Importance and Impact of Host-to-Target Conversions for Ground Motion Prediction Equations in PSHA

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SUMMARY:
The PEGASOS project, a state-of-the-art probabilistic seismic hazard assessment for the nuclear power plant sites in Switzerland has been carried out from 2000 to 2004. The quantification of the epistemic uncertainty in seismic hazard at the four Swiss nuclear power plant sites was the key aspect of the PEGASOS project. After the completion of the project, the Swiss utilities decided to perform a refinement of the study by collecting additional data and using new advances in science, especially in the field of ground motion modeling, to further reduce the identified uncertainties. Some new challenges for the scientific community and the implementing industry have been identified, which of one is adjusting ground motion prediction equations from their host conditions to the target conditions. Here, the comparisons between the obtained results from some host-to-target conversion correction methods are illustrated with emphasis on their significant impact on PHSA results.

Keywords: Site specific PSHA, V_S-Kappa, PEGASOS

1. INRODUCTION

In the PEGASOS Refinement Project (PRP) (Renault et al., 2010) a specific set of ground motion prediction equations (GMPE) were selected, and it was deemed necessary to adjust them for the Swiss rock conditions in order to make them applicable for the site specific PSHA. Nowadays, the host-to-target conversion mainly consists in applying the so-called hybrid empirical method (Campbell, 2003 & 2006, Scherbaum et al., 2004) which defines a method to adjust ground-motion prediction equations to target regions different from the region for which they were developed by using response spectral host-to-target-region-conversion filters. This accounts for the differences in the shear wave velocity profiles (V_S) and Kappa (κ) values of the individual GMPE-host-regions (for which they were implicitly developed based on the regional data) and the conditions in the target region, here the Alpine foreland in Switzerland.

During the PRP several sensitivity studies were performed with respect to the impact of the host-to-target conversion and it turned out to be a key factor with a large impact on the seismic hazard results. A couple of alternatives approaches were developed in order to try to account for the epistemic uncertainty of this correction. Beside the classical hybrid empirical method, some iterative approaches based on the hybrid empirical approach were developed by the experts. Empirical correction values were also derived in order to be able to estimate constraints based on the observed data. In the course of the sensitivity analysis, due to high variation of Kappa ranges and the impact on PSHA, a new approach of estimating Kappa on Fourier spectra based on an inverse RVT approach was introduced in PRP. Furthermore, comparisons to estimates were performed, based on existing V_{S30}-Kappa relationships evaluated for generic Swiss rock conditions and specific hard rock sites.

2. ADJUSTING SELECTED GMPES TO THE SWISS ROCK CONDITIONS

Within the PEGASOS Refinement Project (PRP), the Sub-Project 2 (SP2) experts decided to apply host-to-target corrections for the GMPE to be applicable for the Swiss reference rock profile (anchored at V_{S30} = 1000m/s with Kappa = 0.017s) as well as for the nuclear power plant (NPP) specific site conditions (with V_{S30} between 1100 and 2500m/s). In the course of the project a logic-tree (Fig. 2.1) was developed in order to build a clear structure for the different contributing variables and to cover the epistemic uncertainty.

The SP2 expert panel has selected 11 GMPEs to be considered in the logic-tree for the median models (based on extended selection criteria of Cotton et al., 2006). The selected models include four of the NGA GMPE, two GMPE for Eastern North America, three for Europe and the Middle East, one for Japan and alternative version of the new Swiss stochastic model. Here in this paper we will concentrate on the NGA GMPEs, which are Abrahamson & Silva (2008), Boore & Atkinson (2008), Campbell & Bozorgnia (2008) and Chiou & Youngs (2008).

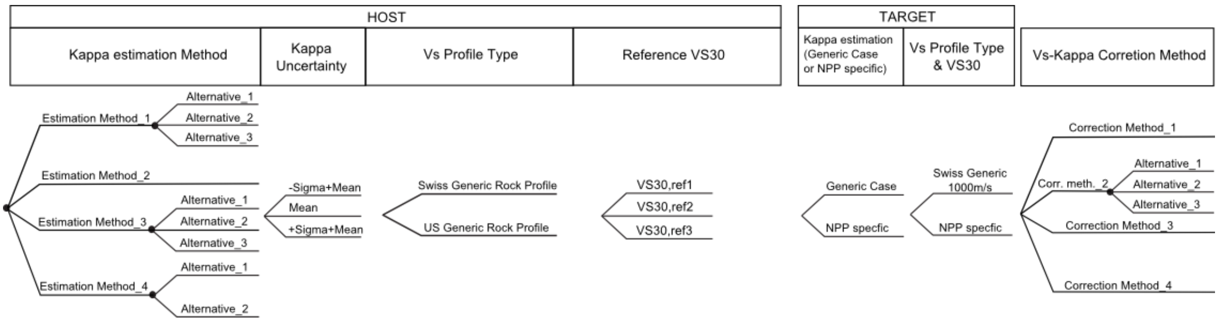


Figure 2.1. Schematic representation of the logic-tree used in PRP for adjusting the GMPEs to Swiss conditions.

In the project, the hazard will be calculated in terms of ordinates of spectral acceleration at 9 response frequencies between 0.5 and 100 Hz. The SP2 experts decided that developing host-to-target region scale factors for the full set of stochastic point source parameters was desired as the stress-drop scaling in Switzerland was not well constrained, but they considered the differences in the shear wave velocity profiles and Kappa to be important effects that should be considered. Therefore, the objective was to isolate the V_S and Kappa correction from the full model correction.

2.1. Sources of uncertainties

The shape (gradient) and values of an underlying generic shear wave velocity profiles for the host conditions are not well constrained (discussed in more detail in section 2.2). Nevertheless, the background models used to evaluate the V_S correction need as input information the crustal amplification and thus, two alternative profiles have been adopted. The same issue occurs for the target profile, but if measurements are available it is justified to develop a single generic hard rock profile to be used. Form the sensitivity analyses it has been seen that the V_S correction is straight forward, robust and has a much smaller impact than the Kappa correction (if done separately).

Furthermore, there are alternative estimates of crustal damping (Kappa) in the host and target region which can be used (discussed in more detail in section 2.3). As Kappa is implicitly part of the dataset for which the GMPE was developed and not directly a modifiable variable in the attenuation model, it is hard to quantify and constrain.

In the framework of the PRP also alternative approaches for the Kappa evaluation were proposed which are based on the development of Kappa-f_{peak} relationships. The approach consists in the simulation of ground motions for different earthquake scenarios with a stochastic model (e.g. with SMSIM) and different Kappa values. Then for each ground motion scenario corresponding to a certain magnitude, distance, Kappa value, and point source stochastic model the characteristic high frequency amplification is identified. In the framework of the PRP different alternative definitions of the characteristic high frequency, where the response spectrum peaks, have been tried. Then, for each point source stochastic model, Kappa versus "f_{peak}" values are plotted for each magnitude and distance scenarios and the parameters of the power fit (*c* and *n*) between Kappa and "f_{peak}" were determined: $\kappa = c \cdot f_{peak}^{n}$. These relationships allow the estimation of Kappa for the different point-source stochastic models knowing f_{peak} for a certain earthquake magnitude and distance.

The host-to-target correction can be performed in a full single step or in a 2-step approach which would consist in first correction from the generic host conditions to the generic target conditions and then applying a second correction towards the site specific target conditions. In order to be able to relatively compare different corrected GMPEs and their correction functions it makes sense to do this for the generic target conditions in order to have a common reference. A sample comparison has shown that the 2-step correction produces slightly higher correction factors (approx. 5%) at the peak of the correction function (around 30 Hz). As a slight difference in the V_S-Kappa correction function can lead to a significant difference in the end results it is worth to assess this difference in more depth.

2.2. V_S profile difference

For the host GMPE V_S profile, there are two sets of reference profiles in PRP: Swiss generic and US generic. A specific generic velocity profile for a GMPE is interpolated from the set of reference V_S profiles. The generic Swiss profile is based on the reference rock V_S profile (Fig. 2.2b). For other V_{S30} values, the Swiss reference V_S profile is shifted to match the V_{S30} of each GMPE as shown in Fig. 2.2b. The generic US profiles consist of the 618 m/s V_{S30} profile for western North America (WNA) and the 2880 m/s V_{S30} profile for eastern North America (ENA) (Boore & Joyner, 1997). The interpolation of US generic profiles between 618 and 2880m/s is done based on Cotton et al. (2006) and shown in Fig. 2.2a. A range of alternative reference V_{S30} values for each GMPE were selected by the SP2 experts to account for its uncertainty.

The references V_{S30} values for the four NGA models are fixed to a single value to be selected by the SP2 expert. A single value is used for these models because the NGA models include V_{S30} as an input parameter in the model. For the other PRP selected GMPEs, which are not discussed here in this paper, the shear wave velocity adjustment is performed based on alternative reference V_{S30} values, intended to capture the possible best estimates consistent with the used site classes. For some of those GMPE the experts also considered shear wave velocities below 618m/s which would have required an extrapolation of the profile. This turned out to be problematic as the shape of the US generic rock profile is very flat in the shallow part. As alternative, measured US shear wave profiles in the range of 400 to 560m/s (personal communication by W. Silva) were used to define profiles based on soft rock profiles. On the other hand it can be seen that those soft rock profiles show a significant different shape than the WNA profile of Boore & Joyner (1997), highlighting again the none-uniqueness of this generic V_S adjustment.

As target V_S profile, the Swiss generic rock shear wave profile and NPP specific versions of it will be used for the PSHA evaluation at each site.

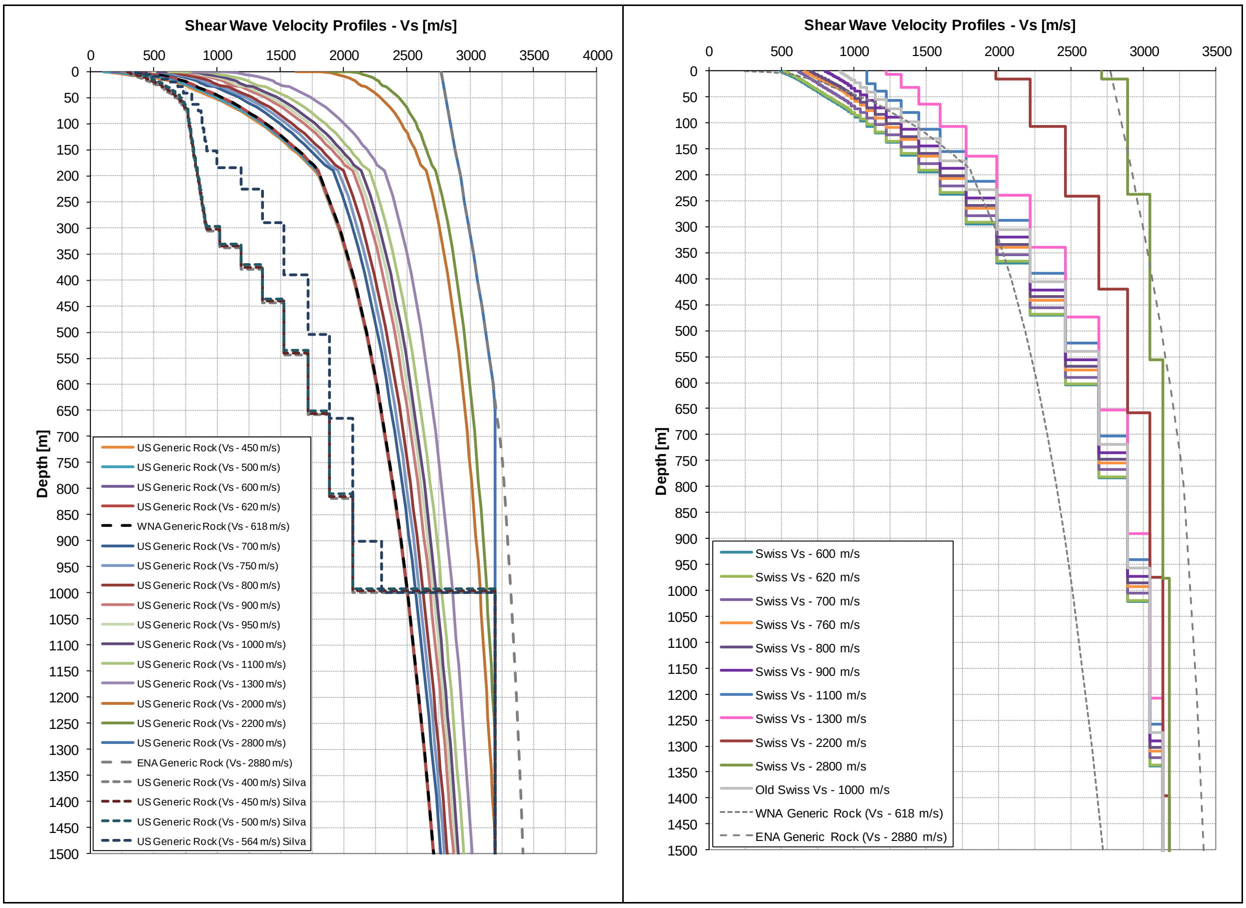


Figure 2.2. Alternative V_S profiles based on the US generic (a: left) and Swiss generic (b: right) V_S profiles. The interpolation of US generic profiles between 618 and 2880m/s is done based on Cotton et al. (2006)

2.2. Kappa difference

In the PRP, estimates of the damping in the upper crust (Kappa) are needed for each GMPE (host region) and for Switzerland (target region) in order to perform a host-to-target conversion to make the GMPEs applicable. Three alternative methods for estimation of the Kappa are considered: Kappa based on response spectral shapes from the GMPE, Kappa based on empirical V_{S30}-Kappa correlations, Kappa based on the slope of the Fourier amplitude spectrum estimated from the GMPE using the inverse RVT (IRVT) approach, and empirical estimates.

2.2.1. Kappa based on Response Spectral Shapes

To improve the robustness of the estimation of Kappa, initially it was proposed that the Kappa value be estimated based on the frequency at which the acceleration response spectrum reaches its peak (f_{peak}) or a representative characteristic frequency (f_{amp}). Using the point-source stochastic model, the relation between the f_{peak} and Kappa can be derived for different magnitude and distances using short distances scenarios (to avoid large effects of Q). When the Kappa is reduced, the peak of the spectrum shifts to higher frequencies. The relation between Kappa and f_{peak} is not strongly dependent of the stress-drop. The relation is also similar for the WUS and CEUS background models indicating that this correlation is fairly robust. Alternative definitions of the characteristic frequency have been evaluated also and the associated standard deviation.

Using this approach, Kappa values were estimated for each of the GMPE selected within the PRP. However, even though the mean Kappa values were quite similar, the point source inversion lead to very different estimates of Kappa values for the four NGA models when the variability of the estimated Kappa values is included.

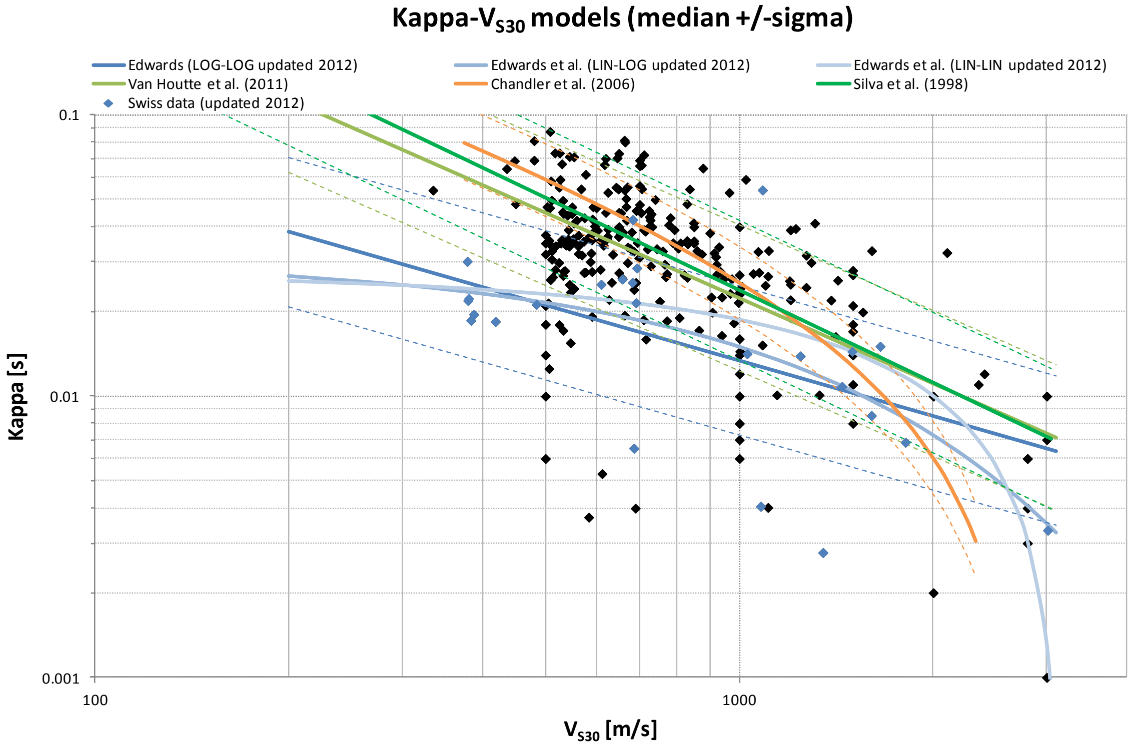


Figure 2.3. Published correlations between Kappa and Vs_{30}. The dashed lines represent +/- one standard deviation about the median relationship (Renault, 2011).

2.2.2. Kappa based on V_{S30}-Kappa correlations

Kappa can be estimated for a GMPE using the V_{S30} for the GMPE and empirical correlations between Kappa and V_{S30}. Two correlation models considered as bounding cases are considered in the PRP: Edwards et al. (2012) and Silva et al. (1998). The Edward et al. model is based on Swiss data using the Kappa estimated for the Swiss stations as part of the development of the Swiss stochastic model. The Silva model is based on world-wide data (mostly California) using Kappa values estimated from inversions of the Fourier spectral values. A recent evaluation of V_{S30}-Kappa relation based on world-wide data using Kappa values based on measured slopes of Fourier spectra is given by Van Houtte (2011). They found a V_{S30}-Kappa relation similar to the Silva et al. (1998) model. A comparison of the different alternative V_{S30}-Kappa relations are shown in Fig. 2.3.

It should be noted that the data is very sparse in the range of hard rock V_{S30} values of interest for the Swiss NPP (1100 – 2500m/s) and that the different empirical models lead to very different kappa estimates for such hard rock conditions. Furthermore, if only data above 1000m/s would be considered, there is no clear trend anymore which could be used to derive a model.

2.2.3. Kappa based on Fourier Spectra from IRVT

Kappa can also be estimated for a GMPE based on the slope of the Fourier amplitude spectrum (FAS) estimated from the response spectrum. This approach consists of deriving V_S-Kappa adjustment functions which are based on the scaling of the Fourier amplitude spectra corresponding to the host GMPE response spectra for differences in Kappa and V_S profiles between the host and target regions. Response spectra-compatible FAS for the host and target regions are obtained through inverse random vibration theory (IRVT) using the computer program STRATA (Kottke & Rathje, 2008). The IRVT procedure uses extreme value statistics, properties of single degree-of-freedom oscillator transfer functions (narrow band with values equal to unity below the natural frequency and approaching zero for frequencies larger than the natural frequency), and spectral ratio correction to develop FAS compatible with GMPE response spectra. A detailed description of the IRVT procedure can be found in Rathje et al. (2005). Basically, in this approach, IRVT is used to estimate the FAS for a given response spectral shape for a given magnitude and distance. For each GMPE and each reference V_{S30}

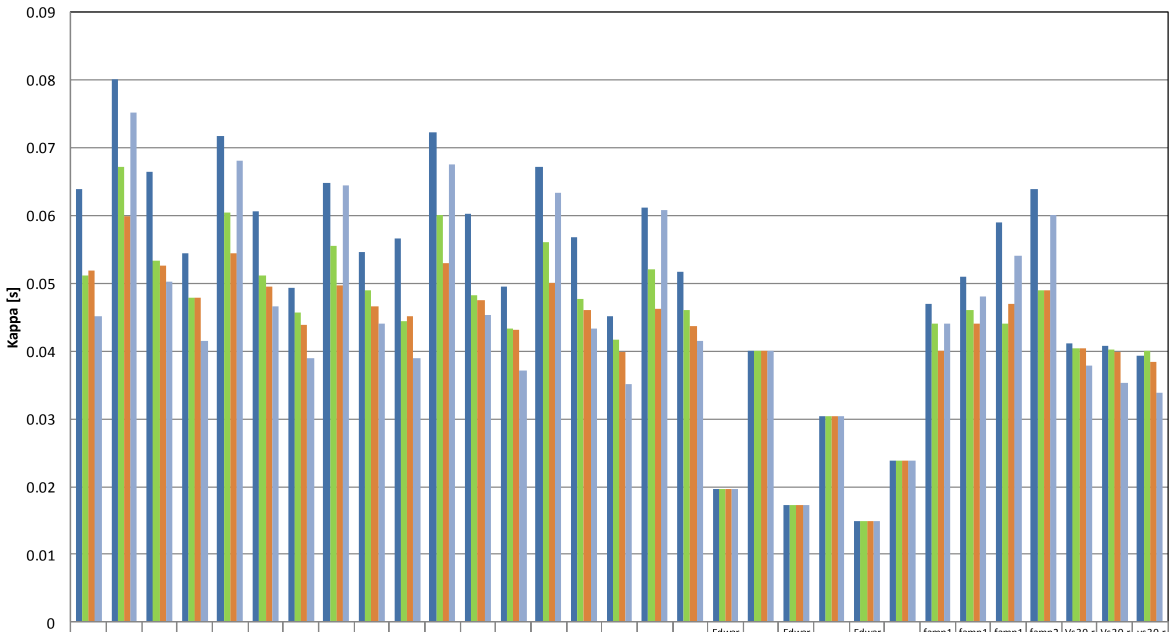
value, this process is repeated for different earthquake scenarios (e.g. magnitudes M_w=5, M_w=6, and M_w=7 and distances R_{jb} = 5, 10 and 20 km).

2.2.4. Kappa Estimation Using Empirical Ground Motion Data

Different Kappa scaling were also derived using empirical ground motion data from Western US (WUS), Central and Eastern America (CENA), and Switzerland. The intention of this evaluation was to try to find some empirical constraints in order to provide guidance on the simulation based Kappa-corrections to be retained. For WUS data, Kappa scaling was evaluated using the within-event residuals of the data with respect to the Abrahamson & Silva (2008) and the Campbell & Bozorgnia (2008) GMPE. For the CENA data, Kappa scaling has been evaluated using within-event residuals of the data with respect to the Atkinson & Boore (2006) model. For the empirical ground motion datasets used herein, Kappa is estimated for each recording using IRVT-based relationships between Kappa and $f_{amp1.3}$, $f_{amp1.5}$, $f_{amp1.7}$ and $f_{amp2.0}$ where $f_{amp1.3}$ to $f_{amp2.0}$ are the highest frequencies of the response spectrum that correspond to spectral acceleration values equal to 1.3 and 2 times the peak ground acceleration (PGA), respectively.

2.2.5. Comparison of different Kappa Estimates

All the above discussed approaches lead to an estimate for Kappa for a GMPE given the different boundary conditions used for the evaluation. The wide range of Kappa values which was obtained in the course of the sensitivity analyses in the framework of the PRP certainly reflects the several uncertainties being part of the evaluation. Fig. 2.4 illustrates the various values obtained for the four selected NGA models. What can be seen is that even within the NGA GMPE, which are more or less based on a similar dataset, the first set of Kappa estimates (2.2.1) are within a large range. On the other hand, the Kappa values obtained on the base of the empirical evaluation of data (2.2.4) and the iRVT approach (2.2.3) show to be more robust and consistent with expert judgment.



	US									CH								
	Vs30,ref1			Vs30,ref2			Vs30,ref3			Vs30,ref1			Vs30,ref2			Vs30,ref3		
	f1	f2	f3	f1	f2	f3	f1	f2	f3	f1	f2	f3	f1	f2	f3	f1	f2	f3
AbSi08	0.0639	0.0801	0.0665	0.0545	0.0717	0.0606	0.0494	0.0649	0.0547	0.0567	0.0723	0.0603	0.0495	0.0671	0.0569	0.0452	0.0612	0.0517
BoAt08	0.0511	0.0672	0.0534	0.048	0.0604	0.0511	0.0457	0.0556	0.0489	0.0445	0.0601	0.0483	0.0433	0.056	0.0477	0.0417	0.0521	0.0461
CaBo08	0.0518	0.0599	0.0526	0.0478	0.0544	0.0495	0.0438	0.0497	0.0465	0.0451	0.053	0.0475	0.0431	0.0501	0.0462	0.0399	0.0463	0.0438
ChYo08	0.0452	0.0751	0.0502	0.0416	0.068	0.0466	0.0389	0.0645	0.0441	0.0389	0.0675	0.0453	0.0372	0.0634	0.0433	0.0352	0.0608	0.0415

	Vs30-Kappa correlation						Empricical				iRVT		
	Vs30,ref1		Vs30,ref2		Vs30,ref3		Vs30,ref1				Vs30,ref1		
	Edwards	Silva	Edwards	Silva	Edwards	Silva	famp1.3	famp1.5	famp1.7	famp2.0	Vs30,ref1	Vs30,ref2	vs30,ref3
AbSi08	0.0197	0.0401	0.0173	0.0303	0.015	0.0238	0.047	0.051	0.059	0.064	0.0412	0.0407	0.0394
BoAt08	0.0197	0.0401	0.0173	0.0303	0.015	0.0238	0.044	0.046	0.044	0.049	0.0404	0.0402	0.04
CaBo08	0.0197	0.0401	0.0173	0.0303	0.015	0.0238	0.04	0.044	0.047	0.049	0.0405	0.0398	0.0385
ChYo08	0.0197	0.0401	0.0173	0.0303	0.015	0.0238	0.044	0.048	0.054	0.06	0.0379	0.0353	0.0339

Figure 2.4. Representation of alternative Kappa estimates obtained through different approaches for the four NGA GMPE. The first 18 columns correspond the approach described in 2.2.1, the Kappa values in column 19-24 to the approach 2.2.2, column 25-28 to approach 2.2.4 and the last three columns to the approach 2.2.3.

3. IMPACT OF HOST-TO-TARGET CONVERSIONS ON HAZARD

It is well known that GMPEs should not be used directly as published for regions other than the one on which the underlying dataset is based and for which the model has been constrained. Their applicability should always be verified or adjustments are necessary based on the local available data. Nevertheless, little attention was paid to the host-to-target correction and its consequences in the past, or was even completely ignored. There is a significant difference in the impact of Vs and Kappa conditions from host-to-target. In the framework of PRP, hazard sensitivity studies have identified these correction functions, derived from the combination of Vs and Kappa conditions, as being one of the most important contributors in terms of effect on the overall hazard results.

3.1. Impact of V_S and Kappa, and their derived V_S-Kappa correction functions

An example of V_S and Kappa correction functions for different host and target conditions combined in the end to a joint correction function and evaluated for the Abrahamson & Silva (2008) GMPE is illustrated in Fig. 3.1. The top left graph shows the corrections assuming a host V_{S30}=800 m/s and corrected to four different target V_S values in the range of 1800-2500 m/s. The top right graph shows the corrections functions assuming a host of Kappa=0.04s and different target values between 0.006 and 0.04s. The combined V_S-Kappa correction shown here was built with the V_S-correction for 2000 m/s (red line) and the different target Kappa values.

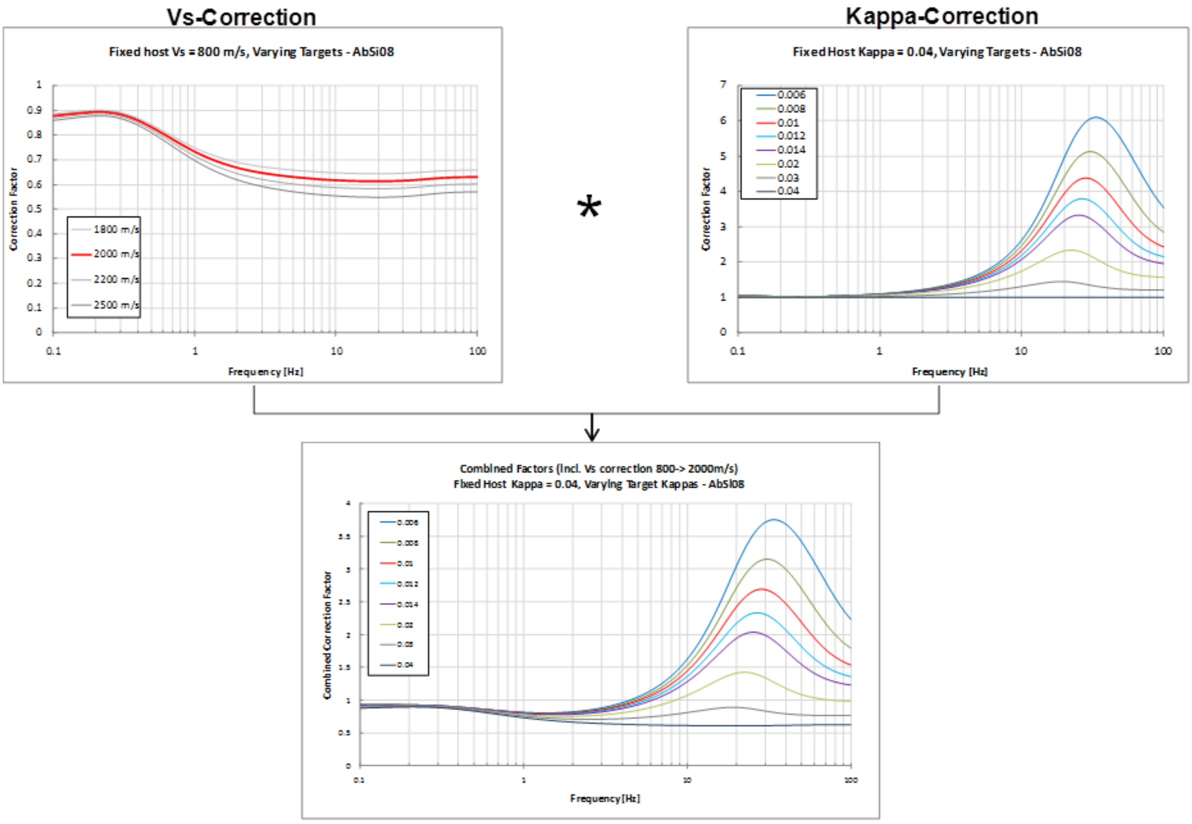


Figure 3.1. Example of V_S- and Kappa-correction functions evaluated for Abrahamson & Silva (2008).

3.2. Impact on Hazard

Fig. 3.2 shows the impact of the correction functions displayed in Fig. 3.1 on the seismic hazard. The effect is not negligible and dominating compared to most other parameters which have been evaluated in the framework of the SP2 refinements. The assumed values for V_S and Kappa in the host and target region are reasonable and credible estimates based on the available information. Nevertheless, it is of course acknowledged that those should not be set independently from each other, as they are correlated. Depending on the selected host and target V_S and Kappa values and their combination the correction can have difference outcome than shown in the example.

It is clear and from the figures below, which show the impact on the hazard at 5 and 33 Hz, that the Kappa correction shows its biggest impact at the higher frequencies up to PGA.

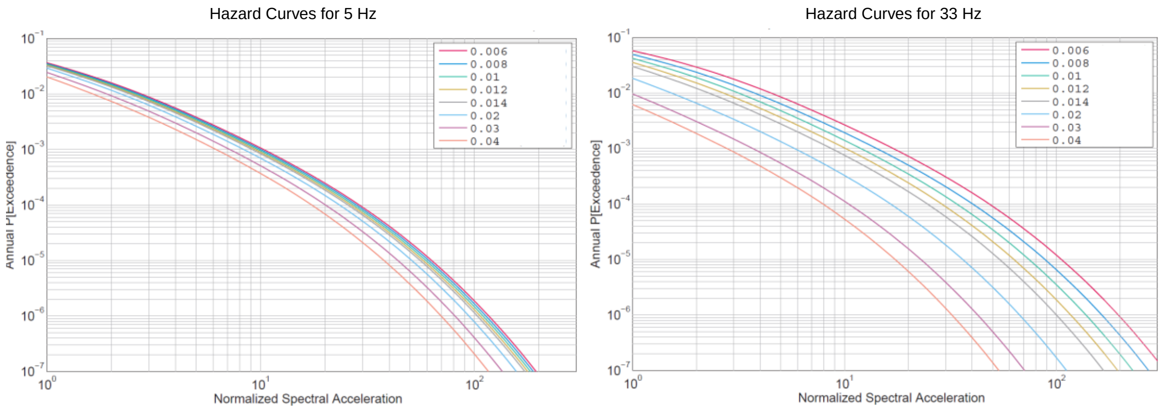


Figure 3.2. Hazard sensitivity to different target Kappa values for 5 Hz (left) and 33 Hz (right) at an example site in Switzerland. The host Kappa is fixed as 0.04s with Vs_{30}=800 m/s. The target conditions are Vs_{30}=2000 m/s with different Kappa values ranging from 0.006s to 0.004s.

4. CONCLUSION

This paper gives an overview of the performed V_S-Kappa sensitivity evaluations with respect to the input values and resulting host-to-target conversion correction factors, which were evaluated with different alternative approaches. Nevertheless, it should be recognized that there is an illusion of precision in the out coming correction function, as many uncertainties are involved in the different steps, and especially with respect to the used input values. Yet, no definitive conclusions could have been drawn as the used parameters, the associated uncertainties in their estimation and used methods are still evaluated and under development, respectively. One of the main issues is certainly that it is hard to account for the correlations of all parameters in the used attenuation models and the used stochastic versions. As the Vs-Kappa correction has been identified as a dominant contributor to the hazard and a source of large uncertainty its scientific investigation deserves some more profound evaluation and attention in the future.

5. OUTLOOK

The next step after having performed the sensitivity studies discussed above is to develop parameterized versions of the Vs-Kappa correction functions which depend on the main host and target variables, V_{S30} and Kappa. The shape of the correction function seems robust enough to perform a multi-dimensional fit (Fig. 5.1) and will provide an easy way to evaluate the necessary correction function for a GMPE and avoiding developing correction functions for each specific case and scenario. This piece of work has not been finalized at this point in time and will be the subject of another paper.

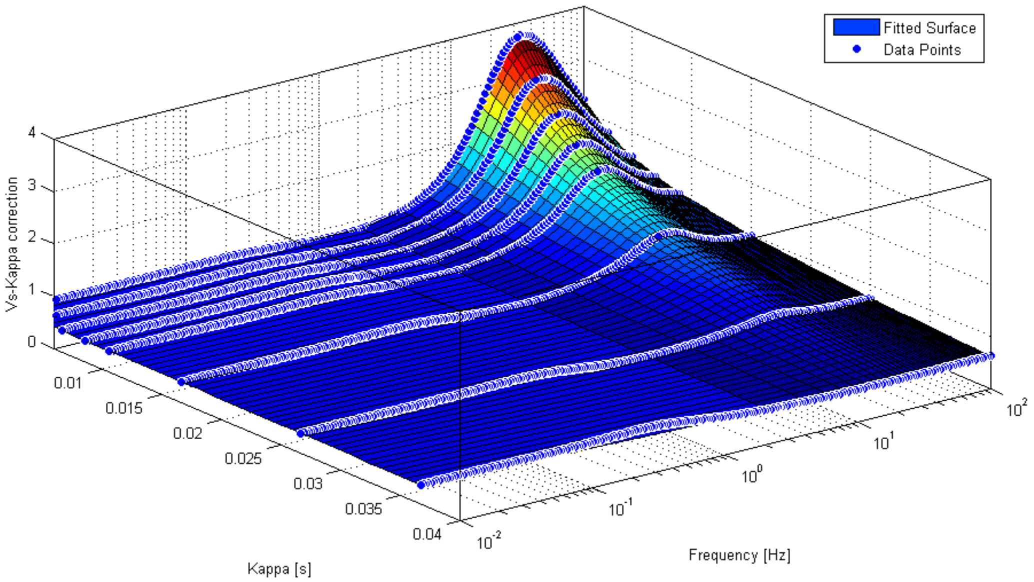


Figure 5.1. Example parameterization of V_S- and Kappa-correction functions by fitting a surface to the evaluated correction functions (here for a given V_{S30} and a range of target Kappa values)

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