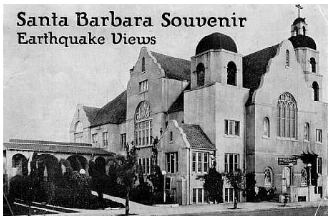

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EMPIRICAL EVIDENCE OF NONLINEAR SITE RESPONSE AT SEVERAL KIK-NET STATIONS

Régnier, J.[1], Bonilla, L.F.[2], Bertrand, E.[1], Semblat, J.F.[2]

[1]*CETE Méditerranée, ERA "risque sismique"*
Nice, 06300
France

[2]Université Paris-Est, IFSTTAR.
Paris, 75732
France

ABSTRACT

This study presents observations of nonlinear soil behavior evidence at several KiK-net sites. First, we compare the site responses performed with 1) the recordings from the aftershocks and 2) the recordings from the main event of the 2011 Tohoku earthquake at four sites. Then, to understand the influence of soil parameters on nonlinear effects, we extend the results to the whole network. We compute the linear (from recordings with surface PGA<20 gals) to nonlinear (from recordings with surface PGA>200 gals) site responses ratio. We study the dependency of this ratio with respect to Vs30, the predominant frequency and the resonance frequency of the linear site response. Finally, to understand the influence of ground motion intensity on nonlinear effects, we compare site responses computed from recordings with different PGA ranges at four KiK-net stations. We define a new parameter f_{nlS} which represent the frequency from which non-linear effect is significant; ie the frequency from which the linear to non linear ratio (lower 68% confidence limit) is above one. We find that f_{nlS} correlate well with Vs30, f_0 and f_{pred} and for most of sites f_{nlS} 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.

INTRODUCTION

It is widely recognized that seismic waves can be locally amplified by subsurface geotechnical properties and 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 amplitude is a main resource 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 ratio 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) presents 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 and is compensated; however, in case of borehole reference station the free surface effect is not homogeneous among frequencies range. Some techniques are developed to correct the spectral ratio from the so-called depth effect (down going wave effect and free surface effect) 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. In California, evidence of nonlinearity was observed in peat, from very low rock PGA; inferior to 10 gals (Seed et al, 1970). In the Garner Valley downhole array (GVDA) in southern California, laboratory tests show that the surface material is nonlinear. However, the limited seismic data indicate no sign of nonlinear behavior (Archuleta et al 1992, Archuleta et al., 1993). In Taiwan, using the well known SMART 1, SMART-2 Arrays and Lotung Large Scale Seismic test site, the comparison of spectral amplification for low and high seismic solicitations indicate that de-amplification due to nonlinear behavior of the soil occurs for a surface PGA around 150 gals (Wen et al., 1994, Beresnev et al., 1995). In addition, such arrays where also used to evaluate seismic soil properties, such as shear modulus or damping ratio degradation curves by means of earthquake recordings inversions (Glaser et al 2000, Zeghal et al, 1995). In Japan, numerous studies based on earthquake recordings have been performed. Thanks to the M_{JMA} 7.2 Kobe earthquake recordings in 1995, extensive studies were carried out in Port Island. Some of them show that such reclaimed soils are prone to high nonlinearity (Sato, 1996; Aguirre et al., 1997; Pavlenko et al., 2003; Kokusho et al., 2004). In dense saturated sand, specific site response from a borehole PGA up to 210 gals are observed which is attributed to sand dilatancy (Iai et al., 1995; Bonilla et al., 2005). In Ashigara Valley, nonlinear behavior is observed for surface PGA around 200 gals (Satoh et al., 1995). Strong motions were also observed at three borehole sites (Amagasaki, Takasago, and Nanko) deployed by Kansai Electric Power. Nonlinear behavior of the soil is observed in two of these sites, Amagasaki and Takasago having a PGA of 507 gals and 187 gals, recorded at the surface respectively (Pavlenko et al., 2003). In 2006, a specific study was performed at KiK-net sites to observe nonlinear behavior in near fault plane (Pavlenko et al., 2006). For 6 sites, nonlinearity is observed (TTRH02, SMNH01, HRSH06, SMNH03, HRSH05). Two kinds of nonlinearity are distinguished. The first one is the soft-type stress-strain. The soils concerned by this type of nonlinearity are characterized by low shear wave velocity and a water table below 10m depth. For such materials, there is de-amplification for strong motions compared to weak motions. The second type of nonlinearity is the hard-type stress-strain for which amplification for strong motions compared to weak motions is likely to occur at low frequencies range. The soil concerned by this type of nonlinearity is characterized by a water table usually above 10 m. The same year, a study on KiK-net data from 23 sites indicates that nonlinear effects are pervasive around 0.1g at the surface (Bonilla et al., 2003).

In low seismicity area, strong ground motions are limited in number or even inexistent. However In such area it is still of importance to be able to take into account the nonlinearities in order to be more accurate in ground motion prediction. Thus, our goal is to define geotechnical parameters that will help to evaluate the nonlinear behavior potentiality of a soil column. This paper aims at providing proxy parameters to estimate the nonlinear behavior from strong motion observations.

We chose the well-characterized KiK-net boreholes in Japan to empirically evaluate nonlinear site response. We first investigate the soil nonlinear behavior during the 11th March 2011 Tohoku great earthquake. We compare the borehole linear site response computed with the aftershocks (having a PGA < 20 gals) with the borehole site response computed with the recordings of the main event. Then, to establish correlations with site and soil proxy parameters, we extend the results to the whole database by selecting KiK-net sites that have recorded at least one recording with surface Peak Ground Acceleration (PGA) above 200 gals. Finally, we compare the linear borehole site response to the nonlinear considering different PGA threshold values.

DATA AND ANALYSIS

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.

To define strong ground motion we use the surface PGA as criteria of ground motion intensity. To investigate the PGA threshold at which nonlinear effects can be triggered, we choose three different PGA values 50, 100 and 200 gals. We selected Kik-net sites that have recorded strong motions and the linear behavior of the selected sites were characterized using ground motion from 1996 to 2011 with surface PGA lower than 20 gals.

In order to ovoid 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 base 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 the frequencies range concerned. 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.

RESULTS AND DISCUSSIONS

Evidence of soil nonlinearity during the 2011 Tohoku earthquake

The Tohoku earthquake that occurred on the afternoon of March 11th, 2011 with a magnitude Mw 9 off the Pacific coast of Tohoku, Japan is one of the largest earthquakes in the world that has been well recorded in the near vicinity of the source (NIED, 2011). Thanks to the KiK-net network, this event represents an important amount of strong ground motion data. We study six areas close to the epicenter: Iwate, Myagi, Ibaraki, Fukushima, Hokkado, and Niigata. In this paper we present the results of our analysis at four stations IBRH11, IWTH21, IBRH16 and MYGH04 that have a Vs30 of 242, 521, and 850 m/s, respectively. The main event produced a PGA of 821, 375, 546 and 504 gals for IBRH11, IWTH21, IBRH16, and MYGH04 stations, respectively. The PGA of the chosen aftershocks is limited to 20 gals. The location of the four KiK-net stations and earthquakes epicenter used is represented in the ***Fig. 1***.

As discussed in the data section, we check the shear wave velocity profile accuracy and the depth effect at this four stations. When comparing the mean linear site response computed from weak motion to 1D linear simulation with borehole and outcrop reference we find that the shear wave velocity were in good agreement with the observations at the four sites. The depth effect is not significant at IBRH11, IBRH16 and IWTH21. However, at MYGH04 the site response is polluted by the down going waves in the borehole recording, the first peak at 6 Hz is not observe when computing the outcrop site response this peak is likely to be related to pseudoresonance.

In ***Fig. 2***, we compare 1) the mean and 65% confidence limits of the borehole site response computed with the aftershocks (PGA<20 gals) with 2) the borehole site response computed with the main event at the four selected KiK-net sites. At IBRH11, the linear site amplification begins at 2.4 Hz, characterized by three main peaks at 2.4, 5.5 and 8.6 Hz. The first frequency peak at 2.4 Hz is linked to the fundamental resonance of the sedimentary layers above the large impedance contrast observed at 30 m depth. The borehole site response computed with the recording of the main event (nonlinear site response) is significantly different from the linear one (the main event site response is out of the 95% confidence limit of the linear one). The peak frequencies are shifted to low frequencies with a decrease of 16, 10 and 2%, respectively for the first second and third peak, compared to the linear site response. The peak amplitudes are decreased by more than one third compared to the linear amplification. IWTH21 linear site response is characterized by a peak at 5.5 Hz followed by a plateau. The nonlinear site response shifts this frequency in 18% and the amplitude is reduced 1.5 times. At station IBRH16, two main peaks characterize the linear site response; the first one has a low amplitude at 1.8 Hz and the second one has a high amplitude at 6.5 Hz. During nonlinear site response, we observe a shift of the peak frequencies of 22 and 12% respectively compared to the linear ones. One can note that, contrary to what was observed at the previous sites; the amplitude of the first peak is slightly increased. Finally, MYGHO4 is a “rock” site according to the Vs30 classification in the Eurocode 8. The linear site response is characterized by a large amplification at 15.5 Hz. When looking at the nonlinear site response we observe that the peak frequency is strongly shifted to low frequency values by 44% with half the amplitude compared to the linear case.

We observe that, for each station, the site response is strongly different when derived from the aftershocks and from the main event. For the four stations we observe a systematic decrease of the peak frequencies. Although the PGA of the main event is not the strongest, the maximal drop occurred at the station MYGH04. The effect of nonlinear behavior on site response amplitude is a decrease, except at station IBRH16 for which the amplitude of the first peak is increased. In numerical simulations, with the equivalent linear model, we expect a decrease of the shear modulus and an increase of the damping ratio. According to the well-known formula $f_0 = Vs/4h$ (linear soil behavior and 1D domain of validity), nonlinear effects should be equivalent to a decrease of the peak frequency and the associated amplitude. The observations during the Tohoku earthquake at the four KiK-net sites selected are in a good agreement with this theory, except at IBTH16 where no decrease in the amplitude is observed at the fundamental frequency.

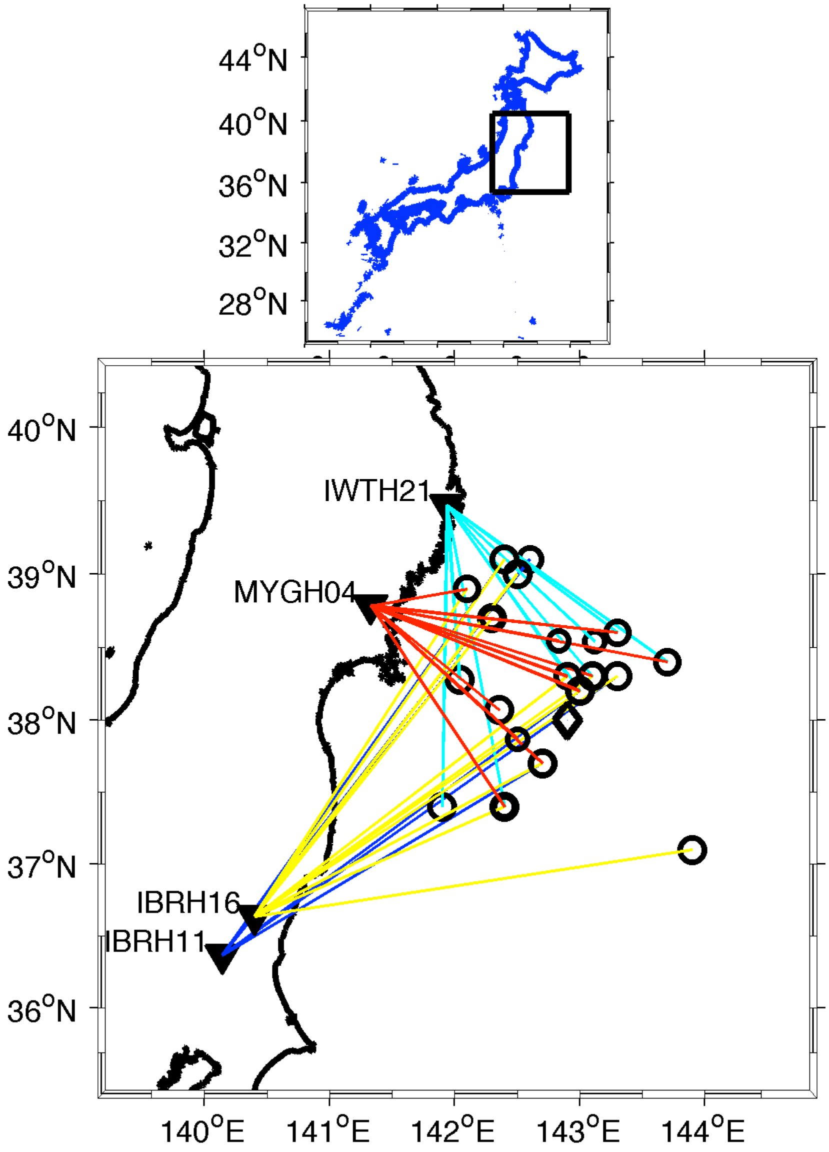

Fig. 1: location of the four KiK-net sites and locations of the epicenter of the earthquakes used to computed the linear borehole site response (black circles) and the main event of the Tohoku earthquake (black diamond).

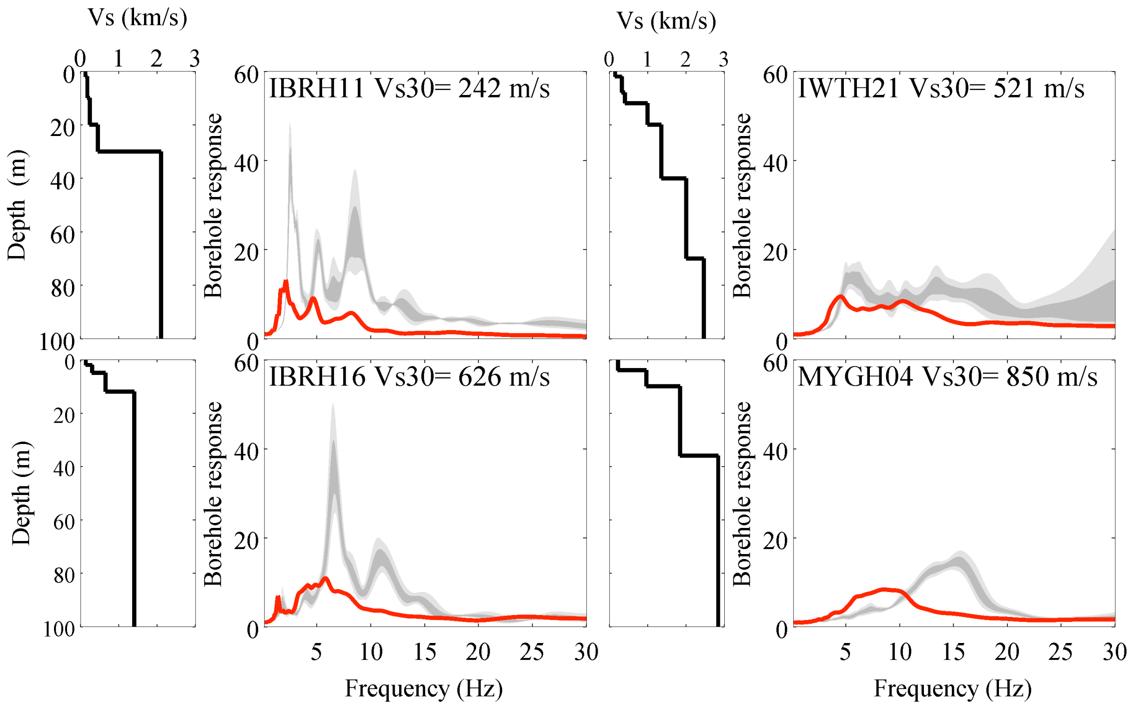

Fig. 2: Comparison of the borehole site response computed from aftershocks of the Tohoku earthquake (PGA<20gal), the dark grey area represents 68% of the observation around the mean and the lighter area 95% with the borehole site response computed with the Tohoku main event represented by the red curve (after Bonilla et al., 2011)

Influence of soil and site response parameters (Vs30, f_0 and f_{pred})

In this section we extend the previous results to the whole network considering not only the Tohoku event but also all the events that produce strong motion at the KiK-net stations. We consider a PGA threshold of 200 gals to distinguish the strong motion from the weak motion. The selected KiK-net sites are located in the fig. 3 according to the Vs30 at the station and the number of earthquakes that were recorded above 200 gals. For instance, five KiK-net sites recorded more than five events with surface PGA higher than 200 gals: IWTH02, IWTH05, IWTH25, IWTH26, IWTH27, NIGH11. Most of the studied sites are located in the area close to the Tohoku earthquake epicenter, in the region of Iwate, Myagi, Ibaraki, Fukushima and Niigata. In the selected sites, a large diversity of soil conditions is represented with Vs30 from less than 250 m/s up to 850 m/s.

We followed the same procedure as Field et al. (1997), who computed the ratio between linear and nonlinear amplification functions. The linear function is the geometric mean of the borehole site response performed with weak motion (PGA<20gals) and the nonlinear amplification is the geometric mean of the transfer function coming from strong recordings (PGA>200gals). Thus, if this ratio is larger than one, nonlinear behavior is suspected at a given frequency band. We note f_{nl} the frequency from which the ratio is greater than one. Fig. 4 shows this ratio as a function of Vs30. One can clearly see that nonlinear soil effects increase with decreasing Vs30 values. The figure indicates a broadband nonlinear behavior for soils having a Vs30 < 800 m/s, from 3-6 Hz to 30 Hz. Another striking result is the presence of nonlinear behavior at « rock » sites (Vs30 > 800 m/s). A closer analysis of their velocity profiles shows that the first 10 m have a shear wave velocity ranging from 200 to 400 m/s, which must explain these observations. Nonetheless, these are average results only; more studies are needed to assess the uncertainties related to these observations.

Fig. 5 presents the mean linear to nonlinear borehole site response ratio as a function of the predominant frequency of the site response (f_{pred}). For sites having a f_{pred} below 5 Hz, nonlinear soil behavior occurs above 2.8 Hz, for sites with $f_{pred} \in [5-10]$ Hz, nonlinear soil behavior occurs between 6 and 25 Hz, for sites with $f_{pred} \in [10-15[$ Hz, nonlinear soil behavior occurs above than 9.5 Hz. Finally, for sites with f_{pred} greater than 15 Hz, soil nonlinearity is less important. We clearly see that nonlinear soil behavior increases with decreasing f_{pred}. f_{nl} decreases with decreasing f_{pred}. Hence, the frequency bandwidth for with the ratio is higher than one is spreader.

The frequency for witch the nonlinear soil behavior become significantly important (in this case, f_{nlS} is the frequency for which the lower band of the 65% confidence limit of the site response ratio is greater than one) is related to the predominant frequency of the site response. In Fig. 6 we compare the correlation between f_{pls} and f_{pred}, f_0 and Vs30. It is clear that the f_{nlS} is related to f_{pred} f_0 as well as Vs30. This frequency lies in between f_{pred} and f_0. For most sites, f_{nlS} is greater or equal to f_0 and are below f_{pred}. One can note that f_{nlS} is farther from f_0 at low values of f_0.
The effect of nonlinear behavior is not similar for all frequencies. The previous observations suggest that a greater part of soil nonlinearity occurs at frequencies higher than the fundamental one, especially when the fundamental frequency is below 1 Hz.; indeed, the lower band frequencies (below the fundamental resonance frequency) are less modified by the nonlinear behavior than the high frequencies (above the predominant frequency) band. This also suggests that most of the soil nonlinearity occurs in the top surface layer where the soil is less compacted. This observation is in agreement with several in situ and laboratory tests (e.g. Johnson et al., 2009). According to this conclusion surface investigations of dynamic soil behavior should be enough to assess the global nonlinear behavior of the site.

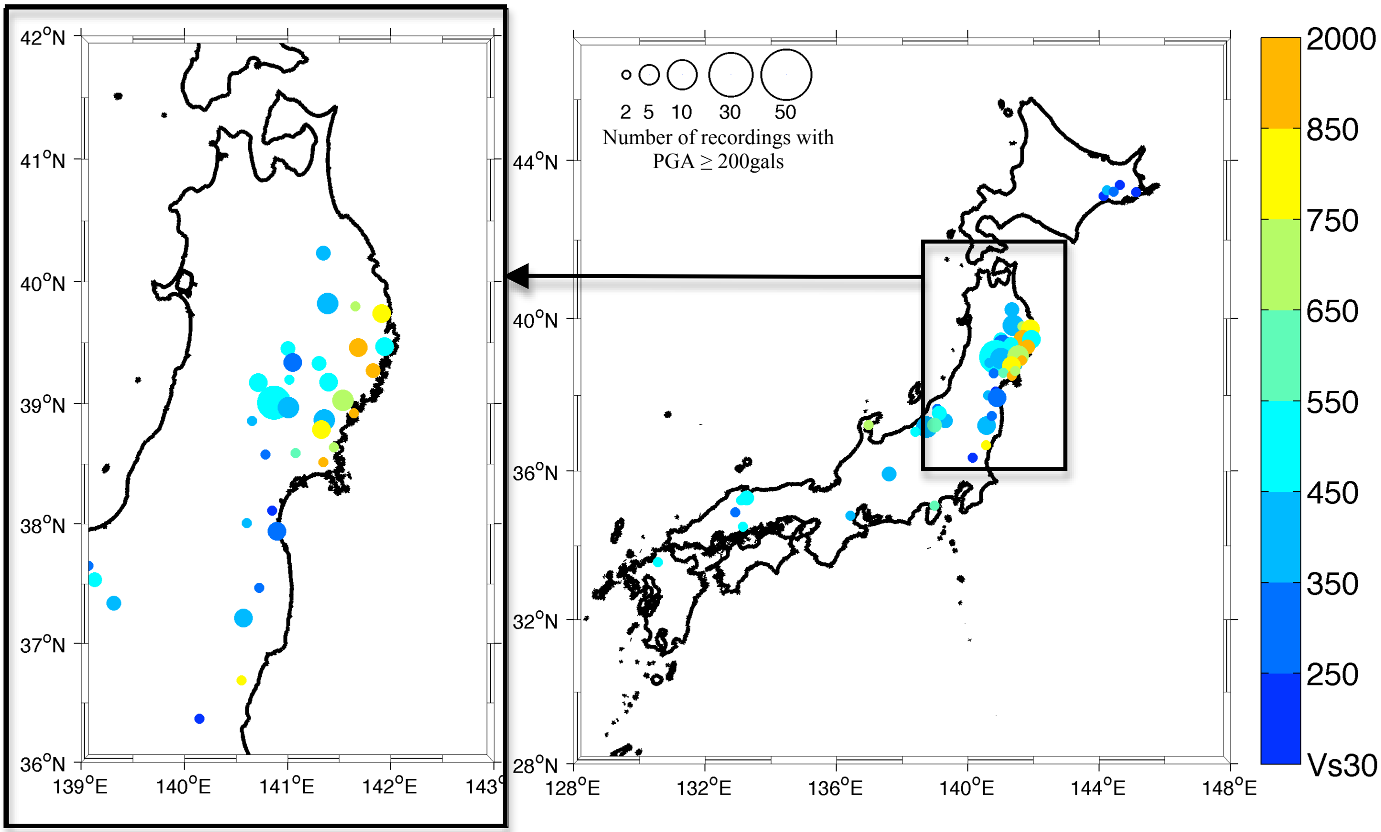

Fig. 3: Position of the selected KiK-net sites, the colors represent the Vs30 (harmonic mean shear wave velocity for the top 30 m of soil) the size of the points represent the number of earthquakes recorded at the sites that have a surface PGA higher than 200 gals.

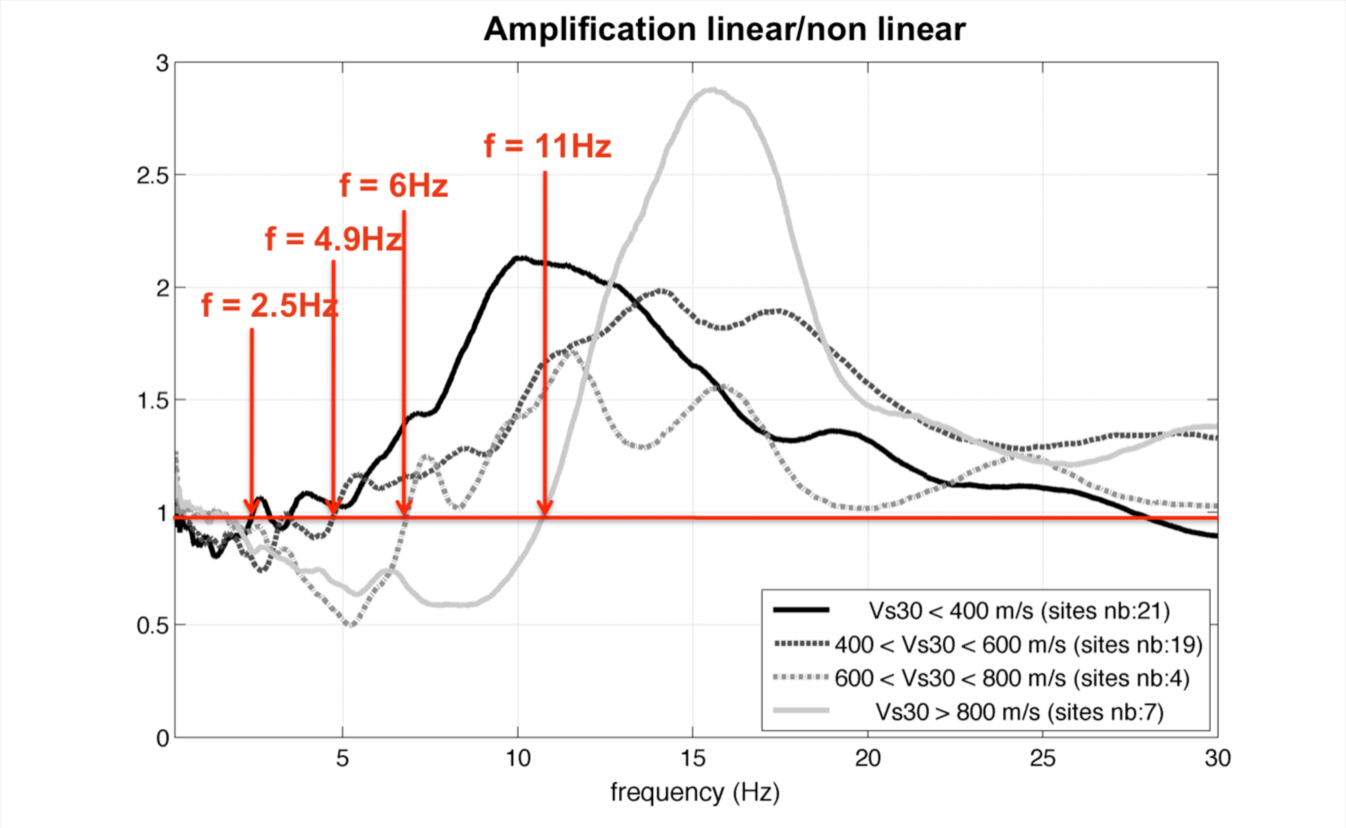

Fig. 4: mean of the Linear to nonlinear borehole site response ratio per Vs30 ranges.

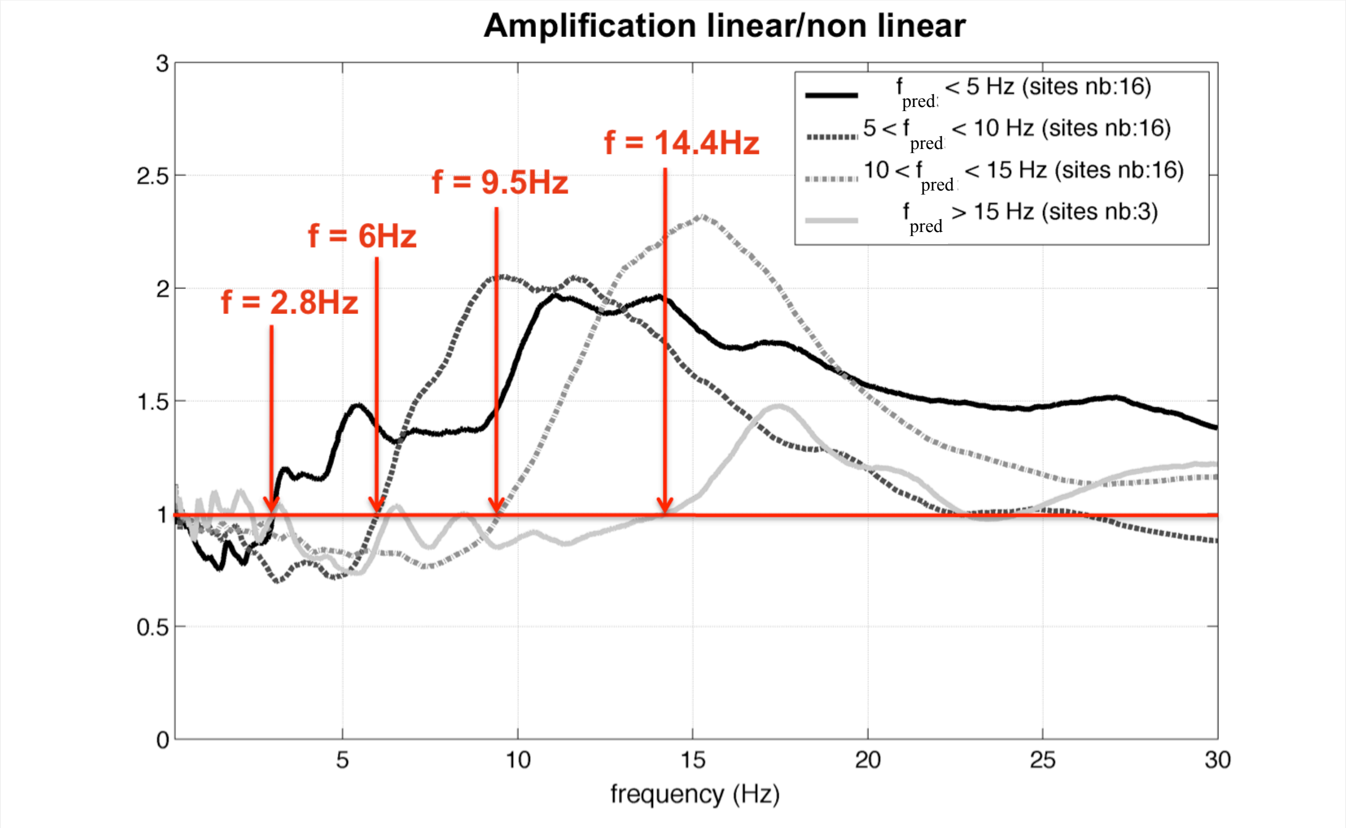

Fig. 5: mean of the Linear to nonlinear borehole site response ratio per f_{pred} ranges.

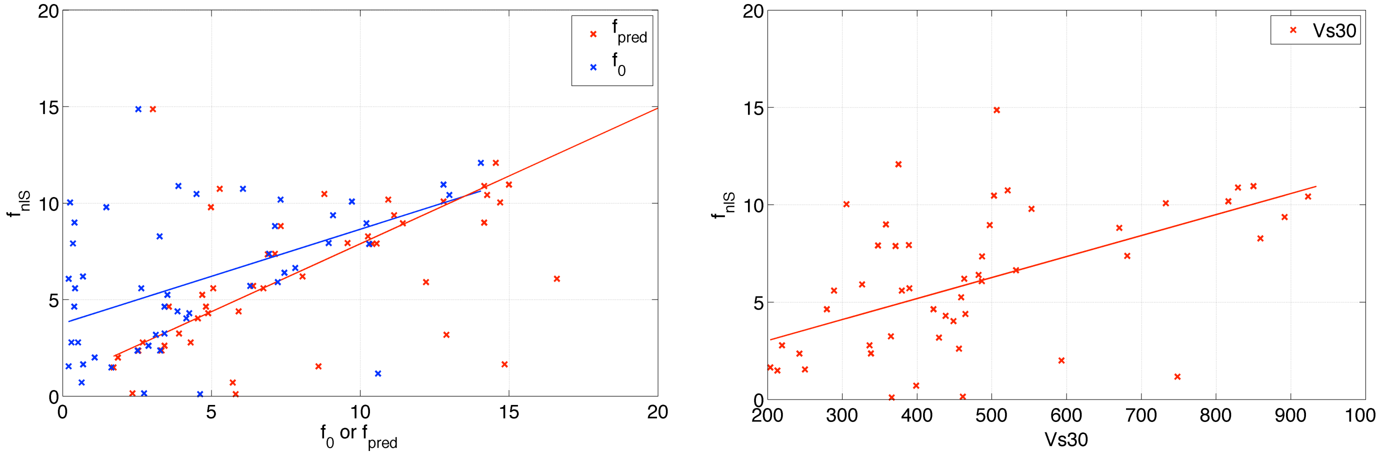

Fig. 6: Evolution of the frequency from which the linear to nonlinear site response ratio is significantly greater than one (f_{nlS}) with: f_0 blue crosses and with f_{pred} red crosses (left plot) and Vs30 (right plot). The lines indicate the linear fit between f_{nlS} and the three parameters.

Influence of PGA

In this section we analyze the impact of surface PGA values on site response considering the mean of the borehole site response as a function of PGA. We computed the geometric mean of the borehole transfer function coming from recordings that have PGA in between $]50-100]$ gals, $]100-200]$ gals and higher than 200 gals.

To illustrate this section, we study the KiK-net sites for which large strong motion data are available. In Fig. 7, the distribution of the surface PGA of Iwate region stations 25, 26 27 and 05 are illustrated. We can see that 7, 18, 15 and 10 recordings are available for PGA $\in]50-100]$ gals, at station IWTH05, IWTH25, IWTH26 and IWTH27 respectively. Furthermore, 7, 12, 4 and 3 recordings for PGA $\in]100-200]$ gals are available at station IWTH05, IWTH25, IWTH26 and IWTH27 respectively. Finally, 5, 12, 3 and 4 recordings with PGA greater than 200 gals are available at station IWTH05, IWTH25, IWTH26 and IWTH27, respectively. Although the number of recordings is too small to perform relevant statistics, the mean is significant in comparison to the linear site response confidence limits. On the other hand, the linear site response and confidence limits are calculated with more than one hundred of recordings. The accuracy of the shear wave velocity profiles and the depth effects ere also checked. We find that the shear wave velocity profiles were in good agreement with the observations at station IWTH05, IWTH25. However, at IWTH26 and IWTH27 the peak frequency of the 1D linear simulations are slightly shifted (0.5 Hz and 1 Hz respectively) compare to the empirical evaluation which may reflected a mistake on the Vs evaluation or a 2D or 3D site configuration. Besides at IWTH26, the first peaks at 2 and 5 Hz are pseudo-resonances; the fundamental frequency should be close to 10 Hz corresponding to the resonance of the first interface at 4 m depth.

In Fig. 8 we compare the borehole site response curves considering different PGA ranges; the shear wave velocity profile is also represented on the left side. The dark grey area represents the 68% confidence limits and the lighter area the 95% confidence limits, respectively. The blue curve represents the mean borehole site response for recordings between 50 and 100 gals, the turquoise curve is the borehole site response between 100 and 200 gals and the yellow curve means the borehole site response for PGA higher than 200 gals. At station IWTH05, we observe a significant nonlinear effect at f_0 (4Hz) from 200 gals characterized by a decrease in the peak amplitude. From 100 gals we observe nonlinear soil behavior only from f_{pred} (11 Hz) characterized by both a shift of the peak frequency to low frequency band and a decrease in the amplitude. At station IWTH25, nonlinear behavior from 50 gals is observed only on the second series of peaks from 5 Hz characterized by a shift of the peak frequency but not associated to significant decrease in amplitude. For PGA greater than 100 gals a significant but weak decrease in amplitude is observed from 11 Hz. At station IWTH26, significant nonlinear behavior is observed at f_0 from a PGA higher than 50 gals. The fact that no modifications are observed on the firsts peaks suggests that no significant nonlinear effects occur at depth. Finally, at IWTH27, we observe a significant nonlinear behavior at 100 gals characterized by a weak decrease of the amplitude at 11 Hz.

Although the shear wave velocity at station IWTH25 did not exceed 600m/s down to 60m, the nonlinear effects are low. At IWTH27, in spite of the strong impedance contrast at 4 m depth, no significant nonlinear effects are produced. Conversely, for IWTH26, strong nonlinear soil behavior is observed in spite of the smaller impedance contrast compared to IWTH27. The shear wave velocity profiles of the sites, alone, cannot fully explain these nonlinear observations. Thanks to station IWTH27 site response, we observe again that nonlinear soil behavior mainly occurs at the surface, in this case in the first 4 m of soil. Concerning the PGA threshold that triggers nonlinear soil behavior, modification on site response is observed at all stations from 11-15 Hz frequencies bandwidth for PGA greater than 100 gals.

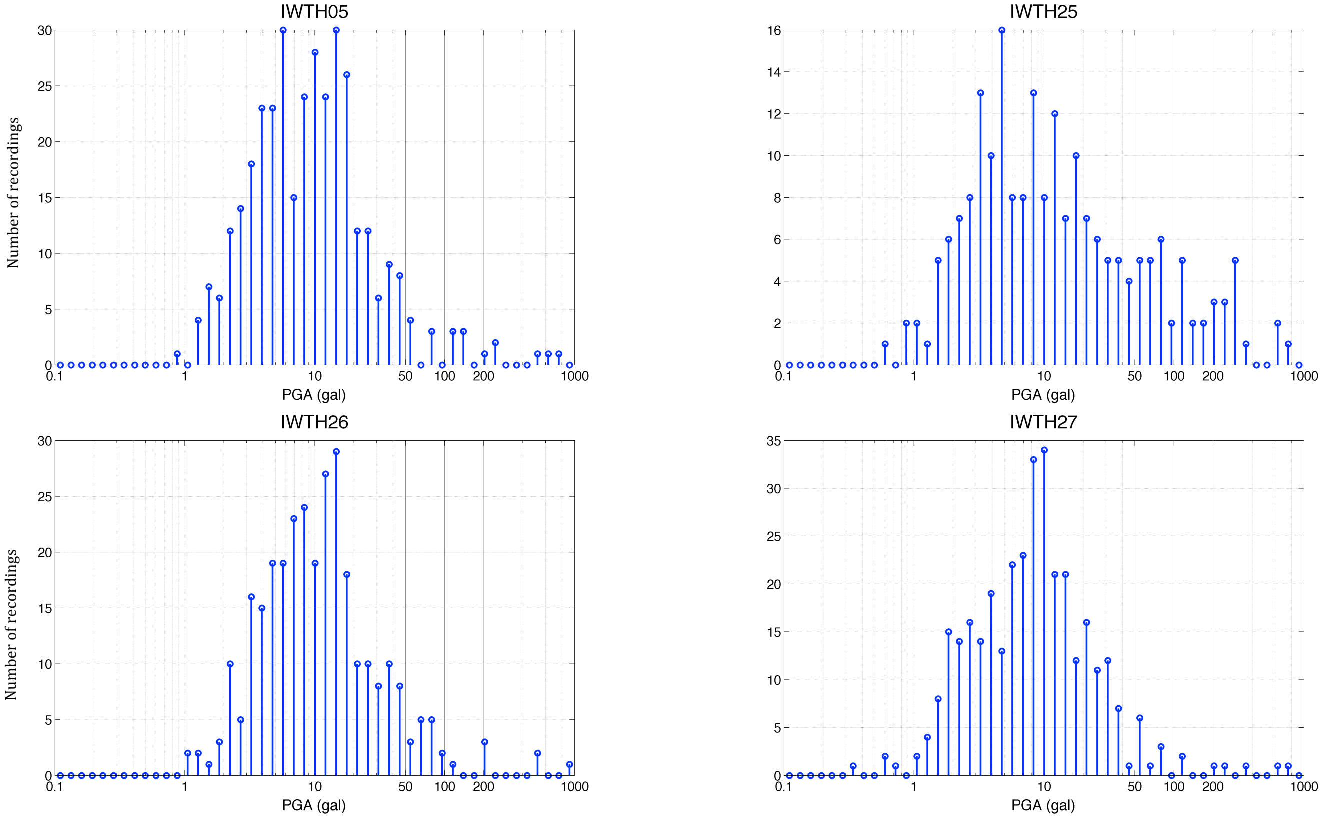

Fig. 7: PGA histograms of the surface PGA at the KiK-net stations IWTH05, IWTH25, IWTH26 and IWTH27.

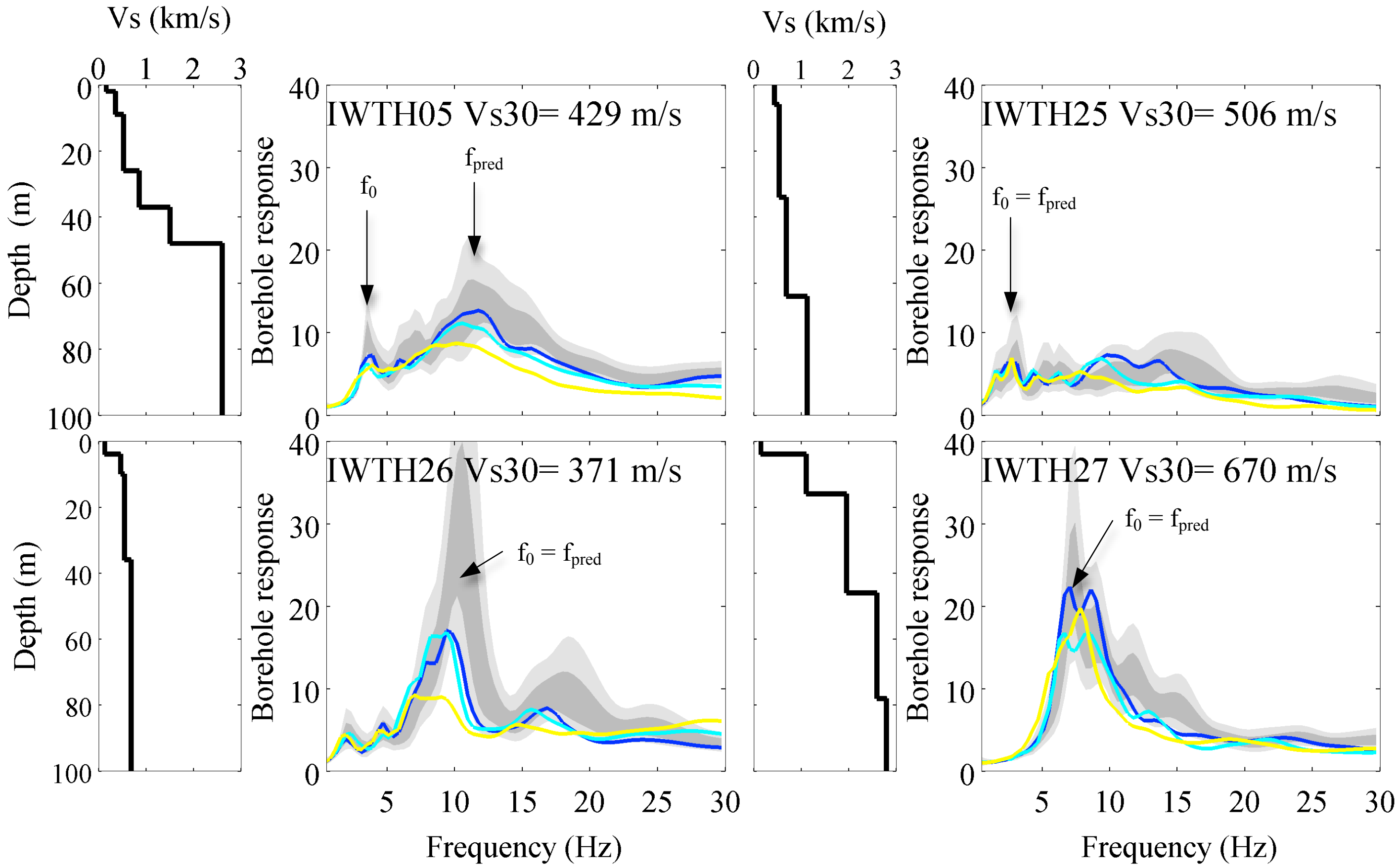

Fig. 8: Comparison of the borehole site response at station IWTH05, IWTH25, IWTH26 and IWTH27. The grey areas represent the 68 and 95% observation around the mean linear site response, the blue curve represents the mean borehole site response performed with recordings with surface PGA between 50 and 100 gals, the turquoise curve represents the mean borehole site response performed with recordings with surface PGA between 100 and 200 gals and the yellow curve mean borehole site response performed with recordings with surface PGA higher than 200 gals.

CONCLUSIONS

We use the KiK-net strong motion database to observe soil nonlinear behavior. First, we study the site response modifications between the site response performed with the recordings from the aftershocks and the main event of the Tohoku earthquake. We find that strong nonlinear behavior occur during the earthquake. Using the whole strong motion recordings, we compute the linear to nonlinear spectral ratio and compare the mean spectral ratio according to Vs30 and the predominant frequency. We find that the effect of soil nonlinear behavior is not similar for all frequencies:

- We see that when Vs30 or the predominant frequency are increased, soil nonlinear behavior is observed on a higher and less spread frequencies bandwidth.
- We define a new parameter f_{nlS} which represent the frequency from which non-linear effect is significant; ie the frequency from which the linear to non linear ratio (lower 68% confidence limit) is above one.
- We find that f_{nlS} correlate well with Vs30, f_0 and f_{pred} and for most of sites f_{nlS} 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. Finally, we compare site response computed from recordings with different PGA ranges at four KiK-net stations; For frequencies higher than 11 and 15 Hz nonlinear soil behavior is observed at the four stations for recordings with PGA greater than 100 gals. We are currently leading investigations in order to add geological information to this study.

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