in the upper 30 meters from the surface, is the basis to account for site conditions. The current GMPEs, however, are not well constrained for V_{S30} larger than 1000 m/s (only a few records on high V_{S30} sites are included in the main accelerometric databases). The presently used approach is based on host-to-target adjustment techniques based on V_{S30} and κ_0 values. This study is investigating alternative methods to estimate reference motions on site effect free, very hard rocks ($1000 < V_{S30} < 3000$ m/s).

We explore methodologies to obtain a prediction for reference motions ($1000 < V_{S30} < 3000$ m/s) by using the "rock" Japanese KiK-net sites with $500 < V_{S30} < 1350$ m/s. Each site presents the advantages of having sensor pairs (one at the surface, and one installed in a borehole at depth between 100 and 200 m for most sites and up to 2000 m) and geotechnical characterization (P- and S-wave velocity profiles) for surface and down-hole sensors. Firstly, the "rock" transfer functions are estimated in two ways: empirically (spectral ratios between surface and depth records) and theoretically (linear SH1D simulation). These two approaches are compared to validate the input parameters and also to select the stations for which the 1D approximation is verified. Then, two new accelerometric datasets characterizing hard rock sites ($1000 < V_{S30} < 3000$ m/s) in free surface condition are developed:

1. Down-hole recordings are modified from within motion to outcropping motion with the depth correction factor developed by Cadet et al. (2012),
2. Surface recordings are deconvolved from site-specific effects with a (surface / outcrop rock) amplification factor derived with the site velocity profile and 1D simulation.

GMPEs with simple functional forms are then developed for each dataset, with a site term based on V_{S30} (assumed to be equal to V_S at downhole sensor depth) and the results are compared, for a specific scenario, to the result obtained with the traditional host-to-target adjustment approach: our hard-rock GMPEs lead to significantly lower estimates at short periods.

Keywords: Hard Rock reference motion – Site effects – KiK-net – GMPE – « host-to-target » adjustments

1. Introduction

A key scientific question in Seismic Hazard Analysis [SHA] is: how do we assess regional seismic hazard? Which methods can we use to obtain a seismic reference motion that be free of site effects? In this paper, this issue will be discussed by investigating a new methodology to develop Ground Motion Prediction Equation [GMPE] for sites characterized by $V_{S30} \geq 1500$ m/s.

To assess regional seismic hazard in areas of low-to-moderate seismicity (classically called target region), we typically use GMPEs, which are based on seismic records from surface stations located in active shallow crustal regions (host region). These GMPEs are in most case developed by mixing different site categories, with a majority of soil sites (see Ancheta et al. 2014 [1] for the NGA West 2 database; Akkar et al. (2014) [2] for the RESORCE database). In the most popular GMPEs, the site is described with respect to the average shear wave velocity over the upper 30 m (V_{S30}) [e.g., 3]. Several studies have shown the interest to also describe the rock motion with respect to its high frequency attenuation properties [e.g., 4-7]. The proxy that is often used in the engineering seismology community to characterize high-frequency content of records at a specific site is κ_0. Anderson and Hough (1984) [8] suggested that κ_0 represents the attenuation of seismic waves in the first few hundreds of meters or kilometers beneath the site and that it is related to site conditions. Classically, κ_0 is obtained after a measurement on several records of the slope $\kappa(r)$ of the high frequency decay of the acceleration Fourier Amplitude Spectrum [FAS] in a log-linear space, and after removing the regional Q attenuation effect added by the distance (r) [8]. The model is described as:

$$a(f)=A_0 \exp[-\pi\kappa(r)f] \text{ for } f>f_E \quad (1)$$

in which a(f) is FAS, A_0 is a source- and propagation-path-dependent amplitude, f_E is the frequency above which the decay is approximately linear, and r is the epicentral distance. A review of the definition and estimation approaches of κ_0 is given by Ktenidou et al. (2014) [9]. The rock motion is defined according to these two proxies, V_{S30} and κ_0, for instance in the stochastic simulation method of Boore (2003) [10]. Otherwise, some recent studies have shown the interest to include the κ_0 proxy in GMPEs to describe the site [11-12].

To predict site-specific ground motions [e.g., 13], a prediction for a hard-rock site (V_{S30}>1500 m/s and low κ_0 values) is most often required for the definition of input motion. However, the GMPEs in the most active regions do not allow this prediction [e.g., 11]. One solution that was adopted in recent PSHA projects (e.g., Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites [PEGASOS]) is to adjust existing GMPEs from the host to the target region, in terms of source, propagation and site conditions [e.g., 14-15]. These adjustments require a good understanding of the mechanisms controlling the ground motion. However, the terms of source (e.g., stress drop, magnitude scaling) and propagation (e.g., quality factor and its frequency dependence) are not well constrained. In recent projects (e.g., PEGASOS Refinement Project [16]; Thyspunt Nuclear Siting Project [13]), the empirically predicted motion has been corrected by a theoretical adjustment factor depending only on site parameters, V_{S30} and κ_0. For example, the adjustment factor proposed by Van Houtte et al. (2011) [17] is a ratio of acceleration response spectra obtained from the stochastic simulation method of Boore (2003) [10]. This ratio is computed for different range of magnitude-distance and between a rock characterized by a V_{S30} of 800 m/s and κ_0 between 0.02 and 0.05 s (characteristics of the host region) and a hard rock characterized by V_{S30} between 2000 and 2800 m/s and κ_0 between 0.002 and 0.012 s (characteristics of the target region). The two site amplifications are assessed from the quarter wavelength method [18, 10] using generic velocity profiles [19, 15] associated with V_{S30}, and the κ_0 effect is then added. Thus the obtained amplifications are smoothed for the two sites. Finally, their theoretical adjustment factor indicates that a hard rock site should undergo a larger high frequency motion than a softer rock site due to its lower attenuation (κ_0 effect supersedes impedance effect).

This host-to-target adjustment factor is associated with large uncertainties, which may greatly impact the resulting ground motions estimates especially for long return periods [e.g., 20]. Several reasons contribute to this variability. The first one comes from the host GMPE. Indeed, even for a rock with a V_{S30} of 800 m/s, the prediction is not well constrained: i] due a lack of records for this category and ii] a simplified site definition with only the V_{S30} proxy. Laurendeau et al. (2013) [11] compared different soft-rock-to-rock ratios: - empirical ratios from classical existing GMPEs dependent on only V_{S30} and developed with a majority of soil sites; - one deduced from a GMPE dependent on only V_{S30} and developed for sites with $V_{S30} \geq 500$ m/s; - theoretical ratios dependent on only V_{S30}; - and theoretical ratios dependent on V_{S30} and κ_0. The observed differences at high frequency between these ratios confirm the fact that the rock motion is not well defined with the existing GMPEs. Secondly, the transfer functions of rock sites reveal amplification peaks, especially at high frequencies, related to local effects [e.g., 21-22] which are not fully considered in the adjustment factor computation based on quarter-wave-length approach. Thirdly, the link between Fourier and response spectra is not linear. That is why adjustments in the Fourier domain are also explored with random vibration theory [RVT] [12].

To get predictions for sites with higher V_{S30} ($\geq$ 1500 m/s), another possibility could be to employ time-histories recorded at depth. Some GMPEs have been developed from such recordings, especially those of the KiK-net database, which has sensor pairs [e.g., 23-24]. However, these models are not employed in SHA studies because records at depth have several drawbacks. In addition to the cost of this installation and heterogeneities coming from different depth, these records do not represent neither outcropping motion nor incident motion. They are indeed "within motion" recordings which are affected by destructive interferences between up-going and down-going waves [e.g., 21, 25]. Therefore, the Fourier spectra shape is modified: a trough appears at the destructive frequency, f_{dest}, which is related to the sensor depth (H) and the mean shear wave velocity of the upper layers (V_S): $f_{dest} = V_S / 4H$. Recently, Cadet et al. (2012) [22] were interested in these downhole motions. The effects of both destructive interference and differences of free surface effects have been highlighted by computing the ratio between surface and depth records both from observations and theoretical linear SH-1D simulation. This ratio is around 1 for frequency lower than 0.5 f_{dest}; at f_{dest}, a large peak is represented due to destructive interference and finally, at high frequency the ratio is around 1.8 from 3 times f_{dest}. The difference in amplitude between low and high frequencies is related to free surface effect which is 2 at surface and varying in function of the frequency at the sensor depth. These effects are observable both in the Fourier and the response spectral domains. From these observations, Cadet et al. (2012) [22] have developed a correction factor for these effects. It is obtained after the analysis of the surface-to-downhole ratios derived on the 5% damping pseudo-acceleration spectra. They chose to work in response spectra domain because its definition implicitly includes a smoothing that limits the effects of destructive interference at depth.

In this study, alternative methodologies to obtain a prediction for reference motion will be explored. These methods consist in developing GMPEs directly from "virtual" recordings characterized by high V_S and with the properties of outcropping surface records (free surface effect and no trough due to destructive interference). In other words, the objective is to apply methods generally used in the target region to define rock motion from surface records corrected of the site effects or from downhole records corrected of the depth effects. From these datasets, simple ground motion prediction equations are developed and the results will be compared both with natural data and with classical adjustment method.

2. The KiK-net dataset

Japan is in an area of high seismicity, where a lot of high quality digital data are made available to the scientific community. The KiK-net network [26] offers the advantage of combining pairs of sensors (one at the surface, and one installed at depth in a borehole) and associated with geotechnical information. In the present study, we have implemented a dataset based on the active Japanese shallow crustal accelerometric dataset build by Laurendeau et al. (2013) [11]. The following events and sites were selected:

- Events between April 1999 and December 2009,
- Events described in the F-net catalog and for which M_{wFnet} is larger than 4.5,
- Shallow crustal events with a focal depth less than 25 km were selected and offshore events were excluded,
- Sites for which in surface $V_{S30} \geq 500$ m/s and at depth $V_{Shole} \geq 1000$ m/s,
- Sites with a complete shear-wave velocity profile between the surface and the depth,
- Surface records with a predicted PGA > 2.5 cm/s^2 using a magnitude-distance filter [27],
- Following a visual inspection, faulty records, like S-wave triggers, and records including multiple events were eliminated or shortened,
- Records with at least 1 s long pre-event noise,

- Records with a signal-to-noise ratio larger than 3 between 0.5 Hz and 15 Hz,
- Events and sites with a minimum of three records.

Our dataset finally consists of 1040 records with magnitudes between 4.5 and 6.9 and rupture distances between 4 and 290 km. Figure 1 shows the V_S distribution of surface and depth records. In surface, there are no sites with V_{S30} larger than 1500 m/s. The downhole sites allow expanding the distribution until 3000 m/s.

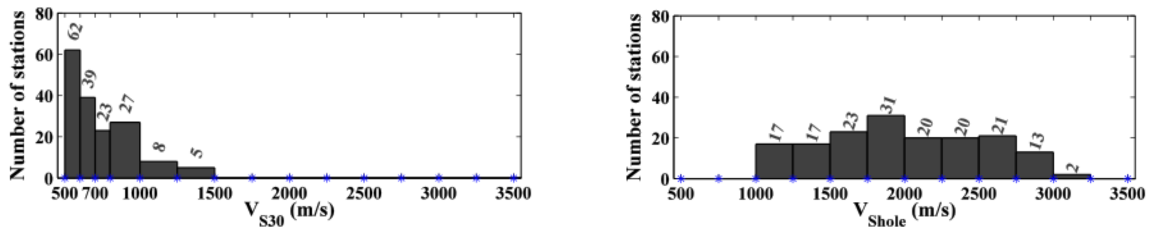

Figure 1: V_S distribution in terms of number of stations: left) at surface and right) at depth.

3. Derivation of hard rock motion datasets

Different methods are implemented to obtain various types of "corrected", outcropping, hard-rock motion estimates.

- The original data are simply the actual recordings -without any corrections: they have been separated in two subsets, **DATA_surf** and **DATA_dh** (for surface and downhole recordings, respectively).
- The second type of data is based on downhole records corrected for the depth effects (correction of the trough in the downhole transfer function and consideration of the free surface effects); it is called **DHcor**.
- The Japanese network offers the opportunity to have for each site two sensors, one at surface and one at depth. However, it is not the case for most other networks, for which only surface data are recorded. This is why a third type of data has been considered, on the sole basis of surface records, corrected for the site response using the velocity profile; it is called **SURFcor**. Two different methods are tested for the site response correction.
- The last model is obtained with the host-to-target methodology and it is called **H2T**. In this case, the GMPE prediction obtained from surface records (DATA_surf) for V_{S30}=800 m/s is adjusted to a hard rock characterized by a V_S around 2400 m/s with the Van Houtte et al. (2011) [17] adjustment factor. The latter is tuned to the κ_0 values provided by the V_{S30}-κ_0 relationships derived by the same authors [17] from worldwide data. This model could be compared with the others datasets only for V_{S30}=2400 m/s.

3.1. Dataset based on corrected downhole records (DHcor)

The downhole records have the advantage to correspond to much larger V_S values (see Figure 1). However, they are "within" motion affected by frequency dependent interferences between up and down-going waves. Cadet et al. (2012) [22] developed a correction factor to transform them into outcropping motion for surface sites with the same (large) Vs values. This correction factor modifies the acceleration response spectrum in the dimensionless frequency space defined by normalizing the frequency by the fundamental destructive interference frequency ($f_{dimensionless}$ = f / f_{dest}). This correction is applied to the KiK-net downhole response spectra, with an underlying assumption of a 1D behavior. The destructive frequency, f_{dest}, was picked directly on the empirical spectral ratios (surface/downhole and HVSR).

3.2. Datasets based on corrected surface records (SURFcor)

The KiK-net network is the only large network that involves pairs of surface and downhole accelerometers at each site. For most of other strong motion networks, only surface records are available. Therefore, in the perspective of applying our developments to other databases, we tested here another way to derive hard rock motion by correcting the surface records (SURFcor): The velocity profiles down to the downhole sensor provided in the KiK-net database are used to compute the linear site transfer functions with a SH-1D simulation code (the 1D reflectivity approach [28] as implemented in the original software written by J.-C. Gariel and P.-Y. Bard and used previously in a large number of investigations [e.g., 29-30, 22]).

In addition to the available velocity profiles $V_P(z)$ and $V_S(z)$, these computations require the unit mass ($\rho(z)$) and damping ($Q_P(z)$ and $Q_S(z)$) profiles. The Brocher (2005)'s relationship [31] is used to get $\rho(z)$ from $V_P(z)$. The quality factors are deduced from $V_S(z)$ according these relationships:

$$Q_P(z)=\max[V_P(z)/20;\ V_S(z)/5] \tag{2}$$

and

$$Q_S(z)= V_S(z)/X_Q \tag{3}$$

in which X_Q is a variable, classically chosen equal to 10 [e.g., 32, 22]. The quality factors are assumed to be independent of frequency.

Two distinct approaches were used to correct the surface signals. The first one (that leads to the SURFcor_SA dataset) consists in the definition of an average amplification factor for each site that is then applied to correct the response spectra of surface recordings. As amplification factors on response factor are very sensitive to the frequency contents of the input motion, we selected 15 accelerograms from RESORCE European databank [2], to cover a wide range of frequency content, with spectral peak varying between 20 and 1 Hz. These accelerograms are used as "input signal" of the SH-1D simulation method detailed above. Although these linear computations are performed in the Fourier domain, the amplification factors are derived from the resulting time series as the ratio between input and output response spectra for each of the 15 accelerograms. The average amplification factor is then the geometric average from the 15 amplification factors. This procedure is repeated for various incident angles in the range [0°, 45°]. It is then used to correct the response spectra of our KiK-net dataset (surface response spectra divided by average amplification factor). This "response spectra approach" is used here because it is often used in the engineering community in relation to site response, for instance in all GMPEs.

For the second correction approach (designated as SURFcor_FSA), all signals from our KiK-net dataset are corrected in the Fourier domain. The Fourier transform of each surface signal is computed and then divided in Fourier domain by the SH-1D transfer function, then converted in time domain by inverse Fourier transform (output signal). This approach is more "physical" that the previous one, since there is no bias induced to the non-linear feature of the response spectra computation.

To apply the two different corrections, the records associated with a PGA lower than 0.1 g (hypothesis of linear domain [33]) and associated to a site and an event having recorded at least three records are selected. Moreover, only the sites with a probable 1D behavior (i.e. with a correlation coefficient between the empirical and the theoretical ratios larger than 0.6, see [33]) are selected. This leads to a set of 704 records.

Fig. 2 (left) illustrates the amplification factor (used in the first method leading to SURFcor_SA dataset) for the example of the NGNH35 station. For this station presenting a large high frequency amplification, the amplification factor is larger for the high-frequency input motions: the amplification factor presents a large variability related to input motions. The standard deviations associated with the three different input parameters are also presented on Fig. 2 (right). The variability associated to the incidence angle (0 to 45°) is very low compared to the one coming from the input motions and the Q_S definitions ($Q_S = V_S / X_Q$ with X_Q =[5, 10, 15, 25, 35, 50, 100]). This variability linked to input motion increases around 3 Hz and stays large and constant at high frequency, while the variability linked to Q_S definitions is concentrated around the resonance peak (here around 12 Hz).

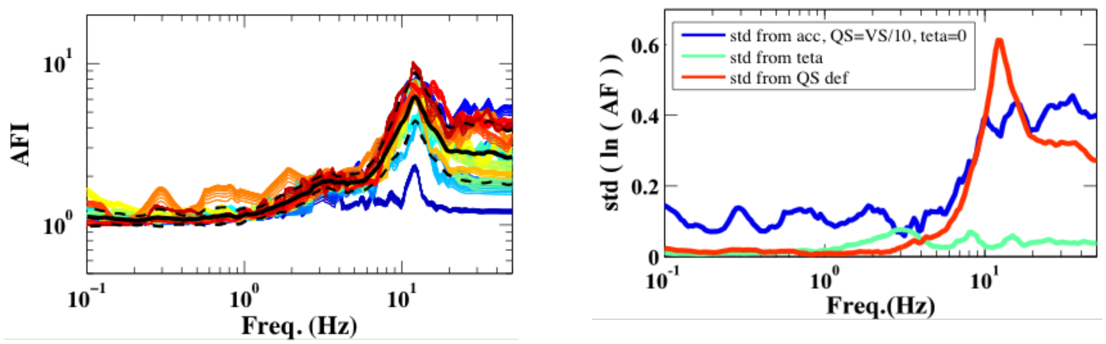

Figure 2: On the left, amplification factors obtained for the station NGNH35 with the 15 input motions (different colors) and different range of incident angles (Q_S=V_S/10) (different lines). The mean and the standard deviation are represented by the black lines. On the right, standard deviation associated with the amplification factor due to three input parameters: in blue, due to input motions; in green, due to the range of incidence angles; and in red, due to the Q_S definition.

3.3. Direct comparison of the response spectra from the different methods

The different corrections applied to the observed data are based on several assumptions which allow corrections on an important database. These corrections are not intended to be valid in the case of a particular records, but only in a statistical way. However, it is still interesting to analyze the effect of the corrections for a given record, to highlight their advantages and disadvantages (see Figure 3).

To test the DHcor method, MYGH06 is a good site because it is characterized by a flat surface / downhole spectral ratio (SSR), except at the destructive frequency. A good agreement is observable between DHcor and DATA_surf (Fig. 3 a), showing the interest of the depth effect correction factor of Cadet et al. (2012) [22]. On the contrary, SURFcor displays lower amplitudes, probably due to a more important correction factor. We have done the comparison for two other sites characterized by a SSR with large amplification at high frequency. For TCGH14 (Fig. 3 b-c), the site amplification seems insufficiently corrected around the peak for all the scenarios tested, as SURFcor is larger than DHcor. However, for larger magnitudes, SURFcor_SA is strongly attenuated at high frequency and becomes lower than DHcor. For NGNH35 (Fig. 3 d-e-f), the response spectra are relatively similar for the intermediate scenarios. The largest differences are observed for the extreme scenarios. The response spectrum of SURFcor appears not enough corrected for the event with the smaller magnitude, while it appears too corrected at high frequency for the event with the larger magnitude, and especially in the case of SURFcor_SA (similar observation than for TCGH14). Indeed, the frequency content varies with the magnitude, and thus the site is excited in different ways.

4. Comparison in term of GMPE results

To analyze the behavior of those different datasets, we have chosen to develop ground motion prediction equations based on a simple functional form in order to get the coefficients directly. Indeed, the functional forms used in the literature are increasingly complex, requiring fixing some coefficients. These fixed coefficients are obtained beforehand either from theoretical simulation or empirically but from a well-defined subset. The "random effects" regression algorithm of Abrahamson and Youngs (1992) [34] is used to derive GMPEs for the geometrical mean of the two horizontal components of SA in g. The following simple functional form is used:

$$\ln(SA(T))_{es} = a_1(T) + a_2(T).M_W + a_3(T).M_W^2 + b_1(T).\ R_{RUP} - \ln(R_{RUP}) + c_1(T).\ln(V_S/1000) + \delta B_e(T) + \delta W_{es}(T) \quad (4)$$

where δB_e is the between-event and δW_{es} the within-event variability, associated with standard deviations τ and φ respectively, and $\sigma_{TOT}=(\tau^2+\varphi^2)^{0.5}$.

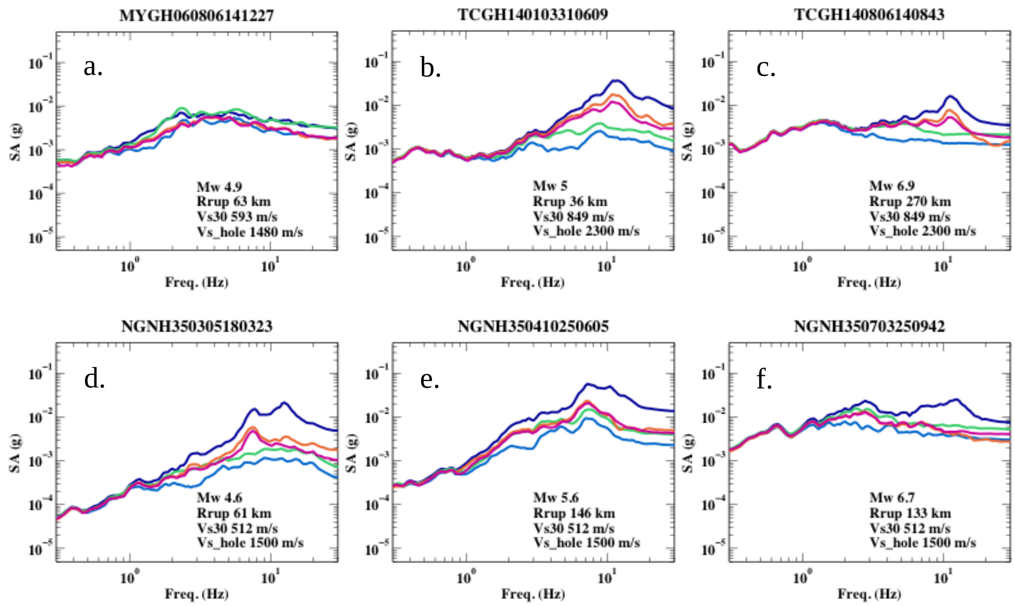

Figure 3: Comparison of the response spectra for different events recorded at three different stations obtained from 5 datasets: dark blue DATA_surf; light blue DATA_dh; green DHcor; orange SURFcor_SA; and pink SURFcor_FSA.

Figure 4 shows the frequency dependence of each coefficient and also of the variability terms for the five different datasets. Apart from the magnitude dependence coefficients (a_1-a_3), the main differences from one dataset to another are observed at high frequency. The site coefficient c_1 is clearly negative at low frequency: as expected, amplification decreases with increasing Vs. However, at high frequency, c_1 is around zero and even positive for SURFcor and DATA_surf. In this case, when V_S increases, the amplification stays stable or even increases. For DATA_surf, c_1 varies steeply between 6.7 and 12.5 Hz from -0.9 to 0.08. For SURFcor, between FSA and SA, the shape is relatively similar, except that c_1 for SA is more positive at high frequency. DATA_dh and DHcor records are relatively similar except than DHcor records are corrected of the depth effects. However, if c_1 is relatively similar at high frequency, it is different at low frequency. Between 3.5 and 8.5 Hz, we observe the destructive frequency correction effect, i.e., a trough for DATA_dh and at the contrary, a bump for DHcor. At low frequency, DHcor is similar to SURFcor. These 2 methods should give similar results but if it is the case at low frequency, at high frequency we observe large differences around the mean peak of resonance (10 Hz). The observed difference for c_1 is compatible with the observed differences on Fig. 3.

The total variability (σ_{TOT}) associated with the different datasets is mainly controlled by the within-event variability (φ) because the between-event variability (τ) is really stable between models. The within-event variability is lower for the models based on downhole records: DHcor and DATA_dh. The within-event variability is larger for the entire range of frequency in the case of DATA_surf. The within-event variability is larger also around 10 Hz for SURFcor, which corresponds to the average amplification peak observed for the stiff-soil / soft rock sites considered here. At larger frequency, the within-event variability is larger for SURFcor_SA than for SURFcor_FSA.

Figure 5 displays a comparison of the motion predicted with all the models [DATA_surf, DATA_dh, DHcor, SURFcor (FSA and SA) and H2T models] for a given earthquake scenario (M_W = 6.5, R_{RUP} = 20 km) and two V_S values (1100 m/s and 2400 m/s). The first one is common V_{S30} to each dataset. The second one was defined so as to make a comparison with the host-to-target method, and especially when the Van Houtte et al. (2011) adjustment factor [17] is used.

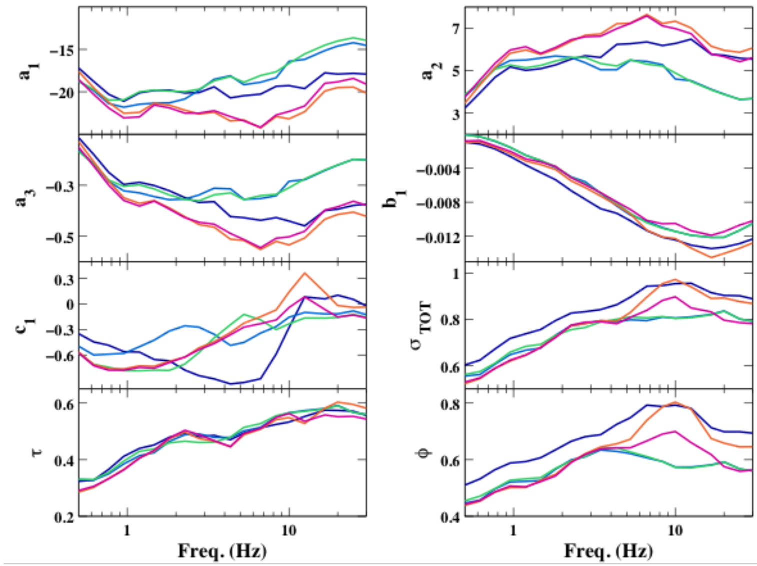

Figure 4: Regression coefficients obtained for DATA_surf (dark blue), DATA_dh (light blue), DHcor (green), SURFcor _SA (orange) and SURFcor _FSA (pink).

For these scenarios, the spectral acceleration predicted by DHcor and SURFcor models are really close for each period in average. However, as discussed previously (see Figure 4), the variability associated with these two models is larger at high frequency in the case of SURFcor. Conversely, DATA_surf presents the largest values at high frequency, while the lowest amplitudes are associated to DATA_dh: the latter is the only model that corresponds to within motion, always smaller than outcropping surface motion. DATA_surf is larger because most of the sites presenting significant to large amplification peaks at high frequency linked to shallow, lower velocity layers. These site effects obviously do not affect DHcor predictions, and are "statistically" removed within SURFcor.

For the scenario with V_S of 2400 m/s, the H2T amplitude is found to be 3 to 4 times larger at high frequency (T < 0.1 s) compared to DHcor and SURFcor. The H2T amplitude is obtained after the adjustment of DATA_surf defined for a V_{S30} of 800 m/s, which have also larger amplitude at high frequency than the other models.

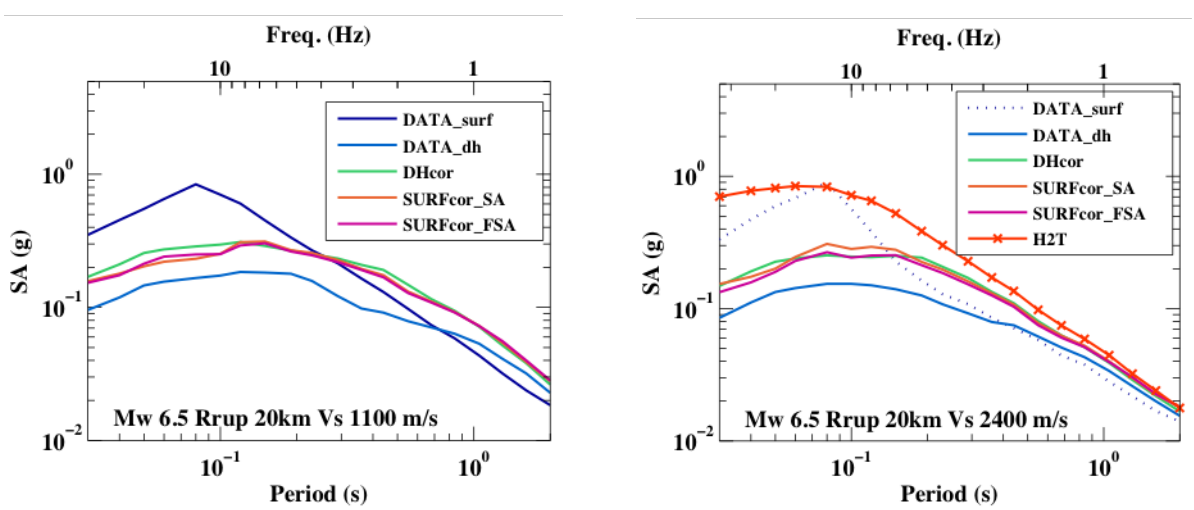

Figure 5: Comparison of the predicted SA obtained with the empirical models for two V_S values and for a specific scenario M_W 6.5 and R_{RUP} 20 km. The models are presented with dashed lines when the V_S value is outside the range of V_S used to develop the model.

5. Discussion

The comparison highlights a very good agreement between the average predicted spectral acceleration of DHcor and SURFcor (FSA and SA) in the case of the tested scenarios (Figure 5). Some differences are still observed in the site model at high frequency (see Figure 4). However, the main difference between the two models of SURFcor and DHcor comes from the within-event variability which is larger for SURFcor at high frequency, and especially for SURFcor_SA. Around 10 Hz (the average amplification peak of the stiff sites included in the dataset), this variability is even similar to the one of DATA_surf for SURFcor_SA. Only the sites with an a priori 1D behavior are selected to implement the SURFcor dataset. However, the selection criterion allows a quite large selection of sites. The variability associated to SURFcor could be explained by a non-adequate correction of site effect, linked with inadequate velocity or damping profiles.

Firstly, this variability can be explained by the selected Q_S values used to compute the theoretical amplification factor. In this study, we have used $Q_S=V_S/10$ since this “scaling” is widely used in earthquake engineering application. However, even if this model allows a satisfactory average fit to the observed site amplification, it is not the best for all sites. In addition, we have shown the large impact of the Q_S definition on the variability associated with the amplification factor (see Fig. 2). To improve this point, one possibility could be to define for each site the best Q_S profile with depth in a similar way to what was one by Assimaki et al. (2008) [35].

Secondly, the variability associated with the amplification factor on response spectra is large, even if the Q_S definition is fixed. This factor depends largely of the frequency content of the input motion used in linear SH-1D simulations. Thus, by considering only the average site amplification factor, DATA_surf is not optimally corrected to obtain SURFcor_SA. The alternative use of a correction in the Fourier domain (i.e., deconvolution) allows to significantly decrease the within-event variability at short periods, so probably to better correct DATA_surf. Indeed, the response spectra computation is nonlinear contrary to the Fourier spectra computation [36]. Thus it is highly probable that the larger variability at high frequency is due to the use of average amplification factors on response spectra. However, even for SURFcor_FSA, the variability is larger around the amplification peak in comparison to DHcor. Figure 3 also indicated that the site amplification is not always well corrected.

However, despite these issues on high frequency variability, the main outcome of this study is to point out an important difference in amplitude between H2T on the one hand, and DHcor and SURFcor on the other hand. This difference reaches a factor 3 to 4 in average at short periods ($T < 0.1$ s), which is very significant, and then decreases for increasing period, to become negligible at long period ($T > 1$ s). This difference can be explained in part from some specificities and assumptions in the H2T approach on the one hand, and from some considerations about DHcor and SURFcor on the other hand.

Firstly, the difference may come from a difference in the site characterization between H2T and SURFcor and DHcor. In fact, the site in the H2T approach is defined through both V_{S30} and κ_0 proxies, while it is characterized only with V_{S30} for SURFcor and DHcor. The site coefficient c_1, characterizing the V_{S30} dependence, for SURFcor and DHcor may therefore implicitly account, at least partially, for a "hidden correlation" between κ_0 and V_{S30}. Indeed, c_1 is close to zero at high frequency which reflects a certain correlation between V_{S30} and κ_0 as shown by Laurendeau et al. (2013) [11]. However, in the Laurendeau et al. (2013) study [11], the GMPE developed with surface records such as DATA_surf showed a bias at high frequency with respect of κ_0. Besides, the median is 1900 m/s for the V_S distribution of DHcor and SURFcor, which corresponds to a κ_0 of 0.0108 s while for 2400 m/s, κ_0 is 0.008 s from the V_{S30}-κ_0 relationship of Van Houtte et al. (2011) [17]. Thus, SURFcor and DHcor may include a related bias, and a κ_0 correction toward a small κ_0 could be resulting in an increase of the spectral amplitudes at high frequency. To fully investigate the κ_0 impact, it would be necessary to measure it for each new dataset, knowing that the corrections in terms of Q_S may have affected κ_0 of each record, and also that the high frequency amplification may considerably alter the reliability of κ_0 measurements and therefore the "traditional" V_{S30} - κ_0 relationships implicitly used in the H2T approach.

Secondly, the adjustment factor of Van Houtte et al. (2011) [17] is applied to DATA_surf GMPE which have yet large amplitude at high frequency. In fact, DATA_surf is defined from sites having an average SSR with an amplification peak around 10 Hz. This amplification is also found in the DATA_surf GMPE. The computation of the adjustment factor is based on the quarter wavelength approach which takes into account only the impedance effects, while shallow velocity contrast may lead to high-frequency resonance effects with significantly larger amplifications. It is thus likely that site effects are not corrected enough for the host region and the amplitude of very hard-rock motion is overestimated with the H2T approach.

6. Conclusion

The purpose of this study is to improve the understanding and the definition of the hard rock motion ($1100 \leq V_S \leq 3500$ m/s) through an original processing of the Japanese KiK-net recordings. The pairs of recordings at surface and depth, together with the knowledge of the velocity profile, allow to derive different sets of outcropping, hard-rock motion data for sites having velocities in the range [1100 - 3500 m/s]. The corrections are based either on a transformation of deep, within to outcropping motion (DHcor), or on a deconvolution of surface recordings using the velocity profile and 1D simulation, which has been performed both in the response spectrum domain (SURFcor_SA) and in the Fourier domain (SURFcor_FSA). Each of these virtual "outcropping hard-rock motion" data sets has then used to derived GMPEs with simple functional forms, using as site condition proxy the S-wave velocity at depth (V_{SDH}). The predicted spectral shapes have finally been compared with those obtained with the classical host-to-target adjustment (H2T) approach, exhibiting strong differences in the short period, where the H2T approach leads to predictions 3 to 4 times larger than the new approach presented here.

The original data set (KiK-net recordings form stiff sites with $V_{S30} \geq 500$ m/s, 1999-2009 only) is limited and has considerably enlarged over recent years. The present results could thus be considered as a first step and should be updated with an updated dataset. However, the consistency between results obtained with completely independent correction methods allows to highlight the probable existence of a significant bias in the classical H2T method, which leads to an overestimation of the hard-rock motion possibly reaching factors up to 3-4 at short periods ($T < 0.1$ s). Our interpretation of this bias is related to the existence of a significant, high-frequency amplification on stiff soils and standard rocks, due to thin, shallow, moderate velocity layers. Not only this resonant amplification is not correctly accounted for by the quarter-wavelength approach used for the V_S correction factor used in the traditional H2T adjustment techniques, but it may also significantly impact and bias the κ measurements, and the (V_{S30}- κ_0) relationships implicitly used in H2T techniques.

The approaches proposed here might be used to other strong motion datasets, provided the velocity profile is known at each recording site in order to deconvolve from the site-specific effects. This emphasizes once again the high added value of site metadata in all strong motion databases.

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8. Copyrights

9. References

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