# Empirical Evidence of Soil Nonlinear Behavior Effects on Seismic Site Response

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**SUMMARY:**

This study presents observations of nonlinear soil behavior evidence at several KiK-net sites. The weak (from recordings with PGA at depth <10 cm/s$^2$) to strong (from recordings with PGA at depth >50 cm/s$^2$) site response ratio. We define a new parameter fNL, which represents the frequency threshold from which site response ratio is significantly above one. We find that fNL correlates well with Vs30, $f_0$ (the fundamental resonance frequency of the site) and $f_{pred}$ (the predominant frequency of the surface to borehole Fourier spectral ratio) and for most of sites fNL is in between $f_0$ and $f_{pred}$. The fact that the predominant frequency or higher modes are more de-amplified than the fundamental resonance frequency suggests that nonlinear soil behavior occurs at shallow depths and that only subsurface investigations of dynamic soil parameters might be enough to characterized the nonlinear behavior of the soil column.

*Keywords: Kik-net, nonlinear site response*

## 1. INTRODUCTION

It is widely recognized that seismic waves can be locally amplified by subsurface geotechnical properties and the soil configuration. These so-called site effects can dramatically increase the seismic motion at the surface and consequently the damages. The precise evaluation of site effect is therefore a high stake for earthquake engineering community.

The increasing number of ground motion observations from low to high amplitudes helps to improve the knowledge on the physics of wave propagation and modeling the sediments response (Field, 1997). To evaluate empirically the site response, the common way is to perform spectral ratios between signals recorded simultaneously on sediments and a nearby reference site, usually a rock site. When applying this technique, the main issue to be overcome is the selection of a reference site. The reference site must not amplify seismic waves and should be close enough to the studied site so as the travelling path from the seismic source remain equivalent for both sites.

Vertical array of accelerometers, with a borehole reference site, overcome this issue. Nevertheless, it is imperative to keep in mind that borehole data (recorded at the bottom of the borehole) present some problems mainly due to the downgoing wavefield (Bonilla et al., 2002). Indeed, the borehole site response can be different from the outcrop site response. At any depth, the particle motion contains the incident wave field and the reflections from the free surface as well as from the different velocity interfaces in the soil column. In the frequency domain, the destructive interference between the incident wave field and the downgoing waves may produce holes in the ground-motion spectrum (Steidl et al., 1996). Consequently, a direct spectral ratio between the surface and the total motion at depth generally produces pseudo resonances where these holes are present. This phenomenon is known as the downgoing wave effect. In addition, when performing standard spectral ratios of both outcrop recordings, the free surface effect is similar for the site and the reference. However, in case of borehole reference station the free surface effect is seen at different frequencies range. Some techniques are developed to correct the spectral ratio from the so-called depth effect (including both down going wave and free surface effects) deconvolution techniques (Kokusho and Sato, 2008) or definition of correction factors based on statistical study on large set of seismic data and numerical simulations (Cadet et al., 2011).

In high seismic activity zones vertical arrays of accelerometers have provided direct evidence of nonlinear soil behavior. Beresnev et al (1995), in their retrospective of studies on strong ground motions, show the effects of soil nonlinear behavior on seismological observations. More recently, evidence of soil nonlinear behavior was shown by comparing site response curves computing from weak and strong motions (e.g., Wen, 1994; Iai et al, 1995; Satoh et al, 1995; Sato et al, 1996; Aguirre et al, 1997; Field et al., 1997; Noguchi et al, 2008; Wen et al, 2011). Acceleration time histories data were also used to determine the shear modulus degradation and damping curves (in Taiwan (e.g., Glaser et al, 2000; Zeghal et al, 1995) and in Japan (e.g., Pavlenko et al, 2003; Kokusho, 2004; Pavlenko et al, 2006). Finally, nonlinear behavior has also been directly observed in acceleration time histories (e.g., Bonilla et al, 2005).

In low seismicity area, strong ground motions are limited in number or even inexistent. However In such areas it is still of importance to be able to take into account the soil nonlinearity in order to be more accurate in ground motion prediction. Our goal is to observe in seismological data, the effects of soil nonlinear behavior on site response and to define some parameters that will help to evaluate the frequency band affected this phenomena.

We chose the well-characterized KiK-net boreholes in Japan to empirically evaluate site response. The main purpose of this work is fulfilling by comparing the borehole linear site response computed with weak motions (having a PGA at depth < 10 cm/s$^2$) with the borehole site response computed with strong events (having a PGA at depth > 50 cm/s$^2$).

## 2. DATABASE

The Kiban-Kyoshin Network (KiK-net) in Japan is composed of 688 stations with surface and borehole high quality digital 3-components accelerometers. Among the KiK-net sites, 668 shear and compressive waves velocities profiles were collected (http://www.kik.bosai.go.jp/). These velocity profiles are deduced from downhole PS logging measurements. Most of the borehole stations are located between 100 and 200 m. Although most of KiK-net stations are located on rock or thin sedimentary sites (Fujiwara, 2004), two thirds of the sites exhibit a Vs30 smaller than 550 m/s.

In order to avoid any signal processing bias, the only processing applied is a baseline correction of the time histories. The P-waves arrivals and the signal end (end of coda waves) were automatically picked as well as the pre-event noise. The algorithm used to pick automatically is based on the calculation of the ratio of the Long Term Average (LTA) over the Short Term Average (STA), which is usually used in earthquake location (e.g Withers 1998). We chose a LTA of 5 sec, a STA of 1 sec and threshold of 0.5. To ensure a suitable picking, we also made several checks 1) the trigger is not due to a small variation in the pre-event noise; 2) the recording must have enough pre-event noise time window; and 3) if several events were detected in the same recording we select the most energetic one.

We did not correct the depth effect in the borehole recording. However, before, using the results from each station we check that 1) the shear wave velocity profiles were correct and 2) the pseudo-resonance due to downgoing waves did not pollute significantly the borehole recording or if it was the case we precise concerned the frequencies range. For the first item, we compare the borehole site response performed with weak motion to the 1-D linear borehole transfer function. A difference in the first amplified frequency is interpreted as either a 2-D or 3-D site configuration or a inaccurate shear wave velocity profile. We control the second condition by comparing the outcrop and borehole transfer functions, the former being computed through linear simulations.

## 3. METHOD

A large number of researchers have studied the hysteretic behavior of soils in laboratory, using constitutive models or by examining the variations of the shear modulus and damping ratio with the deformation (e.g., Isihibashi et al, 1993). In these models, the shear wave velocity decreases with increasing deformation. Consequently, the peak frequencies of the site response curve are shifted to low frequencies (link to the shear wave velocity, considering a 1D site configuration composed of one layer of sediment lying over a semi infinite space of rigid bedrock by the well-known formula $f_n=(2n+1).Vs/4H$, where fn is nth resonance frequency of the layer that has a depth of H and a shear wave velocity of Vs). The amplitude of the site response curve varies according to two opposing phenomena. The first one is the increasing of the damping ratio with deformation, which induces a decrease in the amplitude; the second is an increase of the impedance contrast, linked to the decrease of the shear wave velocity in the sediment layer, which will induce an increase in the site response amplitude at the peak frequencies. These expected effects are based on a simplified model of soil nonlinear behavior. It does not map more complex phenomena such as soil dilatancy, pore water pressure increase or even strain hardening during earthquake solicitations. Soil nonlinear behavior can also be pointed out using accelerometric data as summarized in the introduction.

In this study, we followed the same procedure as Field et al. (1997), who computed the ratio between linear and nonlinear amplification functions. To define strong ground motion we use the PGA at the borehole station as criteria of ground motion intensity. We selected 54 KiK-net sites that have recorded at least two events with PGA at depth higher than 50 cm/s$^2$, the locations of these sites are displayed in figure 1. The linear behaviour of the selected sites were characterized using ground motion from 1996 to 2011 with surface PGA lower than 10 cm/s$^2$, the mean of the site responses computed from weak events represent the linear site response.

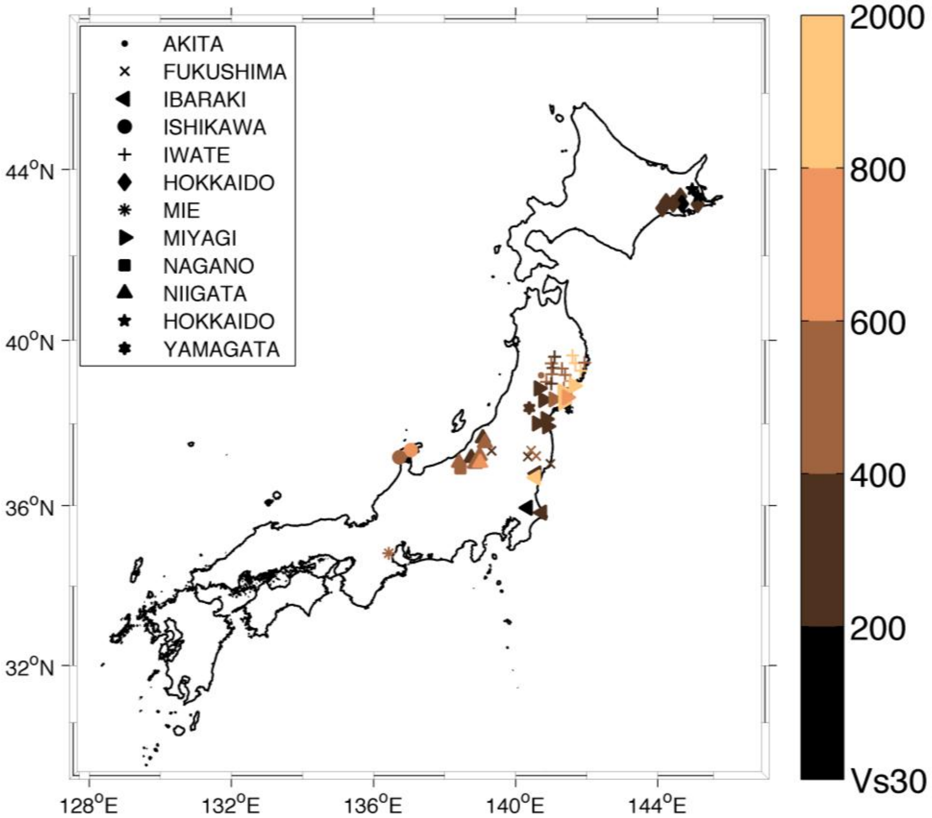


Figure 1. Location of the 54 KiK-net sites that have recorded at least two events with PGA at depth higher than 50 cm/s$^2$.

At each selected KiK-net site, we calculate for each strong motion, (1) the surface to borehole spectral ratio (nonlinear site response) and (2) the linear to nonlinear site response ratio. Thus, we calculate the mean and standard deviation of the linear to nonlinear site response ratio at each selected KiK-net site. Using numerical simulations, Yu et al (1993) studied the differences between linear and nonlinear site responses. They separated the site response into three frequencies band for which they observed different effects on site response. In the low frequencies band no effects are observed, in the medium frequency band, de-amplification compared to linear evaluation is observed, and in the high frequency band they observed amplification. In our observations of the linear to nonlinear site response ratio we note two main features: a de-amplification of the linear site response compared to the nonlinear one curve below a frequency and an amplification above. As displayed in the figure 2, we define a nonlinear site parameter that is the frequency separating these two behaviors in the site response curve (fNL). It is essential to recall that the shift of frequency of the predominant peak in the site response curve during strong motion implies that below this frequency (fNL), the site response computed with strong event is likely to be amplified compared to linear evaluations.

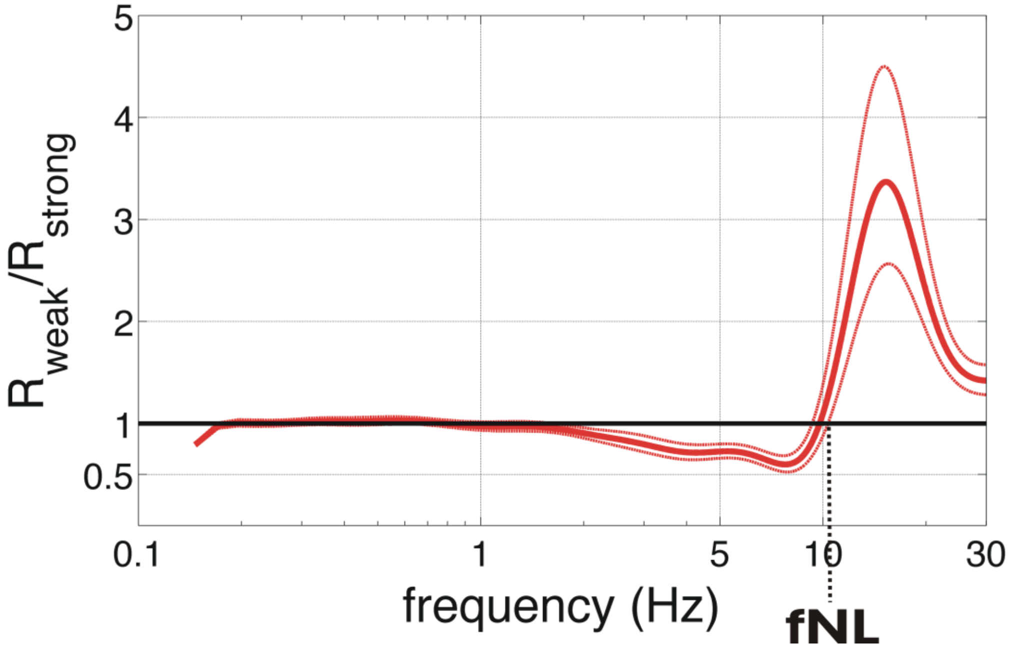


Figure 2. Ratio of site response computed from weak motion and strong motion (mean and 65% confidence limit) at IWTH23. The nonlinear parameter fNL represents the frequency from which this ratio is significantly above one (ie: lower band of the 65% confidence limit is above one).

## 4. RESULTS AND DISCUSSIONS

Figure 3 displays the linear to nonlinear spectral ratio of the 54 KiK-net sites with frequencies normalized by the fNL. The colour scale is associated to the maximum amplitude of the linear BFSR (blue low values of maximum amplitude, orange high values). In this figure we clearly see the two kinds of behavior that were presented in the previous section especially at sites where the maximum amplitude is high. Again this figure highlights the effects of strong motion on site response that is a decrease of the amplitude at high frequencies and in an increase at low frequencies.

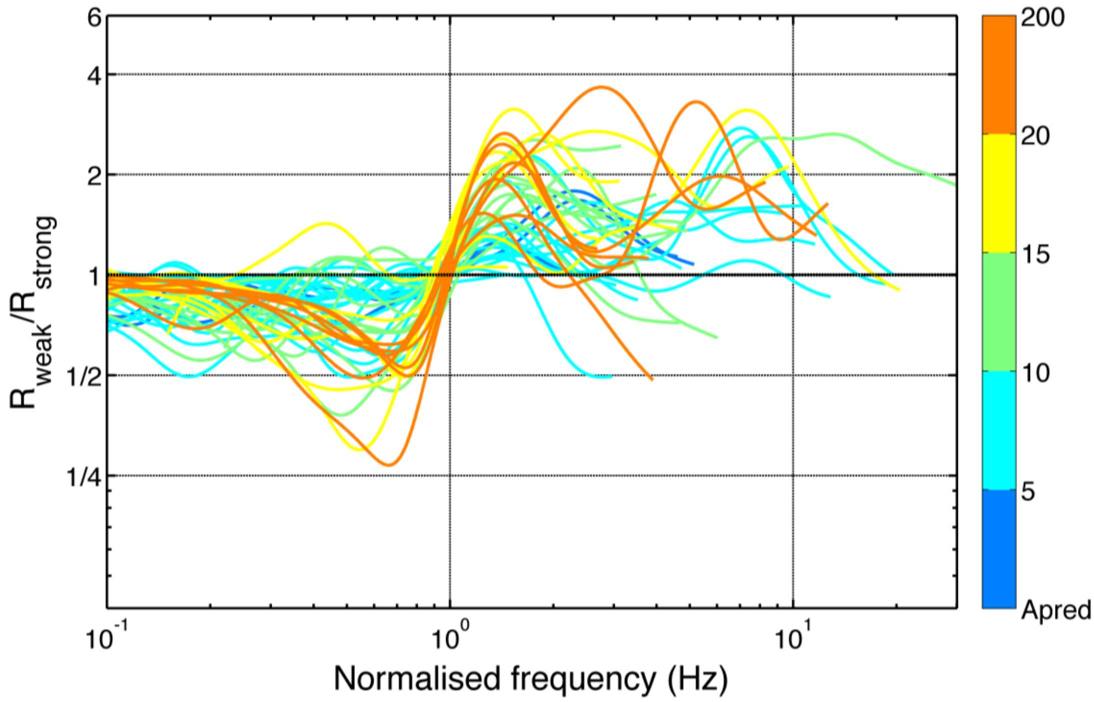


Figure 3. Ratio of the Borehole Fourier Spectral Ratio (BFSR) computed with weak motion and strong motion according to the maximum amplitude of the mean linear BFSR, the frequency is normalized by the FNL of each site.

We then study the correlation of this frequency fNL with soil and site response parameters. We calculated for each KiK-net sites the Vs30, the fundamental resonance frequency of the site and the predominant frequency of the mean linear BFSR (frequency of the maximal amplitude).

The fundamental resonance frequency is the frequency of the first significant peak of the outcrop site response curve. The predominant frequency is the frequency for which the site response curve is the highest. In the introduction, we emphasize the depth effect on the borehole site response, to show that the evaluation of the fundamental resonance frequency is more delicate using borehole site response. The H/V method or receiver function is the ratio of the quadratic mean of the Fourier spectra of the horizontal components by the vertical one. This method is an alternative method to calculate the fundamental resonance frequency that did not require a reference station (Field et al 1995). Although, the origin of the peak in the H/V ratio is still a research topic, a large number of studies has shown that the frequency of the first peak is very well correlated to the fundamental resonance frequency of the site (Langston, 1979; Field et al, 1995; Riepl, et al, 1998). The mean and standard deviation of the H/V at surface performed with recordings with surface PGA lower than 10 cm/s$^2$ is calculated. We pick the fundamental resonance frequency of the site in the H/V ratio (mean and 95% limit confidence) checking that the pick amplitude was significantly higher than 2 (t-test).

As displayed in figure 4, fNL clearly increases with Vs30, the linear correlation between fNL and Vs30 is approximate since the coefficient of correlation is equal to 0.35.

In figure 5, we observe that the fNL is most of the time equal or higher than the fundamental resonance frequency of the site (dark crosses). FNL is calculated using the weak to strong motion BFSR whereas the fundamental resonance frequency was deduced from the H/V at the surface. If the shear wave velocity contrast that produces the fundamental resonance peak is below the borehole depth, then this peak could not be seen in the BFSR. Thus, to check that the previous observation (most of the time fNL>f0) is not due to the fact that the BFSR misses the fundamental frequency, we also calculated the fNL on the ratio of weak to strong H/V at the surface (triangles). Similarly, the fNL on the H/V curves is equal or above $f_0$. Thus, for a large amount of sites the frequencies de-amplified by the nonlinear effects are above the fundamental resonance frequency. The predominant frequency (light crosses) of the BFSR is more correlated to the fNL and is usually higher (with a coefficient of correlation for the robust fit of 0.82). Considering that fNL lies in between $f_0$ and $f_{pred}$, it appears that the soil nonlinear effects de-amplify frequency bands from frequencies in between the fundamental resonance frequency and the predominant one. This observation suggests that the peaks associated with the deepest velocity contrast are less affected by nonlinear behavior than the shallowest ones associated with the predominant frequency. Consequently, it suggests that the soil nonlinear behavior occurs mostly in the subsurface layers. Thus, the characterization of the nonlinear behavior of a soil column could be achieved with surface investigations only. A following work would be to perform inversions in order to find the depth maximum of nonlinear effects that affect the site response. These inversions should be performed on sites where the 1-D configuration is valid. As shown in figure 5, the fNL from H/V curve is very close from the fNL calculated from BRSF, which suggest that the frequency can be deduced using surface recordings only.

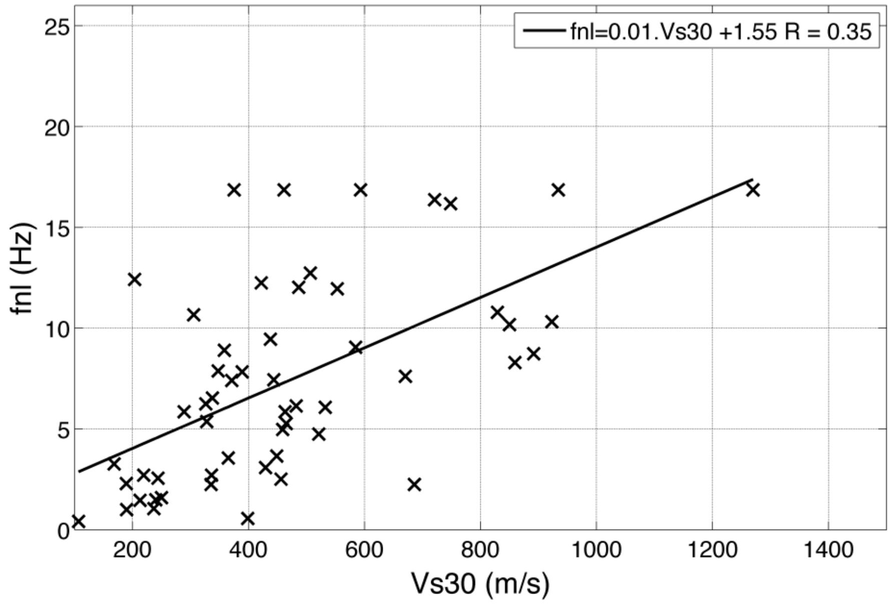


Figure 4. Correlation between fNL with Vs30.

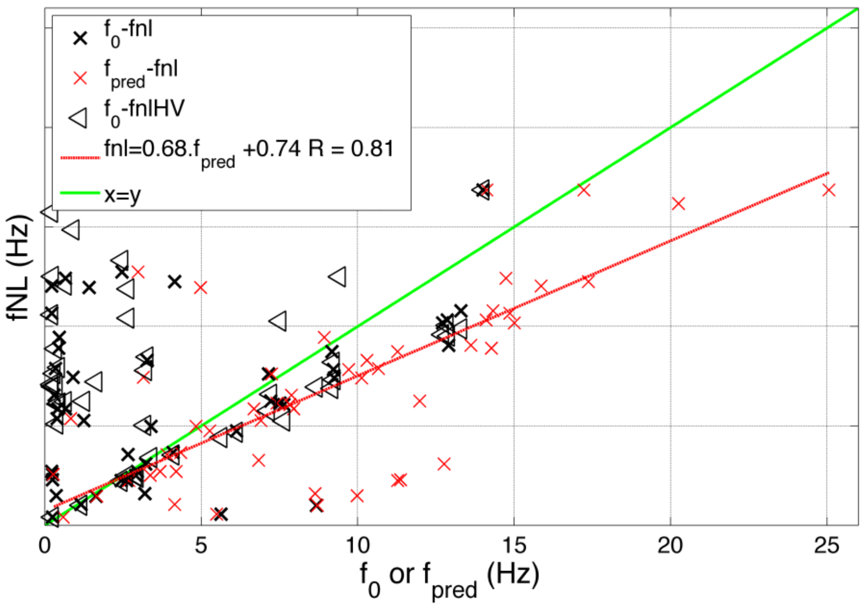


Figure 5. Correlation between fNL (calculate from linear to nonlinear ratio of BFSR or H/V) with $f_0$ and $f_{pred}$.

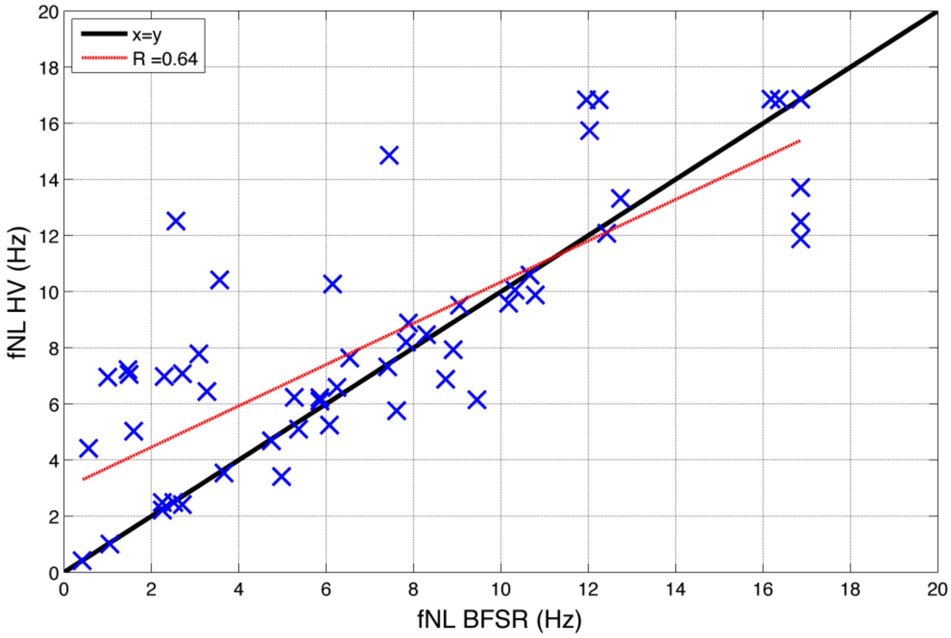


Figure 6. Correlation between fNL (calculate from linear to nonlinear ratio of BFSR or H/V) with $f_0$ and $f_{pred}$.

## 5. CONCLUSIONS

We selected, among the Kik-net network, 54 sites that have recorded strong motions and for each site we calculated the linear to nonlinear site response ratio. We define the frequency from which we observe de-amplification (fNL). We observe that below fNL, the nonlinear site response is amplified compared to the linear site response at sites characterized by high maximum amplitude. The frequency separating these two kind of behavior is related to Vs30 and lies in between the fundamental resonance frequency and the predominant one. This observation suggests that high frequencies are more affected by the nonlinear behavior indicating that nonlinear behavior occurs mostly in the subsurface layers. Consequently, surface investigations of soil nonlinear parameters could be enough to characterize the nonlinear behavior of the whole soil column.

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