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ESTIMATION OF KAPPA (κ) FOR ROCK SITES IN THE NGA-EAST DATABASE AND IMPLICATIONS ON DESIGN MOTIONS

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Abstract

At high frequencies, the amplitude of the Fourier amplitude spectrum (FAS) of acceleration decays rapidly. Anderson and Hough (1984) [1] introduced the spectral decay factor (κ) to model the rate of decay in log-linear space. Its site-specific component, κ_0, comes from damping over the top few km of the crust. κ_0 is an important input parameter in the simulation and prediction of ground motion. It is the principal site parameter controlling the limitation of high frequencies (>5 Hz) at close-in distances (out to ~50 km). Thus, its range of values is important in characterizing strong ground motions for engineering design, particularly in regions of sparse seismicity. Current uncertainty in the estimation of κ_0 is very high (Ktenidou et al., 2014 [2]). In practice, this can have significant implications on seismic risk: 1) for safety-related equipment in nuclear facilities, and 2) for the seismic behavior of small concrete dams.

In October 2014, the NGA-East project published a metadata flatfile for data from Central-Eastern North America (CENA). Those data are important for the creation or updating of current ground motion prediction models (GMPEs). We estimate κ_0 for CENA focusing on rock sites (Vs_{30}>1000 m/s) at short distances (<100 km), so as to avoid path attenuation. We use two band-limited methods to estimate $\kappa_{0,}$ the acceleration spectrum approach (AS) and the displacement spectrum approach (DS) as summarized in [2], and compare the two approaches.

Due to the lack of seismic records on hard rock sites, site effects for hard-rock sites are typically computed using analytical models for κ_0. In current practice and consistent with its original definition, it is assumed that all of the measured κ_0 is due to attenuation beneath the site. We raise two issues: 1. the idea that new datasets that are richer in hard-rock recordings will allow us to evaluate the scaling for hard-rock sites (soft-to-hard-rock correction factors), and 2. the concern that the total κ_0 measured from records may incorporate additional effects that are not directly related to attenuation (e.g. site-specific shallow resonance patterns), which may affect the apparent measured values of κ_0.

We use the NGA-East dataset as an example of a new dataset rich in hard-rock data, and study residuals with GMPEs. The high-frequency response spectra residuals are weakly correlated with κ0, in contrast to the strong scaling with κ_0 in the analytical models. We propose that this may be due to amplification marking attenuation at high frequencies, causing overestimation of the actual attenuation effect on ground motion, and leading to possible (unconservative) overcorrections in GMPE adjustments in current practice. The coupling of site amplification and site attenuation may become a key limitation in measuring and interpreting κ. For this reason, an empirical model is developed for the combined Vs_{30} and κ_0 scaling for hard-rock sites relative to a reference site condition of 760 m/s. This model shows high-frequency amplification that is more similar to the analytical prediction corresponding to a hard-rock κ_0 of 0.020 s rather than the typical value of 0.006 s commonly used for hard-rock sites in the Central-Eastern US. This leads to a reduction of high-frequency scaling of about a factor of 2, compared to the traditional analytical approach.

Keywords: high frequencies, hard rock, attenuation, amplification, ground motion

1. Introduction

Estimating ground motion at high frequencies is important for stiff structures with natural frequencies above 10 Hz, such as small concrete dams [3], and structures with safety-related equipment that sensitive to ground shaking at frequencies above 20 Hz, such as nuclear power plants [4]. Characterizing high-frequency ground motion on hard-rock sites using empirical data has been challenging because there were very few ground-motion recordings on hard-rock sites. In current practice, analytical models for amplification for hard-rock sites are usually used.

One approach is to start with ground-motion prediction equations (GMPEs) for soft rock conditions, for which there are adequate empirical data to constrain the model, and then use analytical modeling to develop hard-rock/soft-rock site factors [5]. In this approach, the analytical modeling typically considers the effects of the differences in the the shear-wave velocity profiles (Vs) and the damping which is assumed to be characterized by κ_0 [1]. There are several methods commonly used: (1) the hybrid empirical method (HEM) of [6,7], where the point-source stochastic model is used to account for differences in response spectra due to the different seismological parameters between host region (native region of GMPE) and target region (region where there is no GMPE); and (2), the inverse random vibration theory (IRVT) approach of [8], where response spectra are converted into FAS to correct for Vs and κ0 and then converted back to response spectra.

If we only account for the differences in the Vs profile (i.e., only consider the effects of the impedance contrast) and ignore κ_0 differences, the computed ground motion will be smaller for hard-rock sites than for soft-rock sites at all frequencies. As an example, the top frame of Figure 1 shows the site factor only considering the VS profile differences. If we assume that κ_0 is related to damping, then the high-frequency content is increased for low kappa expected for hard-rock sites. Typical values used for κ_0 for hard-rock site are in the range of 0.006 to 0.015 sec, whereas, the values are in the range of 0.03 to 0.04 sec for soft-rock sites. The middle frame of Figure 1 shows the effect of differences in kappa relative to κ_0 =0.04 sec. For the lower range of hard-rock kappa values, the effect of kappa can be very large at high-frequencies. The middle frame of Figure 1 shows that the effect of kappa can be as large a a factor of 6. The lower frame of Figure 1 shows the combined effect of the VS and kappa. The hard-rock factors shown in lower frame of Figure 1 reflect the assumption that differences in kappa are due to differences in damping. Reducing damping must lead to an increase in the high-frequency content; however, if the differences in kappa are, in part, due to differences in other factors, such as high-frequency site resonances, then the effect on the site factor would would not be as strong.

The assumption that kappa differences are due to damping differences has been the standard assumption used for hard-rock site factors in the U.S. There is now expanded empirical data sets with large increases in the numbers of recordings on hard-rock site conditions. In this paper, we use the new data sets to develop empirical site factors for hard-rock site conditions that can be used to evaluate the analytical results. We estimate the scaling between hard-rock sites (Vs_{30}>1500 m/s) and soft-rock sites (Vs_{30}=760 m/s) that represents the net effect of site amplification and attenuation (Vs_{30} and κ_0). These empirically-based hard-rock site factors provide an alternative to the hard-rock site factors based on analytical models.

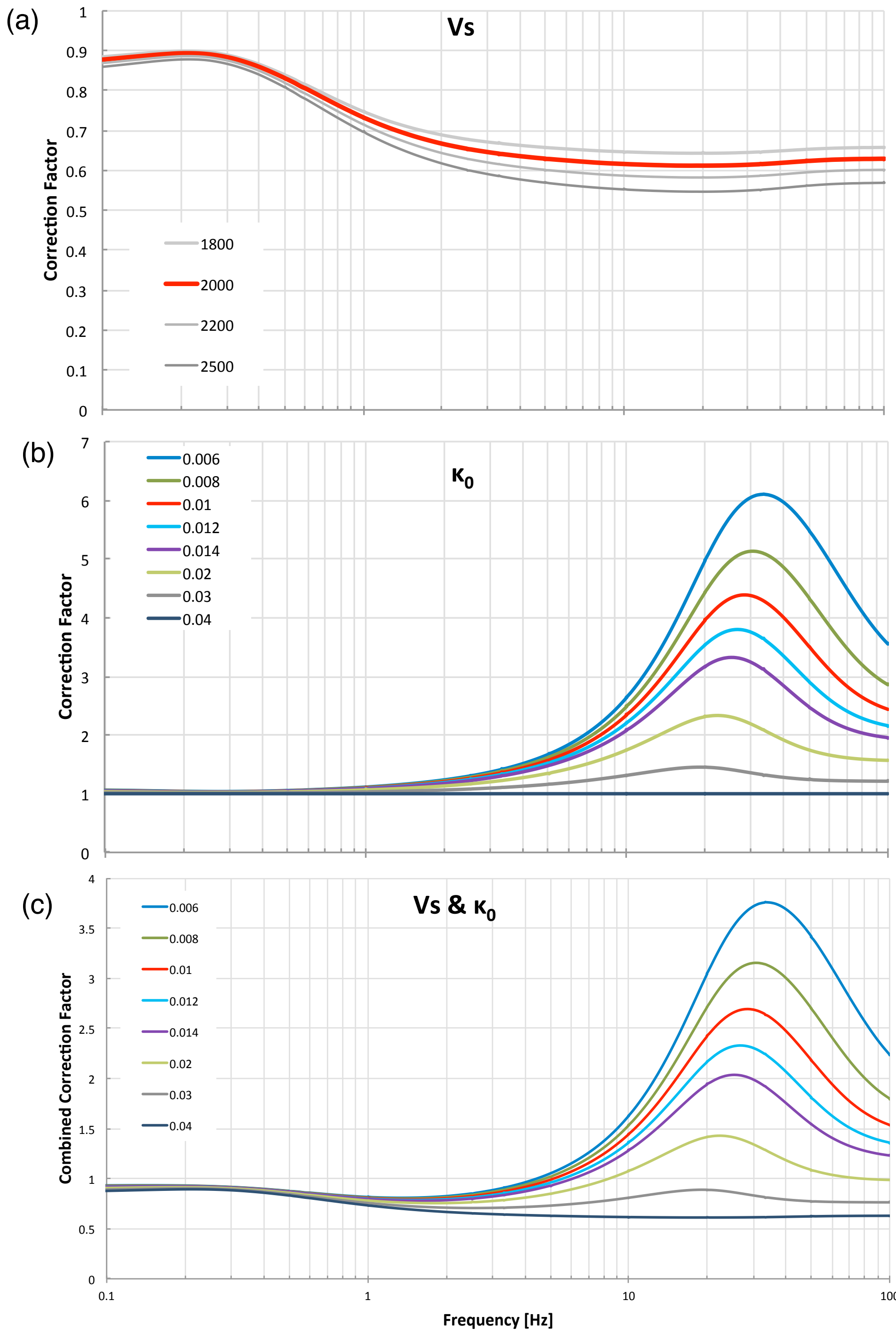

Fig 1. – Soft-rock to hard-rock spectral amplification ratios by [5], accounting for differences in (a) Vs, (b) κ_0, and (c) Vs and κ_0.

2. Datasets for Hard-Rock Sites

One of the largest and best-documented datasets currently used for shallow crustal seismicity in active regions is the NGA-West2 [9]. The sampling of Vs_{30} in the NGA-West2 data set is shown in Figure 2. Of the 21,539 total recordings, only 399 (<2%) are from sites Vs_{30}>1000 m/s, and only 7 (<1‰) on sites with Vs_{30}>1500 m/s (i.e., NHERP class A). If we consider rupture distances within 50 km, to limit the effect of the path attenuation (Q), there are just 3 on sites with Vs_{30}>1500 m/s. This shows that there has not been enough recordings on hard-rock site conditions to constrain hard-rock factors using the NGA-west2 data.

We reviewed several other current datasets which have recently become available:

- The European database RESORCE: The 'reference database for seismic ground-motion prediction in Europe' [10] was used to develop new GMPEs for Europe. Magnitudes range from M2.6-M7.8, and R_{hypo} distances from 2-402 km. Out of 5637 recordings, about only half come from stations with an estimate of Vs_{30}. Of these, 10% are classified as NEHRP class A or B, but only 1% as class A.
- The Pegasos Refinement Project (PRP) database for Switzerland: During the PRP [11], a database was developed. It comprises 4793 recordings with magnitudes ranging from M2-M5.5, distances R_{hypo}=3-370 km, and Vs_{30} from 280-3010 m/s. Of these, 25% within 100 km are from class A rock sites.
- The BCHydro databases from British Columbia: These comprise one database for crustal and one for subduction seismicity [12]. The crustal database comprises 322 recordings, between M2-M4.6, R_{hypo} from 5-429 km, and were recorded exclusively on rock (Vs_{30} is 1000-2500 m/s). The subduction database comprises 9946 recordings, from a magnitude range of M4.4-M8.3, R_{hypo} from 19 to 2060 km, and Vs_{30} ranging from 90-1750 m/s. Less than 7% of recordings come from sites classified as A or B within 100 km.
- The NGA-East database: Described in [13], this dataset contains recordings from the stable continental region of Central-Eastern North America (CENA). It contains 9382 recordings, magnitudes M2.1-M6.7, and R_{rup} from 4-3500 km, from sites with Vs_{30} from 200-2000 m/s. There are 408 recordings within 100 km. Almost half are at distances less than 100 km are from site classes A and B, and a third are from site class A.

The distribution of Vs_{30} with distance for each of these datasets is shown in Figure 2. RESORCE cannot offer a significant amount of data for hard rock. However, the NGA-East, BCHydro and Swiss PRP datasets have enough recordings. Of these, we use here the NGA-East and BCHydro datasets, which together offer 229 recordings on hard rock within 50 km, to develop empirically-based factors for the combined effect of amplification and attenuation between soft-rock and hard-rock sites.

There is a common problem in most datasets when it comes to characterizing hard-rock sites. Due to the difficulty in measuring Vs profiles at such sites, these are often classified using the general geology of the region. For example, in the NGA-East dataset, of the CENA stations classified as A, almost none have measured Vs_{30} values, due to the lack of site characterization in that region, but have been assigned a common value of 2000 m/s [14]. Similarly, in the BCHydro dataset, all rock sites are classified based on surface geology and using correlations to known Vs profiles from similar geological units.

4. κ_0 for NGA-East

Of the two new datasets that will be used to study soft-rock to hard-rock scaling, for NGA-East we estimate κ_0 values for all of the sites with Vs_{30}>1000 m/s at distances closer than 100 km. There are several approaches for estimating κ_0 [2]. We estimate κ_0 values based on the slope of the acceleration FAS (called the AS method in that taxonomy) and the slope of the displacement FAS (called the DS method). The different approaches are used depending on the corner frequency of earthquake: the AS method is used if the corner frequency is below the 5-20 Hz range and the DS method is used if the corner frequency is above the 5-20 Hz range. If the uncertainty in the corner frequency makes the classification ambiguous, then both methods are used. By choosing records only out to 100 km, we manage to avoid corrections for regional/path attenuation (Q), and can consider all individual κr measurements (which typically include both path and site components) as site-specific κ_0 measurements. Thus we can then average over all individual values to get a mean site-specific value of κ_0. More details on the estimation of κ_0 for NGA-East are given in [15].

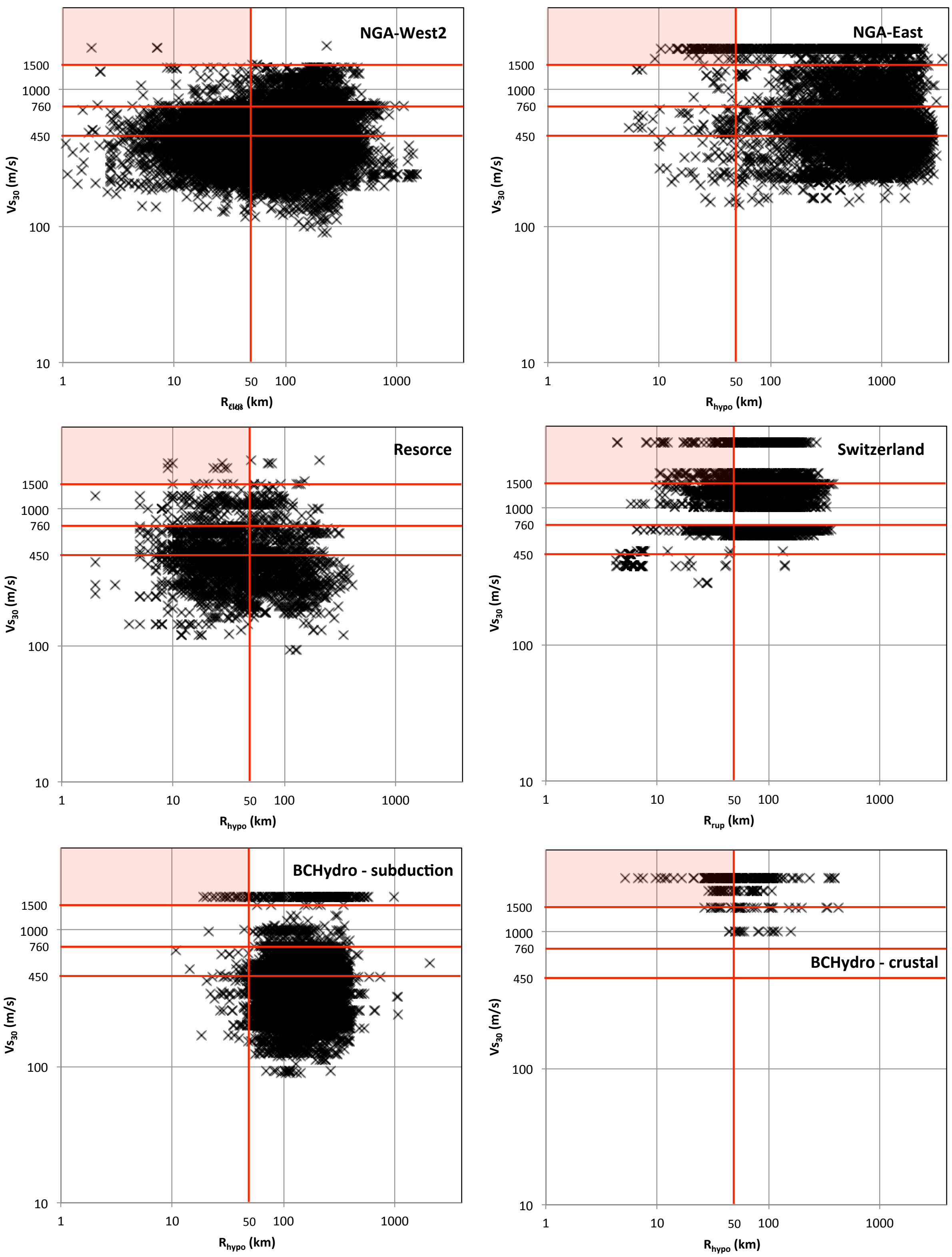

Fig. 2 - Distribution of hypocentral distance and Vs_{30} for the NGA-West2, NGA-East, RESORCE, BCHydro subduction, BCHydro crustal, and Swiss datasets.

Figure 3 shows estimated κ_0 with Vs_{30} for both approaches (left), and the distribution of κ_r per approach (right). There can be systematic differences in the κ_0 values according to the measurement approach used, namely the DS approach (red points) tends to lead to higher κ_0 compared to the traditional AS approach (blue points) for events in which the uncertainty in the corner frequency allows both approaches to be used. However, within each approach, the scatter is still very large, and because most of the A class sites have been assigned a single Vs_{30} value of 2000 m/s, it is not possible to observe a correlation of κ_0 with Vs_{30} for hard-rock sites. It is not clear how much of the scatter in the κ_0 is due to differences in Vs_{30} values for the hard-rock sites.

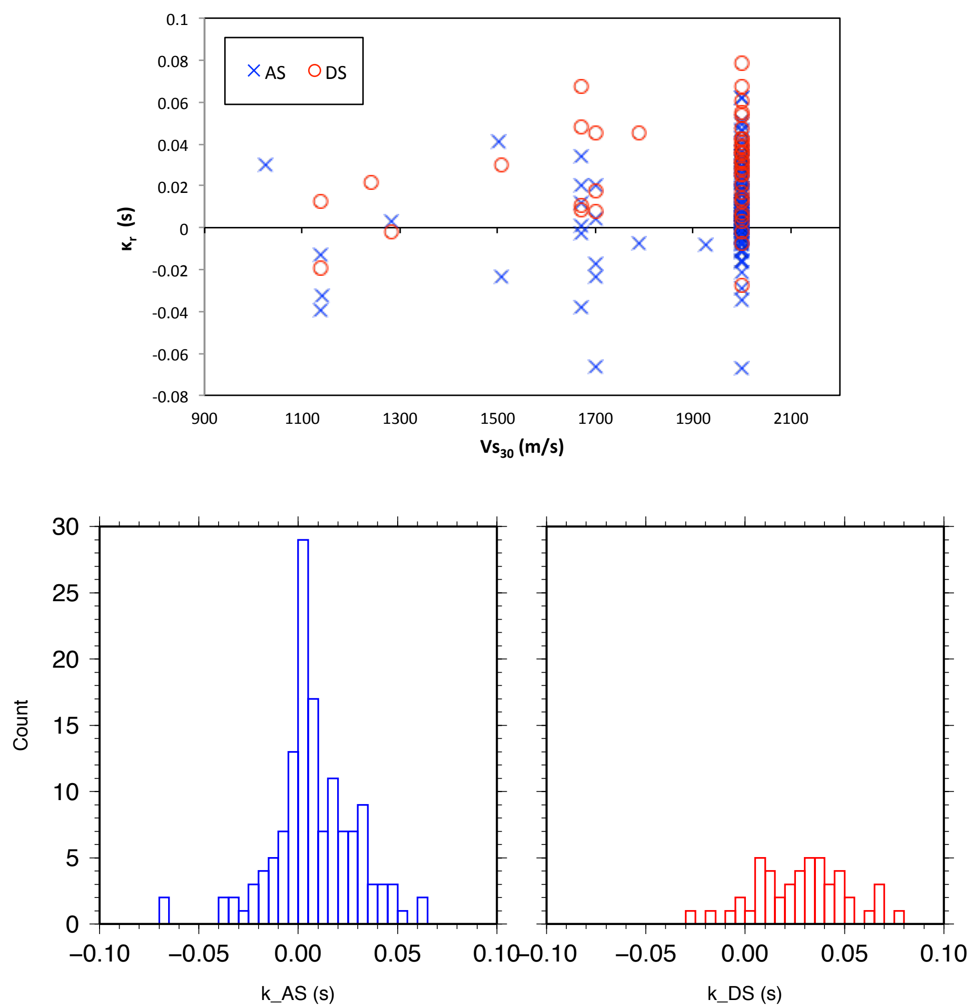

Fig. 3 - Left: Measured κ_r values with Vs_{30} for NGA-East rock stations within 100 km (adapted from [15]). Right: Histograms showing distribution of κ_r values for the AS and DS approaches.

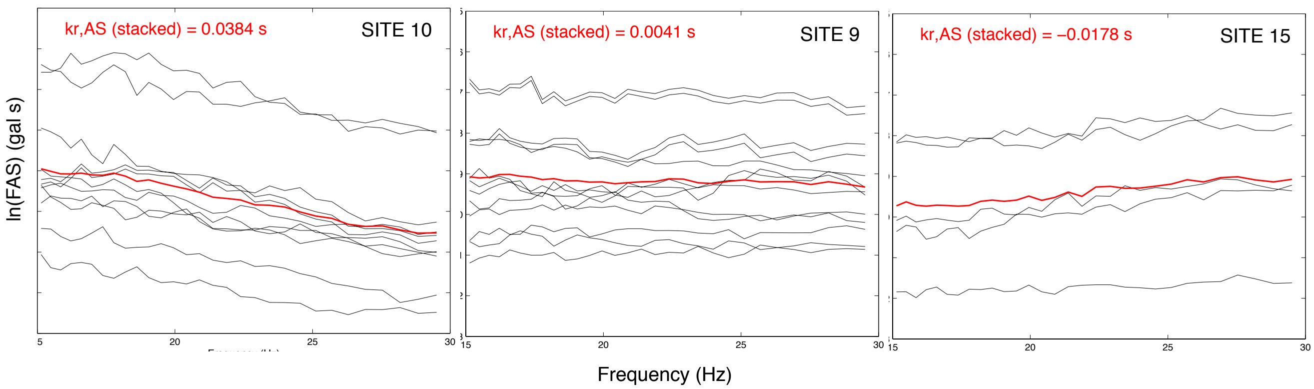

Fig. 4 - Mean FAS derived from stacking all recordings per station for the AS approach, and estimation of mean κ_0 per site (red). Individual FAS are shown in black. The station number is written on the top right (from [15]).

It has also been observed that there may be correlations between site amplification and attenuation in what is measured as κ_0. Figure 4 shows the FAS of acceleration for three hard-rock sites in CENA, on which κ was measured using the AS approach. At site 10 the FAS shows a downward trend above 15 Hz (κ_0=0.038 s), at site 9 it does not exhibit clear decay up to 30 Hz (κ_0=0.004 s), and at site 15 the trend is negative (κ_0=-0.018 s). These observations are consistent per station over the FAS from multiple earthquakes. Therefore, the low or negative κ_0 values may be due to broadband amplification effects at high frequencies; these could give the FAS an upward trend, and partially or completely mask the downward due to the damping. This implies that the measured κ_0 value, which is subsequently used as a proxy of attenuation only, reflects the combined effect of damping and other factors that are not captured in the average amplifications assumed for the hard-rock sites.

The mean κ_0 values estimated over the entire NGA-East hard-rock dataset depend strongly on what flags were considered: the mean κ_{0_AS} value is 0.006-0.008 sec depending on stacking and is similar to the typical κ_0 value assumed up to now for CENA hard rock (0.006 sec). Using the κ_0 values measured, we evaluate the dependency of response spectrum residuals with κ_0. Total residuals are computed with respect to the non-predictive empirical GMPE of J. Hollenback [16, chapter 3]. Figure 5 shows hard-rock (Vs_{30}>1500 m/s) total residuals at 20 Hz versus estimated κ_0 values for distances less than 100 km. The two lines indicate the theoretical scaling of total residuals with κ_0, as predicted from the HEM method (blue line) and from the IRVT method (red line). If the site factor for hard-rock sites scales strongly with κ_0 as indicated by the modeling, then we expect to see a strong negative correlation of the residuals versus κ_0, as small κ_0 values will lead to higher ground motions and, therefore, larger residuals. When it comes to the κ_{AS} values (left), the residuals between κ_0 do not show the strong trend predicted by models; however, the residuals with respect to κ_{DS} measurements (right) do show a trend with κ_0 that is more consistent with the theoretical scaling. With improved (more detailed at high frequencies) site characterization at hard-rock sites, the crustal amplification above 15 Hz could be used to correct the FAS above 15 Hz. With an improved site characterization, the residuals might scale more strongly with κ_{AS} values, as they do with κ_{DS} values.

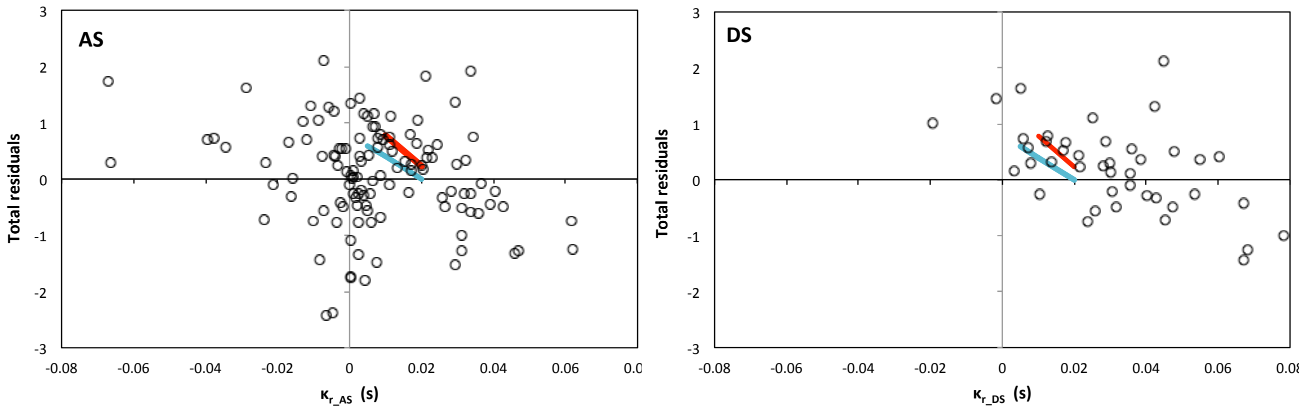

Fig. 5 - Total residuals at 20 Hz for the Hollenback model vs. measured κ_{r_AS} (left) and κ_{r_DS} values (right) for all recordings. The blue and red lines show the theoretical scaling predicted from the PSSM and IRVT (adapted from [15]).

5. Empirical scaling model from soft to hard rock

Given that we do not see strong κ_0 scaling in the NGA-East residuals, and that there are known trade-offs between κ_0 and amplification so it is difficult to decouple κ_0 effects from Vs_{30} scaling, we use the NGA-East and BCHydro data to develop an empirical model for the combined effect of Vs profile and κ_0 with respect to a soft-rock site (Vs_{30}=760 m/s). We consider the subsets of recordings within 50 km to minimize the effect of path attenuation (Q), and for NEHRP class A sites. We only consider earthquakes with magnitudes above M3, because the GMPEs used to compute the residuals are not constrained well below this threshold. For each of the two datasets, we compute total residuals with respect to an appropriate GMPE, but we substitute the sites' actual Vs_{30} values with a reference soft-rock value of 760 m/s. The resulting residuals reflect the net difference in the site response between hard-rock and soft-rock sites. We use total rather than within-event residuals to avoid bias from potential trade-offs between site and event terms. For the NGA-East, we use the Hollenback model mentioned above, while for the BCHydro dataset we use the GMPE of [17]. For each dataset, we compute the mean residual per frequency over all available recordings, giving equal weight to each recording.

The mean residuals are used to compute the Vs-κ_0 site factors. In Figure 6a, at low frequencies (0.5-3 Hz), the factors are in the 0.6-0.9 range, consistent with the scaling for the change in the impedance contrast. At high frequencies (20-40 Hz), for BCHydro there is some amplification (maximum of 1.3) consistent with a reduced κ_0 for hard-rock sites compared to soft-rock sites. For NGA-East, however, there is no amplification above 20 Hz: the Vs-κ_0 site factor ranges between 0.6-0.8. Figure 6a shows that we do not observe strong scaling at high frequencies between soft-rock and hard-rock sites as predicted by the commonly used analytical methods. These results, obtained for recordings within 50 km, do not vary significantly if we consider recordings out to 100 km. For BCHydro, we consider the results reliable above 5 Hz because of magnitude estimation issues for small events, which may inflate residuals at frequencies below the source corner frequency.

In Figure 6a, we also show the analytical site factors based on the HEM approach (PSSM) simulations and the IRVT approach. Our empirical results for BCHydro correspond to the analytical results if we assume that hard-rock sites have κ_0 values close to 0.015-0.020 s, rather than the typical assumed value of 0.006-0.010 s. For NGA-East, the results would indicate even higher κ_0 values, above 0.020 s. We believe that this may be due to the measured κ_0 values not reflecting only damping, but a net effect of damping and amplification. This implies that when selecting κ_0 values to adjust soft-rock ground-motion models to hard-rock site conditions, considering only the damping effect may lead to overestimation of the κ_0 effects.

Based on these comparisons, we develop two models for the hard-rock scale factors at high frequencies (Figure 6b). For both models, the low-frequency range follows the NGA-East amplification, as this is more stable and not affected by magnitude scaling issues. At high frequencies, the first model (orange line) follows the

BCHydro amplification and represents our upper range of amplification. The second model (purple line) is the smooth weighted average of the amplifications of the two empirical datasets. Similar amplification factors can be developed using analytical modeling using hard-rock κ_0 values of 0.015-0.025 s.

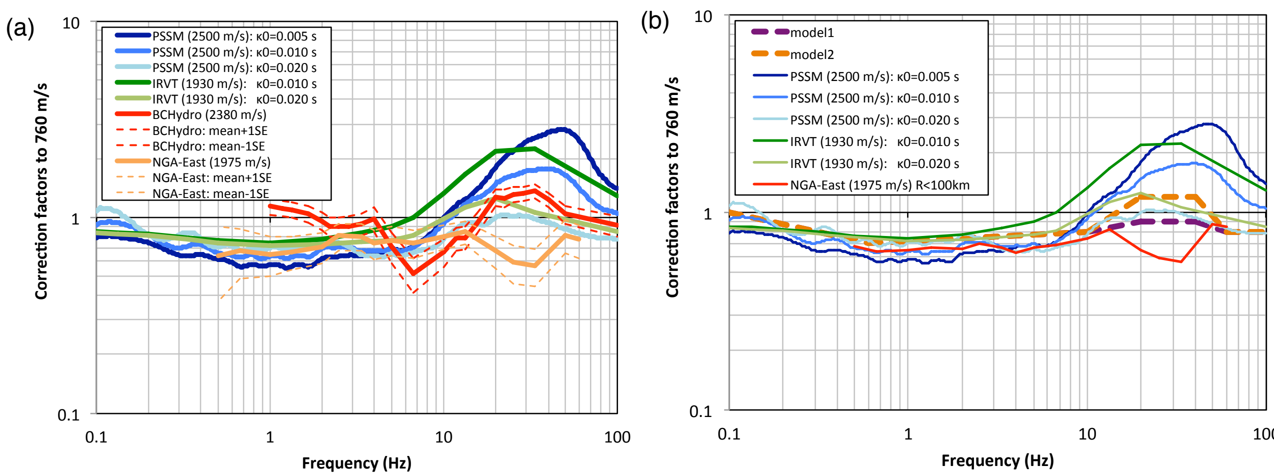

Fig. 6 - a) Comparison of empirical and theoretical soft-rock to hard-rock amplification factor on PSA. Dashed lines indicate the standard error for the empirical estimates. b) Proposed empirical model for soft-rock to hard-rock site factors.

6. Conclusions

The proposed Vs-κ_0 scaling for hard-rock sites related to a reference Vs_{30} of 760 m/s can be used as an alternative to the currently used analytical models. Using analytical models with κ_0=0.020 s will lead to combined Vs-κ_0 scaling generally consistent with the currently available hard-rock data.

A key limitation of the proposed hard-rock site factors is the relatively small data set available. From our review of available datasets for hard-rock ground motions, it is clear that there is a need for additional data from hard-rock sites, and there is a need to better characterize hard-rock sites. Most datasets for active crustal regions in Europe and the US (with the exception of BCHydro) contain less than 10% of rock data (NEHRP classes B and above), and less than 3% hard-rock data (class A), while datasets for stable continental regions contain more than 10% hard-rock data. Of these recordings, some come from stations that are poorly characterized (Vs_{30} values are missing or are assigned rather than measured).

We have not examined downhole data. We believe recordings from downhole stations have the potential to significantly increase the number of available data on hard rock (e.g., KiK-net stations at 100 m and 200 m [18]. [19] used downhole stations on hard rock to suggest that hard-rock κ_0 values may reach an asymptotic value that is region-dependent. If this suggestion is confirmed by more data, then future studies could integrate global hard-rock datasets and assess them consistently, with the aim of characterizing hard-rock response in different regions. Denser permanent instrumentation, including downhole instrumentation, can also help better understand the dispersion in measured κ_0 values and to decouple the trade-off between site attenuation and site amplification.

We also note the need for higher sampling rates and higher low-pass anti-alias filters, which will allow analysis of data at higher frequencies. This could help resolve issues of trade-off between site attenuation and amplification at hard sites with high-frequency resonance patterns, but also between site attenuation and source corner frequency or stress drop. For instance, for the NGA-East, most data come from the Transportable Array (http://www.usarray.org/researchers/obs/transportable, last accessed September 2015), for which the highest usable frequency is only 16 Hz [20].

7. Acknowledgements

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8. References

[1] Anderson, J.G., and Hough, S.E., 1984: A model for the shape of the Fourier amplitude spectrum of acceleration at high frequencies. *Bull. Seismol. Soc. Am*. **74**, 1969-1993.

[2] Ktenidou, O.-J., Cotton, F., Abrahamson, N.A., and Anderson, J.G., 2014: Taxonomy of κ: a review of definitions and estimation approaches targeted to applications. *Seismol. Res. Letts* **85**, 135-146.

[3] Muto M. and Duron, Z., 2015: High-frequency seismic hazard estimation and impact on seismic evaluation for dams. *SSA Annual Meeting*, Pasadena, USA.

[4] Pacific Gas and Electric Company (PG&E), 1988: Final report of the Diablo Canyon long-term seismic program. U.S. Nuclear Regulatory Commission Docket No. 50-275 and No. 50-323.

[5] Biro, Y., and Renault, P., 2012: Importance and Impact of Host-to-Target Conversions for Ground Motion Prediction Equations in PSHA. *15th World Conference of Earthquake Engineering*, Lisbon, Portugal.

[6] Campbell, K.W., 2003: Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in eastern North America. *Bull. Seismol. Soc. Am*. **93**, 1012-1033.

[7] Campbell, K.W., 2004: Erratum: Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in eastern North America. *Bull. Seismol. Soc. Am.* **94,** 2418

[8] Al Atik, L., Kottke, A., Abrahamson, N., and Hollenback, J., 2014: Kappa correction of ground motion prediction equations using inverse random vibration theory approach. *Bull. Seismol. Soc. Am*. **104**, 336-346.

[9] Ancheta, T.D., Darragh, R. B., Stewart, J. P., Seyhan, E., Silva, W.J., Chiou, B. S.J., Wooddell, K. E., Graves, R. W., Kottke, A. R., Boore, D. M., T., Kishida, and Donahue, J. L., 2013: PEER NGA-West2 Database. *Technical Report PEER 2013/03,* Pacific Earthquake Engineering Research, Berkeley, USA.

[10] Akkar S., Sandıkkaya M.A., Senyurt M., Azari Sisi A., Ay B.Ö., Traversa P., Douglas J., Cotton F., Luzi L., Hernandez B., Godey S., 2014: Reference database for seismic ground-motion in Europe (RESORCE). *Bull. Earthq. Eng.* **12**, 311-339.

[11] SED (Swiss Seismological Service), 2013: Flatfile of Swiss records up to 2013. *Report File-ID: EXT-WAF-1019*, prepared for the PEGASOS Refinement Project.

[12] Addo, K.O., 2016: Hard Rock Correction of Computed Seismic Ground Motions. *Report E1352,* BC Hydro.

[13] Goulet, C., Kishida, T., Ancheta, T. D., Cramer, C. H., Darragh, R. B., Silva, W.J., Hashash, Y.M.A, Harmon, J., Stewart, J.P., Wooddell, K. E., and Youngs, R. R., 2014: PEER NGA-East Database. *Technical Report PEER 2014/17*, Pacific Earthquake Engineering Research, Berkeley, USA.

[14] Beresnev I.A., Atkinson G.M., 1997: Shear-wave velocity survey of seismographic sites in eastern Canada: calibration of empirical regression method of estimating site response. *Seismol. Res. Letts* **68**, 981–987.

[15] Ktenidou, O.-J., Abrahamson, N., Darragh, R., and Silva, W. 2016: A methodology for the estimation of kappa (κ) from large datasets, example application to rock sites in the NGA-East database, and implications on design motions. *Technical Report PEER 2016/01,* Pacific Earthquake Engineering Research, Berkeley, USA.

[16] Al Atik, L., 2015: NGA-East: Ground-Motion Standard Deviation Models for Central and Eastern North America. *Technical Report PEER 2015/07,* Pacific Earthquake Engineering Research, Berkeley, USA.

[17] Chiou, B.S.J., and Youngs, R.R., 2014: Update of the Chiou and Youngs NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra. *Earthq. Spectra* **30,** 1117-1153.

[18] Aoi, S., Kunugi, T., and Fujiwara, H., 2004: Strong-motion seismograph network operated by NIED: K-NET and KiK-net. J. Japan Assoc. *Earthq. Eng.* **4,** 65–74.

[19] Ktenidou O.-J., Abrahamson, N., Drouet, S., and Cotton, F., 2015: Understanding the physics of kappa (κ): Insights from a downhole array. *Geoph. J. Int.*, **203**(1), 678-691.

[20] Ktenidou, O.-J., Silva, W., and Darragh, R., Abrahamson, N., and Kishida, T., 2016: Squeezing kappa out of the Transportable Array in a low seismicity region. *Bull. Seismol. Soc. Am*., in review.