Importance of local scattering in high frequency motion lessons from interpacific project sites, application to the kik-net database and derivation of new hard-rock GMPE

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IMPORTANCE OF LOCAL SCATTERING IN HIGH FREQUENCY MOTION: LESSONS FROM INTERPACIFIC PROJECT SITES, APPLICATION TO THE KIK-NET DATABASE AND DERIVATION OF NEW HARD-ROCK GMPE

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ABSTRACT

The effective shear wave attenuation, often denoted Q_{Seff}, is an important parameter for ground motion simulations. However, this parameter is difficult to measure and is often inferred from rules of thumb (e.g., $Q_{Seff}=V_S/X_Q$, where X_Q is a scalar value, frequently chosen as equal to 10). The recent work by Laurendeau et al. (2017), aiming to derive consistent hard-rock GMPEs from KiK-net surface and down-hole recordings, shows the shortcomings of such a Q_{Seff}-V_S scaling at high frequency: using the standard scaling $Q_{Seff}=V_S/10$ leads to an overestimation of the local amplification, computed from 1D simulations, at high frequency.We show that this issue is likely related to a too simple description of the velocity profile using a limited number of homogeneous layers. Using invasive measurements from the InterPacific project (Garofalo et al., 2017), we show that 1D simulations based on high resolution velocity profiles (as provided by the PSSL method) lead to a significantly higher effective attenuation at high frequency in comparison with the use of lower resolution velocity profiles (as provided by the down-hole method). This observation is clearly due to the back scattering induced by non-smoothed profiles.We then work on the stiff-soil-to-rock KiK-net sites used by Laurendeau et al. (2017) and we introduce a random perturbation to the former simplified profiles provided for each KiK-net site. These perturbations are consistent from a geostatistical point of view with values found in the literature (even though they were not measured on the KiK-net sites) and on the few InterPacific sites. The 1D simulations with these modified profiles, coupled with the standard Q_{Seff}-V_S scaling, were found to well reproduce the high frequency attenuation.A new hard-rock GMPE was then derived from the KiK-net surface recordings corrected for the theoretical site response defined from this optimized simulation, and was compared to the previous results of Laurendeau et al. (2017).

Keywords: Seismic Hazard; Hard-rock motion; Scattering; GMPE; KiK-net; High frequency

1 INTRODUCTION

Akey component in site-specific seismic hazard assessment (SHA) is the determination of ground motion on very hard-rock sites (e.g., Rodriguez-Marek et al., 2014; Aristizabal et al., 2017). These sites are characterizedby high values of the shear wave velocity, Vs. However, ground motion prediction equations (GMPEs), used to assess regional seismic hazard, are not representative for these high Vs values, due to a lack of accelerometric stations on very hard-rock sites(e.g., Laurendeau et al., 2013).To solve this issue, the state-of-the-art technique employed the "host-to-target" adjustment (H2T) which is based on a site correction procedure between the "host" sites (generally described in the GMPE) and the "target" site (the studied specific site). There are different implementations of this approach, with a correction in term of response spectrum (SA) using the point source stochastic model (PSSM, e.g., Campbell 2003; Scherbaum et al., 2004; Cotton et al., 2006; Van Houtte et al., 2011) and a correction in terms of Fourier amplitude spectrum (FAS) using the inverse random vibration theory (IRVT, Al Atik et al., 2014).

However, all the site correction procedures use the couple of parameters "V_{S30}" and "κ_o". The

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parameter V_{S30} is the average shear wave velocity up to 30 meters which has been used as a proxy to describe the sites, especially in GMPEs (e.g., Boore and Atkinson, 2008) and construction codes. The term "κ_o" is related to the high-frequency attenuation properties, and has focused the interest of the engineering community to complement the V_{S30} proxy, at least for rock sites. It has been introduced first by Anderson and Hough (1984) to characterize the attenuation of seismic waves in the first few hundreds of meters or kilometers beneath the site. Classically, "κ_o" is obtained after a measurement on several tens of records of the high frequency decay "κ"of the acceleration FASaccording to the following spectral model:

$$A(f) = A_0(M, R, fc).\exp[-\pi.\kappa(R).f] \text{ for } f > f_E \quad (1)$$

in which A(f) is FAS, A_0 is an "attenuation-free" amplitude term combing the source component (through magnitude and corner frequency fc), and the crustal geometrical spreading component, f_E is the frequency above which the decay is approximately linear, and R is the epicentral distance. In such an equation, the spectral decay parameter "κ" depends not only on the site damping but also on the attenuation process along the whole source-to-site crustal path. The site-specific attenuation term "κ_o"is therefore retrieved after removing its dependence on the epicentral distance R, according to the relationship $\kappa(r)=\kappa_o+\alpha.R$, where the trend coefficient α is related to the regional Q attenuation effect (Anderson and Hough, 1984). These two site proxies for rock sites have been used in different studies (Boore 2003; Campbell 2003; Cotton et al., 2006, Van Houtte et al., 2011, Al Atik et al., 2010) and "κ_o" was proved to be important as a complement proxy to V_{S30} to better estimate the rock motion (Laurendeau et al., 2013; Bora et al., 2015). It has been shown however that its measurement may suffer from different sources of uncertainties or even bias (Parolai and Bindi 2004; Ktenidouet al.,2014; Perron et al., 2017).

The standard-rocktohard-rock ratio, obtained from the different physics-based correction procedures (PSSM and IRVT)combined with assumed V_{S30} - $\kappa_o$relationships, predicts a larger amplification for the hard-rock sites than for the rock sitesat high frequencies (see Ktenidou and Abrahamson 2016 for a comparison). This result is due to the characterization of the hard-rock sites with a much smaller attenuation parameter. On the other hand, Ktenidou and Abrahamson (2016) and Laurendeau et al. (2017) found another behavior from empirical observations, i.e., smallermotion on hard-rock sitesover the whole frequency range.Ktenidou and Abrahamson (2016)analyzed a large data set including NGA-east data and others from sites with $V_{S30}\geq1500$ m/s, and concludedto significantly smaller motion on hard-rock sites, together with significantly higher $\kappa_o$values, than what is predicted by current HTT models. Laurendeau et al.(2017) obtained a similar result for the standard-rocktohard-rock ratio from a KiK-net dataset ($1000\leq V_s\leq3000$ m/s) using on one hand,thedownhole records corrected of depth effects (DHcor) and on the other hand, surface records corrected from their site effects (SURFcor). They found a large discrepancy at high frequency between the H2T corrections and the empirical results, reaching up to a factor of 4 at high frequencies for hard-rock sites with a 2400 m/s S-wave velocity.

However, the work of Laurendeau et al. (2017) presents a weakness in the way the shallow attenuation is accounted for.This definition is used both in the depth correction factor and in the computation of the borehole transfer functions "BTF" obtained from linear SH-1D simulations to correct the surface recordings. In fact, the comparison of the mean site responses computed in the empirical way through the standard spectral ratios (SSR) and in the theoretical way (BTF) revealsan overestimation of the amplification beyond 10 Hz in the latter case. This issue was attributed to the too simple definition of Qs, derived from S-wave velocity through a scaling factor as $Q_S=V_S/10$ (classical definition used in numerous studies, e.g., Cadet et al., 2012; Maufroy et al., 2015). Laurendeau et al. (2017) were wondering in the discussion if the extreme simplicity of the Qs definition could explain, at least partially, the observed differences between H2T and both DHcor and SURFcor. Several attempts were found in the literature to better define the attenuation terms in numerical simulations. Parolai et al. (2015) and Pilz and Fäh (2017) have shown that the introduction of scattering assumptions in the numerical simulations can lead to a drop in the high-frequency response at a given site. In addition, the observed differences between laboratory measurements of damping and"$\Delta\kappa_o$" (i.e. differences in κ_o between surface and downhole recordings) shown by Cabas et al. (2017) could be explained by the presence of scattering.On the other side, invasive measurements from the InterPacific project (Garofalo et al., 2016) provide velocity profiles with high resolution (as provided by the PSSL method, suspension logging) which helps to show that 1D simulations based on high resolution velocity profiles can lead to a significantly higher attenuation at high frequency compared to that obtained by the lower resolution velocity profiles (as provided by the down-hole method).

The first objective of this paper is to introduce scattering in the Qs definition, with vertical heterogeneities in the KiK-net velocity profiles, to improve the fit at high frequencies between the mean BTF and SSR. Secondly, a new hard-rock GMPE is developed from the surface recordings corrected from the new site transfer functions, including scattering (SURFcor_scat). Finally, this GMPE is compared to the ones developed in Laurendeau et al. (2017) and to the H2T results. In the present study, the same subset of KiK-net accelerometric data previously built by Laurendeau et al. (2017) is used. This dataset consists basically of shallow crustal events recorded on stiff sites (V_{S30}≥500m/s and V_{SDH}≥1000 m/s, Vs at downhole sensor).

2 ESTIMATION OF REFERENCE MOTION

2.1 Estimation of site-specific responses

Laurendeau et al. (2017) computed the transfer functions of a subset of KiK-net sites, characterized by V_{S30} ≥ 500m/s, both from the standard spectral ratio method (SSR) and from linear SH-1D simulation (BTF). They found a good agreement between the two methods up to 10 Hz, frequency for which a peak of amplification is observed (as shown by Figure 1, black and dashed blue curves, respectively). However, BTF overestimates the results from SSR for larger frequencies.
The simple definition used for Qs could be an explanation for this difference. After this previous work results, the attention is drawn in the present work to the contribution of various energy loss mechanisms to the surface-downhole theoretical transfer functions to improve the fit with the observed SSR results. That's why introduction of scattering assumptions will be addressed in the next section.

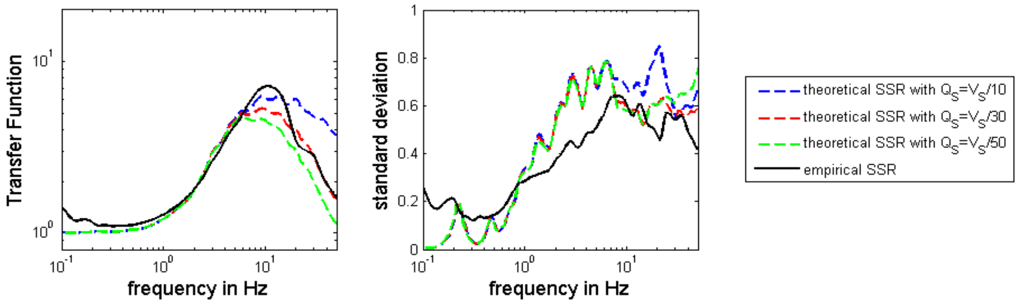

Figure 1: Comparison of the mean transfer functions and the corresponding standard deviation (site-to-ste variability over all considered sites obtained with different methodologies: empirical SSR approach (black), and from the 1D numerical simulation with various X_Q scaling factor (dashed colored lines).

2.1.1 The linear SH-1D method (BTF) as used by Laurendeau et al. (2017)

The theoretical transfer functions (TF) is computed from a 1D reflectivity model to derive the response of horizontally stratified layers excited by a vertically incident SH plane wave (original software written by J.-C. Gariel and P.-Y. Bard and used previously in a large number of investigations: e.g., Cadet et al. 2012). This method requires at least the knowledge of the shear-wave velocity profile, Vs(z). The other geotechnical parameters, Vp(z) and ρ(z)are deduced from Vs(z) using the Brocher (2005) relationships. The quality factors (Qp(z) and Qs(z)) are deduced from Vs(z) as follows:

$$\text{Qp(z)} = \max \begin{Bmatrix} \text{Vp(z)}/20 \\ \text{Vs(z)}/5 \end{Bmatrix} \quad (2)$$

$$\text{Qs(z)} = \text{Vs(z)}/\text{X}_Q \quad (3)$$

where X_Q is the Vs-Qs scaling factor, usually taken equal to 10 (e.g., Cadet et al. 2012; Maufroy et al. 2015).

Figure 1 shows the mean BTF obtained for different values of X_Q(dashed curves). Lower Qs values (larger X_Q) result in a lower peak amplitude and a better fit of the high-frequency decay. However, the peak amplitude at 10 Hz is underestimated and the site-to-site variability increases at high frequency. Note that for the calculation of the theoretical transfer functions (BTF), the smoothing of Konno and Ohmachi (1998) was applied with a smoothing value of b=30.

2.1.2 Introduction of scattering assumptions

The main idea was to understand the high frequency drop, and a physical aspect that could stand behind is the scattering by shallow heterogeneities. In real Earth, such heterogeneities are distributed in the whole 3D space, but for 1D simulations, it may be mimicked through thin sub-layers with variable velocities. In fact, this issue was addressed in a recent study by Parolai et al. (2015) in which a set of three models was used, one of which is a model considering scattering effects. This study showed that considering a random perturbation in the travel time for the first 100m would lead to a decay in the high frequency spectra. Another similar analysis was done by Pilz and Fäh(2016) based on the contribution of scattering to near-surface attenuation: they showed on the basis of statistical observations of the seismic wavefield at sites of the Swiss seismic networks, that attenuation properties show a clear dependency on the local shallow subsoil conditions with differences in the structural heterogeneity of the shallow subsoil layers producing different scattering regimes. Thus, the introduction of such scattering assumptions in the simulations definitely sounds physical and realistic.

We thus approximated the effect of scattering by introducing in a similar way thin sub-layers down to some maximum depth. Parolai et al. (2015) consider the top 100 m; for the present case of stiff KiK-net sites, we have chosen the depth range to be 50 m. The implementation can be summarized as follows:

- It is needed to introduce thin sub-layers (1 m thick) over the whole considered depth range on which a perturbation in the travel time is applied.
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- Scattering is taken into account by introducing a random delay in the S-wave travel time.which is associated to a perturbation (P) in the velocity profile for each sub-layer according to the following equation:

$$t_{new} = \frac{h}{P \times V_s} \quad (4)$$

where t_{new} is the perturbed travel time, $V_s$is the original, unperturbed S-wave velocity, h is the sub-layer thickness (= 1 m), and P is the random perturbation introduced.

- The perturbation amplitude "P" is chosen to follow a lognormal distribution with a mean valueμ_{scat}=0 (median P value of 1) and a standard deviation variating between 0.2 and 0.5. The standard deviation will be abbreviated by "sigma for scattering" or "σ_{scat}" and will be tuned later on a few real measurements.

The only constraint is that the total travel time in each "constant velocity layer" of the original profile should not change. It is also important to note the quality factor Qs is estimated for the 1D simulation using the scaling relation with X_Q =10, and thus also reflects the velocity heterogeneities. The results of these assumptions are illustrated on Figure 2 for a single site (NGNH35) chosen arbitrarily to check the model and its impact on a specific site transfer function. The standard deviation of the perturbation (σ_{scat}) was set to 0.3 in this simulation (note it is also the standard deviation of the log of S-wave velocity perturbation). This example of BTF proves that there is a possibility to have an impact on the high frequency part.

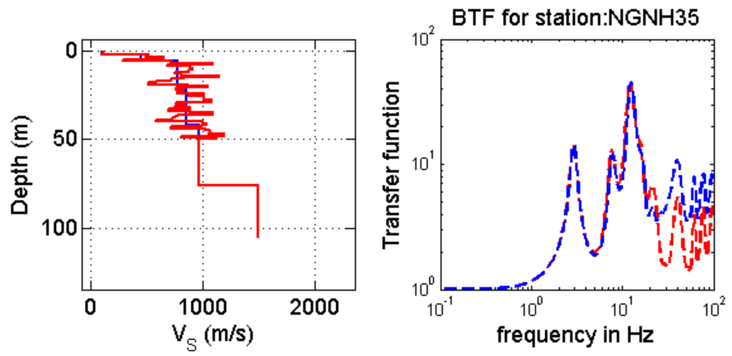

Figure 2: Example station (NIGH15) showing smooth Vs profile (blue) from a downhole measurement and the velocity profile resulting from the introduction of scattering assumptions (red). The corresponding BTFs are plotted (right).

Such random vertical sub-layering was thus introduced for every profiles of the 106 KiK-net sites, and the resulting average BTF was compared with the mean SSR. Distinct levels of scattering were considered with different values of σ_{scat}, from 0.2to 0.4. The results are summarized in Figure 3. It clearly shows that larger $\sigma_{scat}$are associated with more pronounced high-frequency decay, with an optimal fit obtained for $\sigma_{scat} = 0.4$. One may notice that larger scattering also results in larger high-frequency variability.

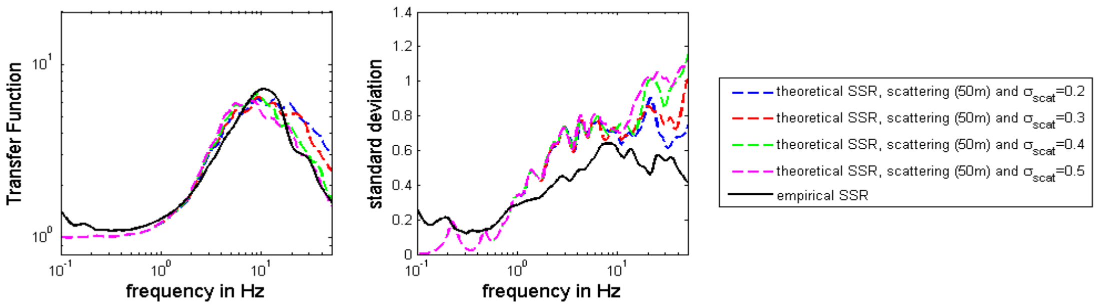

Figure 3: The mean theoretical BTF of all stations after using the profiles with scattering assumptions of $\boldsymbol{\sigma_{scat}}$=0.2, 0.3 and 0.4 for a depth of 50 m (left). The resultant standard deviations are shown (right).

2.1.3 Testing the amount of velocity perturbations

To check whether such a model is actually more realistic from a physical point of view, it is necessary to compare the required velocity perturbation level with the available data. In that aim, we considered the velocity logs obtained with different measurement methods within the framework of "Inter-Pacific project" (Garofalo et al., 2016) for three different sites in France. Figure 4 displays the velocity profiles obtained with downhole and PSSL (suspension logging) techniques, and we can clearly see the significant differences in homogeneity of the measured profiles.

The corresponding 1D transfer functions are displayed in Figure 5 for the Cadarache and Grenoble stiff-soil sites: the BTF derived from the PSSL measurements (those which exhibit a short scale vertical variability) indicate smaller amplification in the high frequency part.

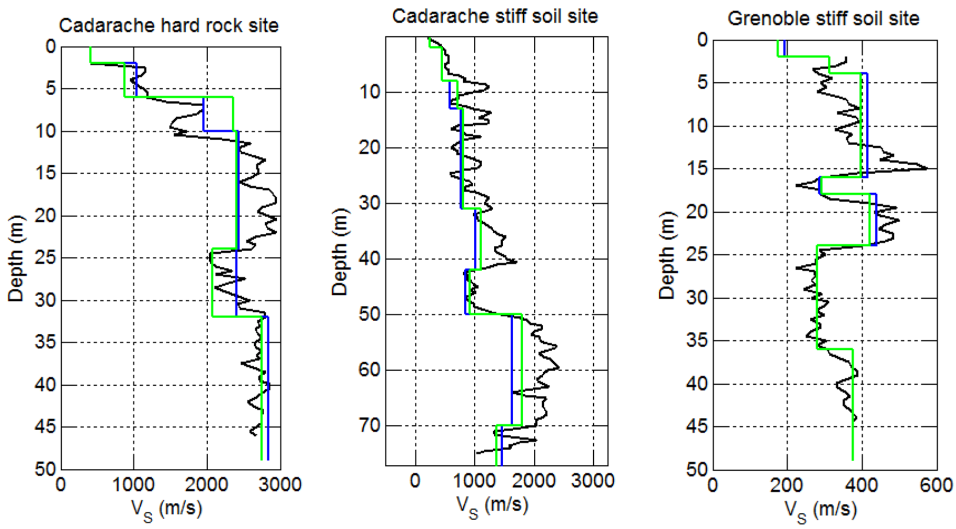

Figure 4: Some measured Vs profiles from the InterPacificproject for 3 sites: Cadarache (hard-rock and stiff-soil sites) and Grenoble (stiff-soil site) using two different downhole measurements (green and blue curves) and PSSL measurements (black curves).

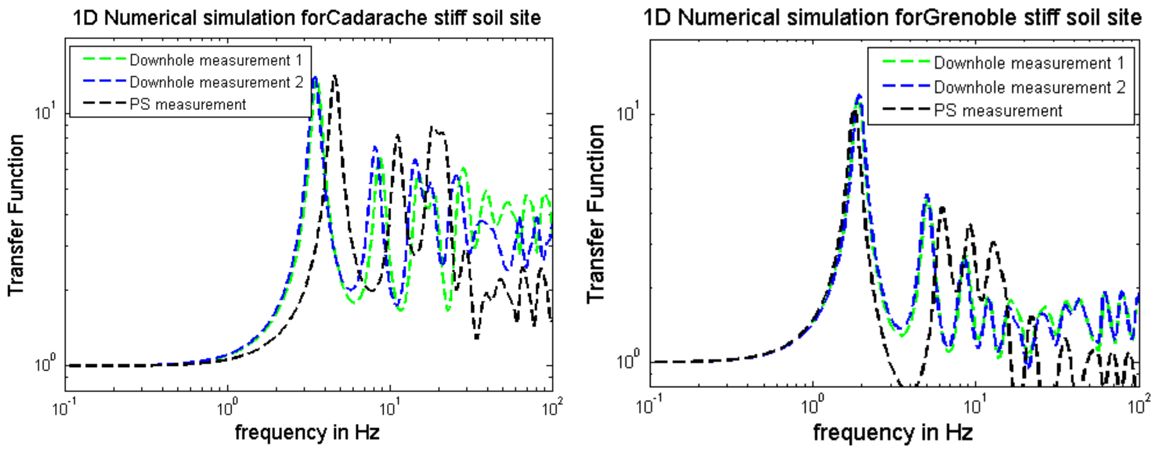

Figure 5: The theoretical BTF of two stations in Cadarache and Grenoble using the different measured profiles in Figure 4.

The amount of heterogeneities present in these measured profiles can be compared to the ones we have used for the KiK-net simulations through the"σ_{scat}" values. The mean and standard deviations of the perturbations can be compared with the formula:

$$\mu_{meas} = e^{\mathrm{mean}(\ln(VS_{dh}) - \ln(VS_{ps}))} \quad (5)$$

$$\sigma_{meas} = \sqrt{\sum_{i=1}^{n} \frac{\left(\ln\left(\frac{VS_{dh}}{VS_{ps}}\right)\right)^2}{n}} \quad (6)$$

where $VS_{dh}$and VS_{ps} are the S-wave velocity profilesas obtained from downhole measurements and PSSL measurements. The values are summarized in Table 1.

Table 1: Statistical comparison between DH and PSSL measurements for the three French sites: mean ratio (second column) and standard deviation of PSSL variability.

Site	μ_{meas}	σ_{meas}
Cadarache hard-rock site	1.024	0.225
Cadarache stiff soil site	0.920	0.287
Grenoble stiff soil site	1.018	0.235

These results can be considered fairly consistent with the σ_{scat}values considered in the simulation. Note however that the variability needed for the Japanese stations (sigma equal to 0.4or higher) is slightly higher than those measurements, which may be interpreted either as geological differences between the two regions, or as limitations of PSSL techniques to identify all small-scale heterogeneities, because of the characteristics of the measuring tool device (metric distance between receivers).
A further sensitivity study was done on the depth down to which the scattering assumptions are imposed. The results displayed in Figure 3indicate that when considering a fixed depth of 50 m, the best fitting is observed with a high level of heterogeneity (σ_{scat}=0.4). Figure 6shows the effects of assuming 30minstead of 50m with the same set of σ_{scat}values (0.2, 0.3, 0.4 and 0.5). Again, we can see that the best fit is obtained when we impose higher value of σ_{scat}(0.4).

Another possibility is to test the effect of using multiple depths for a given level of heterogeneity. Figure 7 displays the results when considering the same (high) value of σ_{scat} (0.4) and different scattering depths (30, 50 and 90 m). All the resulting mean BTFs exhibit a good fitting, but the BTF corresponding to the larger depth (90 m) is showing a slightly lower amplification around 10 Hz. This can be explained with the quarter-wavelength approach: the larger the affected depth in the soil, the lower the minimum frequency down to which it will affect the transfer function. After doing these sensitivity tests, we can be confidently state, at least for the considered profile database consisting of 106 stiff soil profiles, that the scattering is leading to some kind of high frequency attenuation (beyond 10 Hz) and is likely to be a satisfactory explanation for the discrepancy between measured SSR_dh and BTF derived from down-hole measurements. We thus consider the value of 0.4 for σ_{scat} and 50 m for the depth in the computation of BTF to correct the surface recordings and then develop a new GMPE.

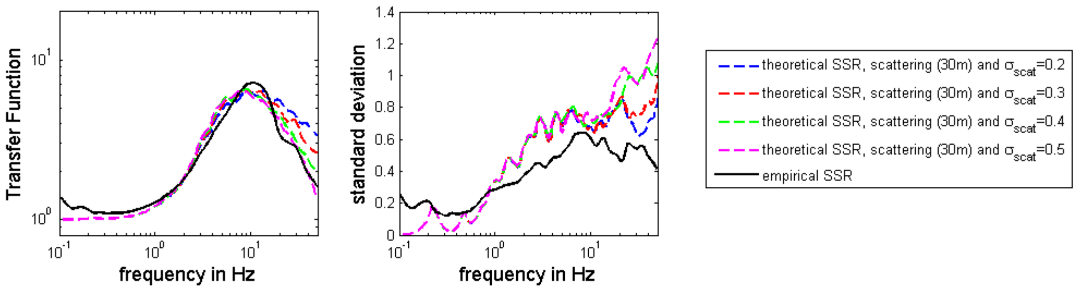

Figure 6: The mean theoretical transfer function (BTF) using the scattering assumptions of same depth (30 m) but with different $\boldsymbol{\sigma_{scat}}$ values (left). The corresponding standard deviations are plotted (right).

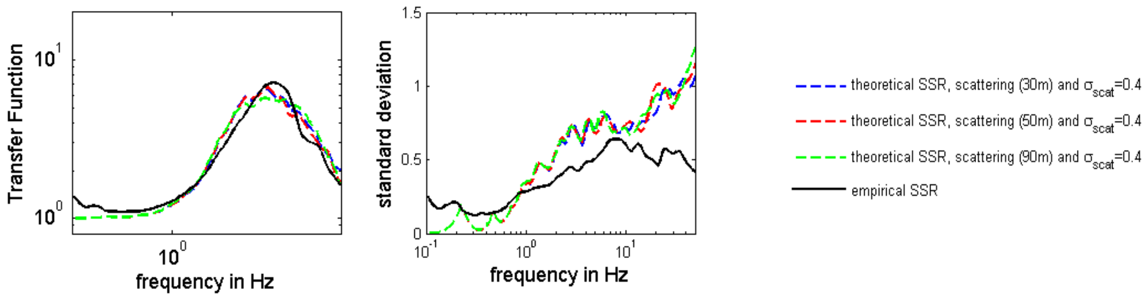

Figure 7: The mean theoretical transfer function (BTF) using the scattering assumptions of different depths (30, 50 and 90m) but with same σ_{scat}=0.4 (left). The corresponding standard deviations are plotted (right).

2.2 Derivation of hard-rock motion:

Benefiting of the fact that only the KiK-net network involves pairs of surface and downhole accelerometers at each site, Laurendeau et al. (2017) proposed a new approach to have hard-rock motions in the host side with a methodology classically applied in the target side. This methodology consists in correcting the surface records from their theoretical site transfer function. This correction approach (designated as SURF_cor) consists in computing the Fourier transform of each surface signal and then dividing it by the SH-1D transfer function with respect to an outcropping rock, consisting of a homogeneous half-space with a Vs equal to the velocity at the depth of the down-hole sensor. The estimated virtual outcropping rock spectrum is then converted in time domain by the inverse Fourier transform, and the associated acceleration response spectrum is computed.

Since the transfer functions to be used in the deconvolution process come from SH-1D simulations, only sites with a probable 1D behavior are considered (i.e., with a correlation coefficient between empirical and theoretical ratios larger than0.6 are selected, as proposed by Thompson et al., 2012). Only the records associated to a site and an event having recorded at least three records were selected as performed in Laurendeau et al., (2017).

We call SURFcor_scat the new subset computed in this study, in the same way that SURFcor but with the inclusion of scattering. The new results will be compared with the other subsets tested by Laurendeau et al., (2017): the original uncorrected recordings were separated into two datasets: DATA_surf which contains surface recordings and DATA_dh which contains downhole recordings; and the DHcor dataset based on the downhole records corrected with the procedure developed by Cadet et al. (2012); the H2T approach as defined by Van Houtte et al. (2011) using the V_{S30}-κ_0 relationship presented in the same study.

3 RESULTS IN TERMS OF GMPES AND DISCUSSIONS

A new GMPE is developed from SURFcor_scat from the same simple functional form as Laurendeau et al. (2017) to have comparable results. The “random effects” regression algorithm of Abrahamson and Youngs (1992) is used to express the geometrical mean of the two horizontal components of SA (in g):

$$\ln(SA(T))=a_1(T)+a_2(T).Mw+a_3(T).Mw^2+b_1(T).R_{RUP}-\ln(R_{RUP})+c_1(T).\ln(V_S/1000)+\delta B_e(T)+\delta W_{es}(T) \quad (7)$$

whereδB_eandδW_{es} are the between-event and the within-event residuals, associated with the standard deviations τ and φ respectively, and $\sigma_{TOT}=(\tau + \varphi)^{0.5}$.Here,$V_S$ takes the values of the down-hole sensor V_{SDH}.

Figure 8 displays the predicted SA in terms of $V_{S30}$for two frequencies in the case of the new SURFcor_scat GMPE compared tothe other GMPEs developed previously in Laurendeau et al. (2017).At 12.5Hz (a frequency for which the behavior of the standard-rocktohard-rock ratio is different), the predicted SA increases with decreasing V_{S30} for DATA_surf and SURFcor as already shown by Laurendeau et al. (2017). On the contrary, the predicted SA of DATA_dh and DHcoris almost constant. In the case of SURFcor_scat,we obtain a comparable slope than for the DHcor case. This result can confirm a better correction of the surface recordings.

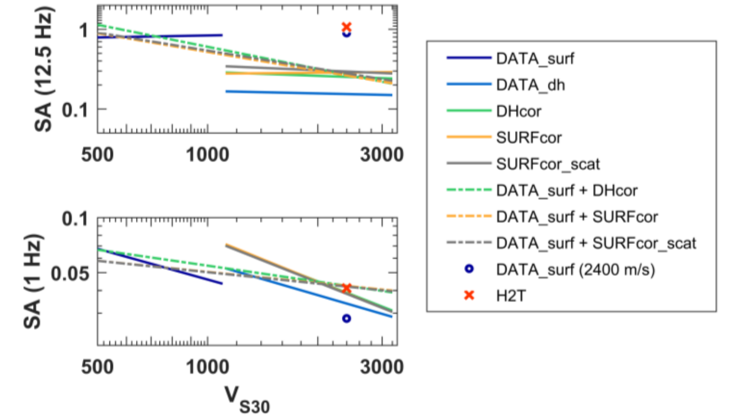

Figure 8: Predicted spectral acceleration (SA) at 12.5 Hz and 1 Hz, as a function of V_{S30} (with M_W =6.5 and R_{RUP}=20 km).

Figure 9 shows a comparison of the predicted spectral acceleration for a given event (M_W=6.5, R_{RUP}=20km) and a given site (Vs=2400m/s). We can note a slightly higher predicted SA for SURFcor_scatthan for SURFcor, as well as a slightly higher within-event variability at high frequency (no change is observed in the between-event variability). In fact, introduction of scattering assumptions is leading to a higher attenuation and thus to a larger $\Delta\kappa_o$ included in the correction, implying a lower "κ_o" in the case of the corrected records. The lower the "κ_o" is, the higher the SA is at high frequency. However, the corresponding increase remains very limited, and could by no means bridge the huge difference with the classical HTT approach.

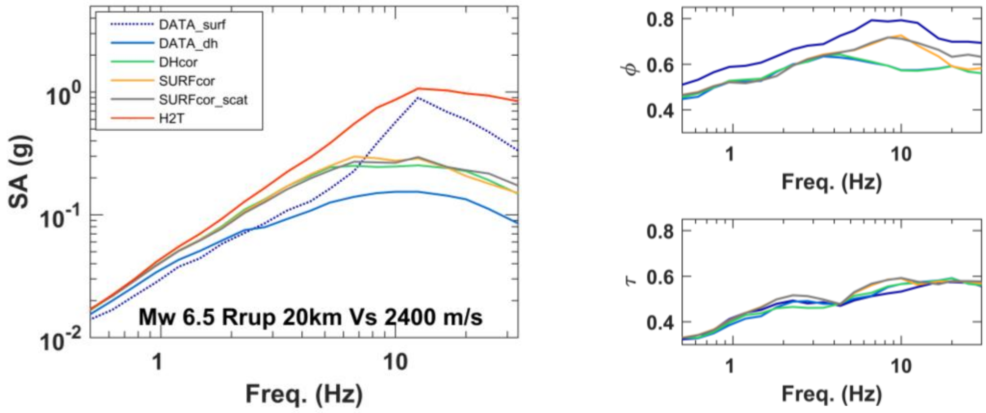

Figure 9: Comparison of the predicted spectral acceleration SA obtained before and after including scattering in the correction process, with the traditional H2T method results.

Figure 10shows an important summary of the results of Laurendeau et al.(2017) in terms of ratios of predicted ground motion between standard rock (V_S=800 m/s)and hard-rock sites (V_S=2400 m/s) in comparison to the result of the classical H2T method. The hybrid GMPE (DATA_surf + SURFcor) was developed again taking into account scattering assumptions in the deconvolution process and compared to the previous one (without scattering), showing slightly lower ratios beyond 10 Hz. Once again, the resulting SURFcor_scat ratios show a significant amplification of the standard rock site with respect to the hard-rock site, which is far from what is obtained by the H2T method.

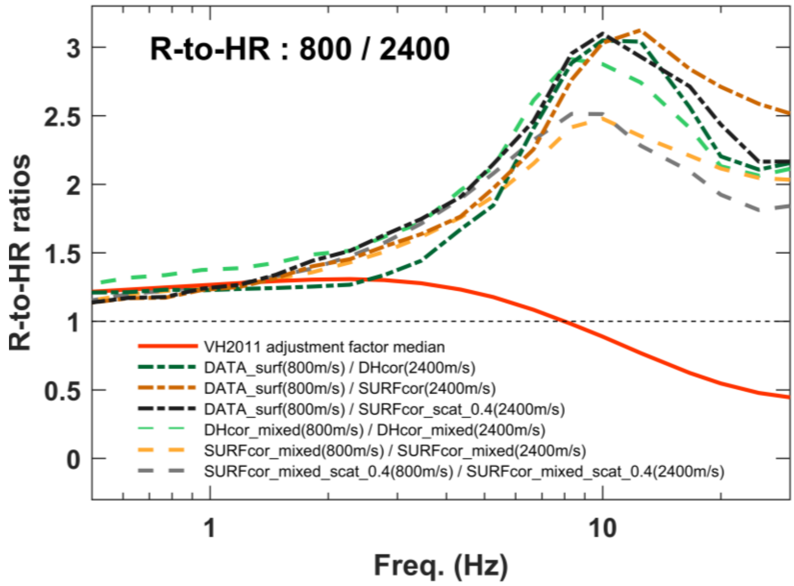

Figure 10: Comparison of the different ratios between standard rock (V_S=800m/s) and hard-rock (V_S=2400m/s) obtained with the different GMPEs developed in Laurendeau et al. (2017), compared to the new GMPE (SURFcor_scat) and to the ratio obtained from the H2T technique.

After showing these results, it is important to mention that scattering conditions are best taken into account when considering at least 2D structures. The kind of vertical heterogeneity we introduced in the S-wave velocity profiles seems to be overestimating the reality of scattering. The present work introduces this kind of heterogeneities in 1D simulations to show their potential impact in the high frequency domain. Another question that could be posed, if the current approach was used, is the ability to well estimate the amount of heterogeneity σ_{scat} that plays the key role in such definition. In the absence of downhole sensors, the control by an observed borehole transfer function is not possible. Thus, the values of σ_{scat}must be measured using precise velocity profiles such as those used in the present study from the PSSL measurements of the InterPacific project (Garofalo et al., 2016).

4 CONCLUSIONS

The main objective of this study is to highlight the impact of scattering in the high-frequency motion observed on rock-to-hard-rock sites to better estimate the site transfer functions using numerical simulations. This work has been done on the KiK-net network which benefits from the presence of sensor pairs at surface and depth. The work done by Laurendeau et al. (2017) allowed to estimate the theoretical site transfer functions and control it with the observed transfer functions which showed an overestimation of the amplification at high frequency. The issue raised by Laurendeau et al.(2017) appears to be originating from the definition of the S-wave quality factor scaling relation (Q_S=V_S/10) due to simplification of reality by the smooth S-wave velocity profiles provided by the used down-hole methods. Motivated by observations from some French sites (Garofalo et al., 2016) and previous studies (Parolai et al., 2015;Pilz and Fäh,2016), the introduction of scattering assumptions in a similar way to what was found in the literature (Parolai et al., 2015) resulted in better understanding of the high frequency issue and thus proving the importance considering vertical heterogeneities in the medium.Accounting for scattering allowed to reach a better fit between the theoretical transfer functionsand the observed ones. Their later use in the deconvolution process is thus likely to result in more reliable estimates of the hard-rock motion. The same ground motion prediction equation (SURFcor_scat) as that of Laurendeau et al.(2017)was developed, but this time with scattering assumptions, and was compared to previous results. The resulting GMPE show an improvement that can be seen in terms of the dependency of the predicted spectral acceleration on the V_{S30} as compared to the previous GMPE. In terms of the rock-to-hard-rock ratio, although the new GMPE developed lead to slightly smaller ratio at high frequency than the previous GMPE, the results once again deeply question the appropriateness of the H2T corrections when applied with the commonly accepted V_{S30}-κ_0 corrections. This work opens new questions on how to account better for scattering conditions on one side and how to define and estimate the key parameters in such scattering assumptions.

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