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# Non-linear site response: a focus of thick sedimentary deposits. Learnings from Japanese strong motion recordings

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## ABSTRACT

This contribution presents a statistical analysis of the non-linear behavior that can be detected on strong motion recordings obtained on thick Japanese sedimentary sites from the KiK-net and K-NET networks, together with a comparison with other site types involving thinner deposits and/or higher fundamental frequencies. The non-linear effects are quantified by comparing various kinds of site-response characteristics (surface-to-borehole spectral ratios, H/V spectral ratios) for moderate to large motion to their weak motion counterparts. While a non-linear behavior can be detected on thick and thin sites as well, thick sites do not exhibit the peculiar high-frequency reduction predicted by most non-linear simulations because of increased damping. This inconsistency constitutes a warning on the use of classical non-linear degradation curves derived from measurements at limited confining pressures corresponding to depths not exceeding a hundred meters.

**Keywords:** Non-Linear behavior, Thick sites, Degradation curves, K-NET and KiK-net data

## 1 INTRODUCTION

Numerical simulations of the non-linear response of thick sedimentary deposits give extremely variable results depending on the maximum depth considered for the non-linear behavior of soils. For (non-exceptional) cases where the deep bedrock is hard enough to generate a significant ( $\geq 2$ ) velocity contrast with the deepest sediments, the application of widely accepted degradation curves to the entire soil column generally leads to a significant reduction of high frequency ground motion even for relatively moderate shaking levels, because deformation levels are high enough to result in significant damping increase over the whole sediment thickness. Nevertheless, as most of these degradation curves have been developed from lab measurements performed under limited confinement pressure, their extrapolation to large depths (exceeding a few hundred meters) can be questioned. The objective of the present study is to compare the observed NL response of thick deposits with typical numerical predictions and those observed on other sites.

## 2 MOTIVATION: THE GRENOBLE EXAMPLE

An exercise was performed within the framework of the Sigma Project (Pecker et al., 2017) to investigate the

NL response of the 690 m thick sedimentary site of Grenoble corresponding to the location of a nuclear research reactor. For this exercise, as detailed in Ameri et al. (2014), the objective was to estimate the surface motion for a 100 000 year return period with different approaches, from the generic one considering available GMPEs and a VS30 value of 370 m/s, to site-specific ones coupling 1D non-linear site response with Deepsoil (2012) and 3D visco-elastic simulations with Vs and damping values tuned from the 1D approach.

Figure 1a displays the Vs profile, characterized by a gravel layer at shallow depth overlying a thick, rather stiff lacustrine clay deposit with an important velocity gradient, overlying a very hard bedrock (Vs value of 3200 m/s) located at a depth of 690 m. This specific profile exhibits a large velocity contrast at large depth, which automatically results a) in a low fundamental resonance frequency (around 0.3 Hz), and b), for all kinds of wave propagation computations, in a significant strain increase between bedrock and the base of soil column. When considering classical, widely accepted non-linear degradation curves such as Menq (2003) for the top gravel layer, and Darendeli (2001) for the thick clay unit, together with a series of rock input motion with an average pga around 0.5g (black spectra on Figure 2), the NL effects result in a very significant decrease of

surface ground motion compared to the linear case, as also displayed in Figure 2a (surface response spectra) and 2b (amplification factors). Such a decrease is effective over a broad period range (0.01 – 2 s), i.e. above the site fundamental frequency (0.3 Hz / 3 s), and reaches a factor of 2 at 1 Hz / 1s, and around 3 for frequencies beyond 2 Hz (periods below 0.5 s). The reason of this large, broad band reduction can be understood by looking at the damping and strain profiles displayed in Figure 1b: even though the low strain (elastic) values are around 1%, the strain levels generated over the whole soil column result in much higher damping values, from 3.8 % at the bottom of the clay unit to over 10% at 50 m depth. Considering the ratio between thickness and wavelength, not only the resonance due to vertical interferences can no longer exist because waves are too strongly attenuated through their travel up and down in the soil column, but also the primary arrivals are considerably damped during the upward propagation of (large amplitude/large strain) direct waves.

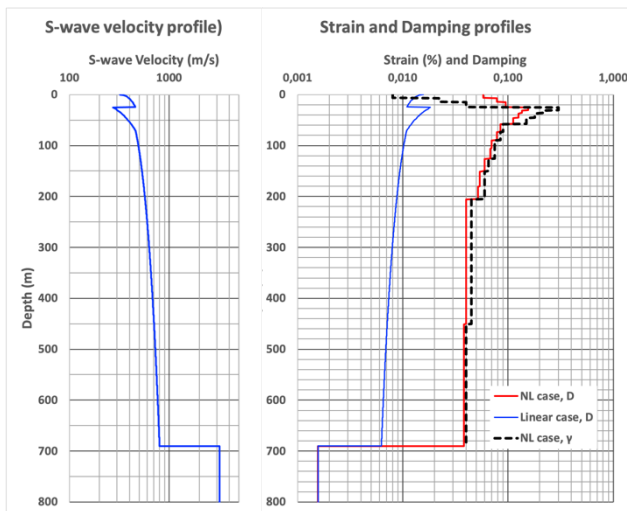


Figure 1: Velocity profile for the Grenoble site (left), and damping profiles (right) corresponding a) to strain levels (dashed black line) reached for a 100 000 year / 0.5 g input ground motion (solid red line), and b) to the linear case (blue solid line).

The predictions on Figure 2 are largely controlled by the sensitivity of shear modulus and damping degradation curves to the confining pressure, i.e. to the depth. While such a term does exist in the Darendeli model, there are only very few lab tests providing NL measurements for pressures corresponding to a depth of several hundred meters, and a number of geotechnical engineers prefer not to use them at depths beyond 100 m (A. Pecker and M. Koller, personal communication). As the site response of thick sedimentary deposits is a challenging issue for many areas throughout the world (Mississippi Valley, Japanese coastal plains, Groningen area, among many others), it is important to check whether the available data are supporting such predictions. This is the goal of the next sections, on the

basis of the rich set of weak and large amplitude recordings obtained since 1996 by the K-NET and KiKnet stations in Japan.

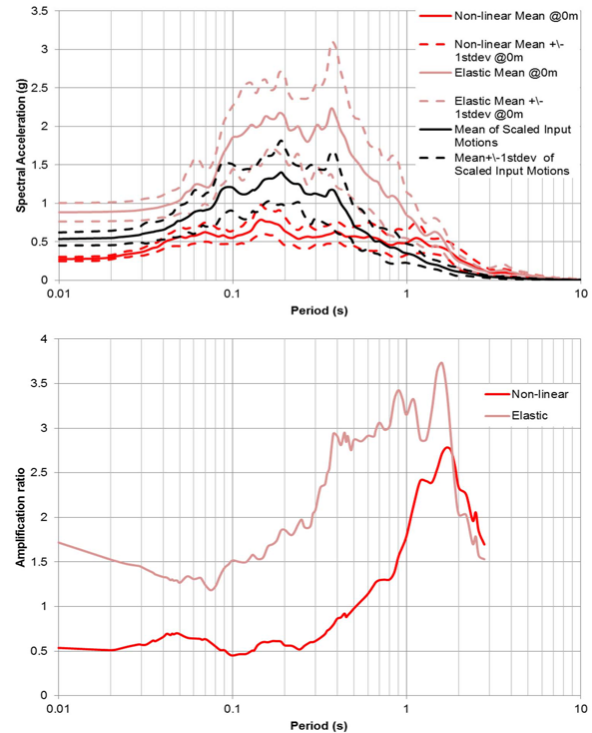


Figure 2: Ground motion amplification predicted at the Grenoble site in the linear and non-linear cases. Top: Range of surface ground motion predicted in the linear (salmon) and non-linear (red) cases for a set of hard rock input accelerograms corresponding to a 100000 year return period (black). Solid lines stand for mean acceleration response spectra, and dashed lines to mean  $\pm$  1 standard deviation. Bottom: Corresponding average surface / hard bedrock amplification factors

### 3 PGA AMPLIFICATION FOR KIKNET BOREHOLE SITES

Increased damping over thick soil columns is expected to produce the largest reduction of ground motion amplification for high frequencies. As PGA is essentially a high frequency ground motion intensity measure, a first check is to investigate the evolution of surface to borehole PGA amplification with increasing ground motion level.

In that aim, we considered the KiKnet data set used in Derras et al. (2020) and Régnier et al. (2016), gathering a total of 2927 recordings from 132 different sites, with surface pga exceeding 20 cm/s<sup>2</sup>. The major part of these data corresponds to recordings obtained before 2009, augmented by larger amplitude recordings with downhole pga exceeding 50 cm/s<sup>2</sup> obtained in the period 2010-2014. The richness of KiKnet metadata allows to associate different site proxies to each site, including  $V_{S30}$  and the fundamental frequency  $f_{0HV}$ .

For each site  $i$  and event  $j$ , the PGA surface/downhole amplification ratio  $AF_{PGA,ij} = PGA_{surf,ij} / PGA_{dwh,ij}$  has been computed. Such a ratio is expected to decrease with

increasing loading, for instance with increasing  $PGA_{surf}$ , but it is also varying from site to site in relation with the site-specific velocity profile. Therefore, in order to focus only on the evolution (expected reduction) of  $AF_{PGA}$  with  $PGA_{surf}$ , we have normalized this ratio, for each site  $i$ , by its low loading value, i.e. the average value of  $AF_{PGA,i}$  obtained for recordings with a surface pga between 0.1 and 10  $cm/s^2$  (Régnier et al., 2016).

$$AF_{PGA,ij}^{norm} = AF_{PGA,ij} / AF_{PGA}^{LIN,i} \quad (1)$$

Examples of such evolutions are shown in Figure 3 for 3 sites, two which exhibit a marked NL behavior with a clear decrease of site amplification with increasing PGA, and one which does not, even though the site has experienced quite large accelerations (up to 0.7 g). For information the displayed sites are characterized by varying fundamental frequencies and  $V_{S30}$ , as listed in Table 1.

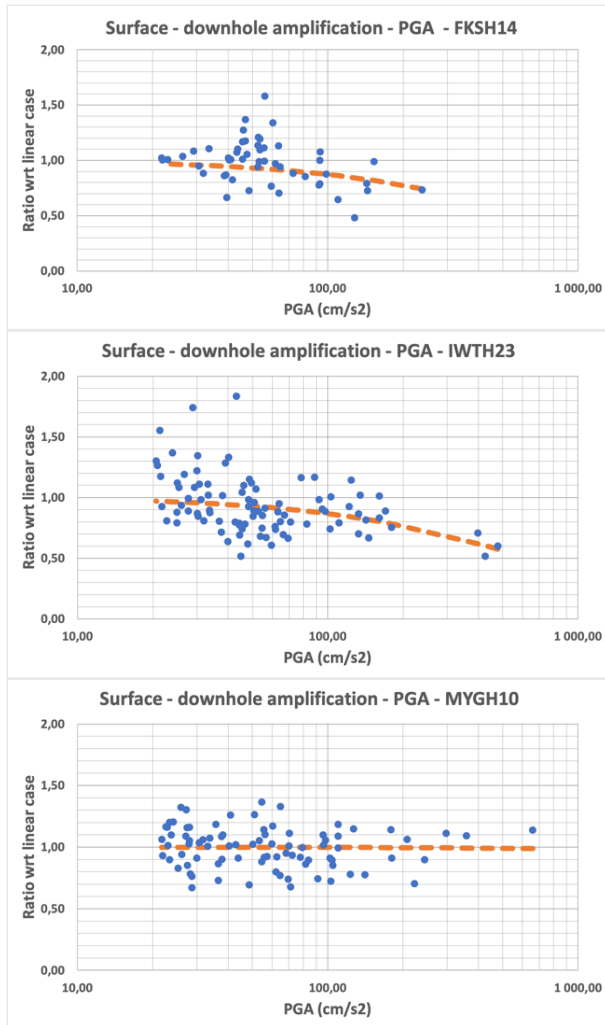


Figure 3: Dependence of normalized  $AF_{PGA}$  amplification with surface PGA for three KiKnet sites. The blue dots are the measurements, the dashed orange line corresponds to the best fitted hyperbolic law.

Table 1: Site proxies and recording characteristics (number, maximum PGA value) for the example KiKnet stations

Site	$F_{0HV}$	$V_{S30}$	Number of recordings (pga > 20 $cm/s^2$ )	$PGA_{max}$
FKSH14	0.22	237	52	238
IWTH23	12.9	923	93	478
MYGH10	0.34	348	85	659

Similar evolutions have been analyzed for all possible sites in the above mentioned data base, and could be fitted to an hyperbolic law in the following form for a total of 119 sites with varying site characteristics, from soft to stiff and thick to thin.

$$AF_{PGA,ij}^{norm} = 1. / (1 + \frac{PGA_{surf}^{ij}}{PGA_{ref}^i}) \quad (2)$$

This equation corresponds to the classical non-linear assumption according which PGA at a given site  $i$  cannot exceed a site-specific maximum  $PGA_{max,i}$  related to its strength characteristics. From the above equations, this maximum is at least equal to  $PGA_{ref,i}$ . It is therefore instructive to analyze the sensitivity of these  $PGA_{ref,i}$  values to the site characteristics. Figure 4 displays the variability of  $PGA_{ref}$  with the fundamental frequency  $f_{0HV}$  (top) and the S-wave velocity proxy  $V_{S30}$  (bottom), for all 119 KiKnet sites. The size of the blue symbols is proportional to the quality of the fit, i.e. to the variance reduction provided by the hyperbolic fit (while open symbols correspond to cases where there is no variance reduction, i.e., there is no detectable trend for a decrease of amplification with increasing loading). These figures call for several comments:

- i) While almost all soft sites with  $V_{S30}$  below 300 m/s do exhibit a clear non-linear trend, there exist a few low  $f_{0HV}$  sites (thus quite thick sites) which do not.
- ii) As emphasized in Régnier et al. (2016) and Derras et al. (2020), non-linear behavior can be detected also on stiff sites with  $V_{S30}$  beyond 600 m/s, or on high  $f_{0HV}$  sites, i.e. for sites with very thin soft layers over stiff bedrock.
- iii) A number of sites do not exhibit any clear NL behavior, which results in very high  $PGA_{ref}$  values above 5g (open circles).
- iv) Whenever a non-linear behavior can be detected (solid blue circles),  $PGA_{ref}$  values do not exhibit any clear trend with either  $f_{0HV}$  or  $V_{S30}$ . They are varying in the range 200 – 1000  $cm/s^2$ , with an average around 600  $cm/s^2$  for sites with  $f_{0HV}$  below 1 Hz.

A similar analysis has been performed with replacing the loading parameter " $PGA_{surf}$ " by the parameter  $PGV_{surf}/V_{S30}$ , which is often considered as a proxy for the peak strain (Idriss, 2011; Chandra et al., 2016; Guéguen et al., 2019), and thus thought preferable to PGA as a measure of the loading intensity for non-linear behavior. A "reference strain proxy"  $STP_{ref}$  has thus been

derived for the same set of 119 sites, and its sensitivity to  $f_{0HV}$  and  $V_{S30}$  has been investigated. Though not shown here because of limited space, this sensitivity exhibits some differences with respect to those shown on Figure 4:

- The reference strain proxy  $STP_{ref}$  is clearly changing with  $V_{S30}$  and  $f_{0HV}$ : the softer or the thicker the site, the larger is  $STP_{ref}$ . The differences reach a factor of 10 (from around 0.01% for  $V_{S30}$  around 700 m/s or  $f_{0HV}$  around 10 Hz, to 0.1% for  $V_{S30}$  below 300 m/s and/or  $f_{0HV}$  below 1 Hz).
- This might look in qualitative agreement with the fact that usual NL curves such as Darendeli (2003) consider a dependence on confining pressure (i.e., the depth), as low  $f_{0HV}$  sites correspond to thicker soils where NL behavior is expected to occur at larger depth (see Figure 1). Nevertheless, there is major quantitative disagreement since the observed variability of  $STP_{ref}$  exceeds a factor 10, while the shear modulus degradation curves are shifted to higher strains by a factor of only 2 from a 25 m depth (2 atm) to a 200 m depth (14 atm).

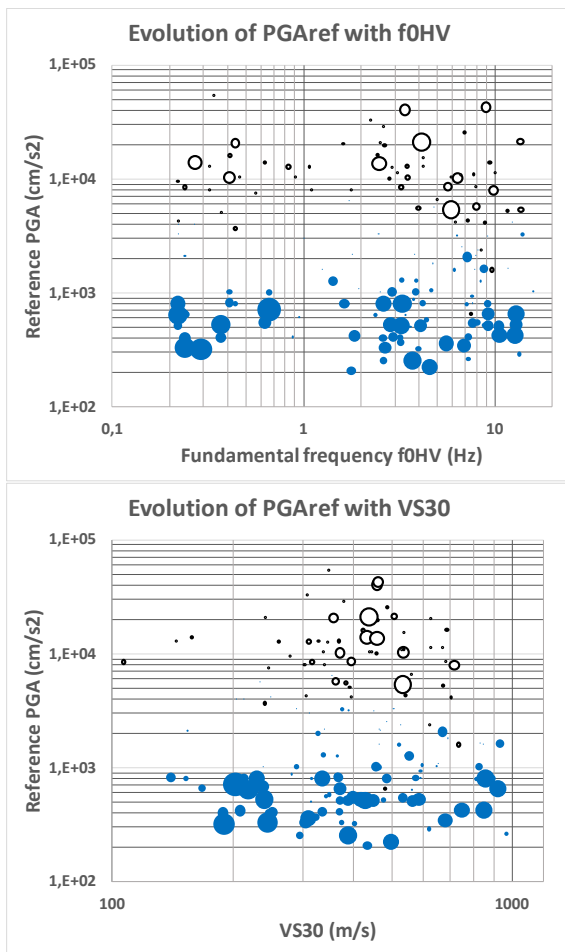


Figure 4: Evolution of "reference acceleration  $PGA_{ref}$  (cm/s<sup>2</sup>) with fundamental frequency  $f_{0HV}$  (top) and  $V_{S30}$  (bottom). The size of the blue circles is proportional to the goodness-of-fit to a hyperbolic law, and open circles correspond to sites without any clear non-linear trend (such as MYGH10, see Table 1)

Similar analyses have been performed for the amplification of a few other scalar ground motion intensity measures (PGV, PGV, Arias Intensity, Cumulative Absolute velocity, root mean square acceleration), but cannot be shown here. We prefer to show a few other frequency domain results.

#### 4 FREQUENCY DOMAIN RESPONSE: RSRNL APPROACH

Two approaches have been considered to investigate the evolution of frequency domain site response with the loading level. The first one applies the "RSRNL" approach proposed by Régnier et al. (2013, 2016), consisting in characterizing the non-linear effect by the spectral ratios between the "Borehole transfer function BTF" (i.e., ratio of Fourier acceleration spectrum at surface with respect to the same spectrum at downhole sensor) obtained for a given (strong motion) recording and the "linear BTF", i.e. the same surface / downhole spectral ratio averaged for many weak motion recordings (surface PGA between 0.1 and 10 cm/s<sup>2</sup>). Our approach is intermediate between the statistical one considered in Régnier et al. (2016a) (average RSRNL for three classes of  $V_{S30}$  and/or  $f_{0HV}$  and for 3 acceleration thresholds), and the neural network model developed in Derras et al. (2020) allowing to predict RSRNL as a function of a loading parameter (PGA, PGV or STP) and one or more site proxies (among which  $f_{0HV}$  and  $V_{S30}$ ).

As we focus here on thick, rather soft sites, we consider 5  $f_{0HV}$  classes (<1, 1-3, 3-5, 5-8 and above 8 Hz) and 10 loading level bins corresponding to an equal number of data (<20, 20-33, 33-45, 45-70, 70-81, 81-92, 92-105, 105-124, 124-156, 156-232, >232 cm/s<sup>2</sup>). Since the previous section concluded at a non-dependence of  $PGA_{ref}$  on  $f_{0HV}$  or  $V_{S30}$ , we decide to present here only the results obtained with PGA as the loading intensity measure (rather than STP). We then computed, for each ( $f_{0HV}/PGA$ ) bin, the average RSRNL ratio, and plot them as a function of loading level (PGA) for the two extreme  $f_{0HV}$  classes in Figure 5.

One can notice that the RSRNL curves for the low frequency (thick) sites do exhibit a high frequency decrease for the large PGA bins (especially the last one,  $PGA > 232$  cm/s<sup>2</sup>), but this decrease is significant only for frequencies exceeding 7 Hz, with a maximum reduction of about a factor 2 above 10 Hz. For the Grenoble ground motion predictions shown on Figure 2 ( $f_{0HV}=0.3$  Hz,  $PGA_{surf} = 0.25$  g), the amplification reduction due to NL behavior is around a factor 3 for frequencies exceeding 2 Hz (periods below 0.5 s), and reaches a factor 2 around 1 Hz: such reductions are much higher than those shown in Figure 5 top.

From another viewpoint, NL behavior can be clearly identified again on the large PGA bins for high frequency sites (Figure 5 bottom): the main difference with low frequency sites is that amplification decrease can be seen only beyond 10 Hz (in which frequency



range it is approximately comparable to the statistics for low frequency sites), while there is marked amplification increase between 4 and 8 Hz in relation with the non-linear shift of site fundamental frequency: such an amplification increase is much less pronounced for low frequency sites.

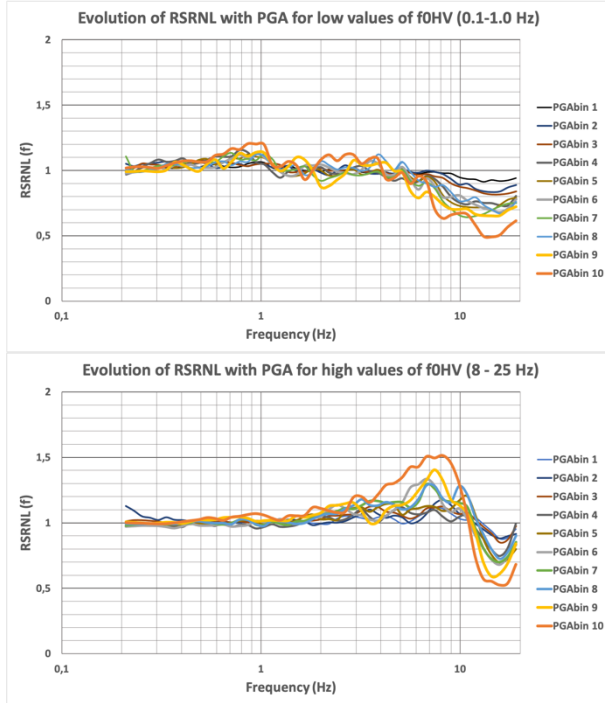


Figure 5: Statistics of RSRNL ratios for different PGA bins (curves with different colors) and the groups of low frequency sites ( $f_{0HV} < 1$  Hz, top) and high frequency sites ( $> 8$  Hz, bottom)

## 5 FREQUENCY DOMAIN RESPONSE: HVSR APPROACH

The DPRI team has developed an original approach to estimate the NL behavior without needing any reference station: Wang et al. (2021, 2023) compare the H/V ratio  $HVSR_E^{NL}(f)$  from the S-wave portion of large amplitude (i.e.,  $PGA \geq 100$   $cm/s^2$ ) earthquake recordings to similar ratios  $HVSR_E^L(f)$  averaged for all weak motion recordings (PGA between 4 and 15  $cm/s^2$ ) at the same site, in order to fit two shift parameters  $\alpha$  and  $\beta$  according to the following equation

$$HVSR_E^{NL}(f) = HVSR_E^L(f * 10^\alpha) * 10^\beta \quad (3)$$

- $\alpha$  represents a frequency shift on a logarithmic frequency scale.  $\alpha$  values are expected to be positive to mimick the low frequency shift due to the NL decrease of shear modulus and wave velocity
- $\beta$  stands for an amplitude shift : positive values correspond to a NL increase of amplification, while negative values to an amplification decrease

An example is shown on Figure 6,  $\alpha$  and  $\beta$  are fitted through a grid search algorithm minimizing the absolute distance between observed and predicted HV curves, measured over the 0.5 – 20 Hz frequency range with a

logarithmic scaling for both frequency and HVSR amplitude values. More details can be found in the two above mentioned papers and in Wang (2022).

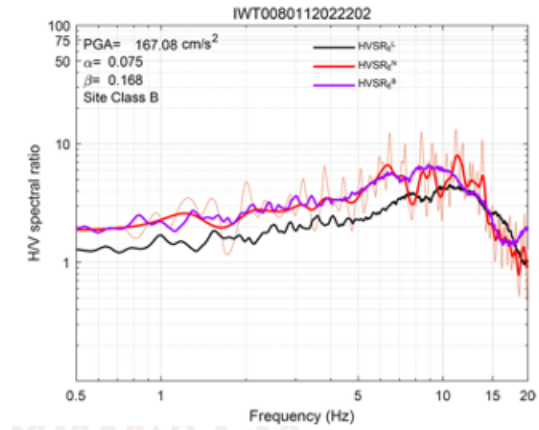


Figure 6: Principle of determination of  $\alpha$  and  $\beta$  parameters by comparison of  $HVSR_E^{NL}(f)$  (red) and  $HVSR_E^L(f)$  (black) curves for an event at station IWT008. The purple curve is the best-fitting, twice shifted black curve with parameters  $\alpha$  (horizontal shift) and  $\beta$  (vertical shift). (From Wang et al., 2023).

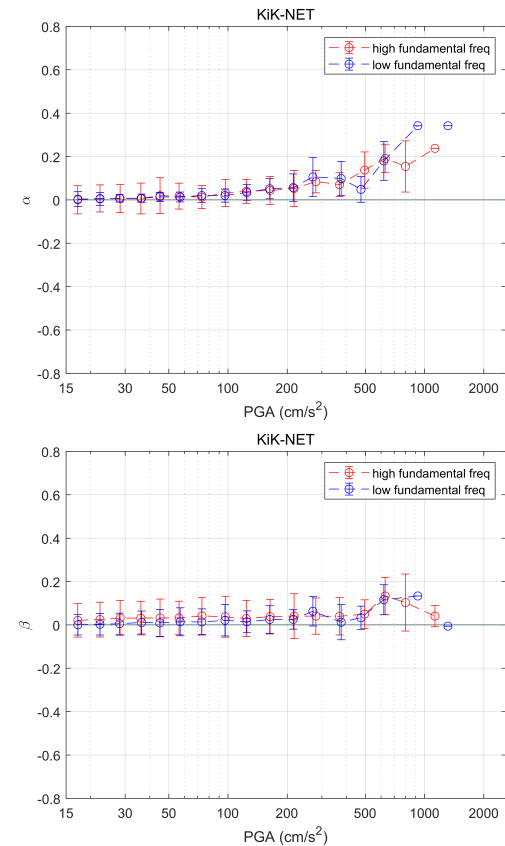


Figure 7: Comparison of  $\alpha$  (top) and  $\beta$  (bottom) parameters as a function of PGA bin for low (blue) and high (red)  $f_{0HV}$  KiKnet recordings

While the initial H/V analysis by Wang et al. (2023) considered all K-NET and KiK-net recordings from 1996 to 2020, and all sites having at least 5 weak motion recordings to constrain the linear H/V ratio, we consider

here only a selection of low frequency (62) and high frequency (48) sites performed on the basis of linear  $f_{0HV}$  values. Each strong recording ( $PGA > 100 \text{ cm/s}^2$ ) has been analyzed to derive the  $\alpha_{ij}$  and  $\beta_{ij}$  values for each site  $i$  and event  $j$  we have considered here. For simplicity sake, only the statistics on  $\alpha$  and  $\beta$  values for the two site classes have been derived for different PGA bins. The results, displayed in Figure 7 do not exhibit actually any major change between low and high frequency sites, especially on the  $\beta$  parameter, which are mostly positive up to a PGA of  $700 \text{ cm/s}^2$  and thus indicate a NL trend to increase the average amplification in the considered [0.5 – 20 Hz] frequency range. Once again this result is definitely at odds with the predicted Grenoble site response displayed in Figure 2.

## 6 CONCLUSION

A multi-approach analysis was performed on observed, large amplitude recordings with rich enough site metadata to analyze the NL modifications as a function of loading parameter AND site characteristics related to thickness and softness ( $f_{0HV}$  and  $V_{S30}$ ). We did not find any convincing evidence that very soft and/or very thick sites exhibit a large decrease of intermediate to high-frequency amplification under strong loading. The normalized borehole surface PGA amplifications, the surface to borehole Fourier spectral ratios, and the H/V Fourier spectral ratios, do depict some statistical differences between the thick or soft, and thin or stiff sites. However, such differences are far less pronounced than those predicted by Non-linear / Linear equivalent site response computations for several hundred meters thick sedimentary sites with a large velocity contrast at large depth, such as the Grenoble site. These observations are consistent with the latest degradation curves proposed by Wang & Stokoe (2021) on the basis of lab measurements with very high confinement pressure, which exhibit a larger sensitivity to depth, and a significantly lower non-linearity at large depth.

We also looked at another, more qualitative information: the distribution of site proxies ( $V_{S30}$ ,  $f_{0HV}$ ,  $H_{800}$  and  $Z_{1.5}$ ) for all Knet and KiKnet sites, and their values for all sites having experienced a surface PGA exceeding 0.4 g. Would there be, as for Grenoble, a strong reduction of HF contents for large ground motion, the site proxy distribution for the large pga sets should be shifted towards higher  $V_{S30}$ ,  $f_{0HV}$ ,  $H_{800}$  or  $Z_{1.5}$  values. Though not shown here, the two distributions do not exhibit any significant differences.

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