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## **NON-LINEAR SOIL RESPONSE AT STRONG MOTION OBSERVATION SITES WITH A FOCUS ON BOREHOLE ARRAY**

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### **ABSTRACT**

This paper has been a review of publications since the 80's about the observation of non-linear soil behaviour in seismological data. It focuses mainly on vertical arrays as an exceptional natural laboratory to study the propagation of seismic waves through the subsurface soil layers. The review highlights the breakthroughs that were performed such as the demonstration of the significance of the non-linear soil behaviour or the proposal of methodologies to back calculate the non-linear soil properties.

The PGA is one of the most used parameters to describe the level of seismic solicitations. The reported PGA threshold from which non-linear soil behaviour is observed, has been decreasing since the 80's thanks to the increase of available data, the improvement of the data quality, of the computational efficiency. The results of all studies lead to (1) new methodologies to invert data and provide in-situ characterisation of soil behaviour and (2) the definition of proxy parameters that reflect the impact of non-linear soil behaviour on site responses. From these proxies it is now possible to take into account non-linear soil behaviour in the analysis of site responses without using numerical simulations. Future perspectives in this field concern the densification of the instrumented sites and the characterisation of soil properties to provide natural laboratories that are well-constrained. For the assessment of the in-situ non-linear soil properties, the quantification of the uncertainties and spatial variability also represent a challenge. To do so we need to gather even more the data which have been made available through international collaborations.

*Keywords: in-situ, non-linear soil behaviour, vertical arrays.*

### **INTRODUCTION**

It is now well-recognised that the site effects can be significantly different during strong events as compared with small ones. This has not always been so. Since the 80's the community of seismologists have been working hard to show that non-linear soil behaviour has a significant impact on site responses and consequently on the prediction of strong ground motions while non-linear soil behaviour was observed for a very long time in laboratory tests (e.g. Hardin and Drnevich, 1972; Dobry and Vucetic, 1987).

The main effects of non-linear soil behaviour are a degradation of its shear modulus and an increase in its attenuation properties with strain level. The main impacts of these changes on site responses are a shift of the resonance frequencies towards lower values together with a reduction in the associated amplifications.

The in-situ characterisation has many advantages compared with lab measurement: it considers the whole soil in its environmental conditions: with its heterogeneities, its confining pressure, its scale and with minor disturbances of the soil. On the other hand laboratory tests are associated with large uncertainties related to the soil sampling disturbances, the scale of the specimen, the measure of the strain and the interpretation of the laboratory results to get the non-linear soil data to be used in site response analysis (Régnier et al., 2018). These uncertainties were already underlined in the proceedings of the NSF/EPRI Workshop on Dynamic Soil Properties and Site Characterisation (Tang, 1989) and are one of the greatest motivations of all the works reviewed in this paper.

Since 1980 more than 80 papers dealing with observation/ quantification and the understandings of non-linear soil behaviour in seismological data have been reviewed. This review is not yet exhaustive and will require several iterations to be so with, hopefully, the input from the participants of this conference. The goal is to provide the reader with some key-findings with new investigation methodologies, figures of existing data and some guidelines for future explorations.

## **REVIEW**

### **Review of reviews**

Six papers reviewed the observations of non-linear behaviour between 1989 to 2001. In 1989 during the NFS EPRI workshop (Tang, 1989) the scientists indicated that arrays data were the highest priority to be used to back calculate the in-situ soil dynamic properties. They insisted on coupling the accelerometers with additional devices such as strain and piezometers in saturated soils. In the specific vertical array section the authors indicated that an associated site characterisation was also recommended. Later, in 1992, Pender reviewed observations of site amplifications and non-linear soil behaviour in seismological data. He indicated that most studied sites where no evidence of non-linear behaviour was seen were stiff soil for which the non-linear soil behaviour was not expected. In 1993 Aki made a review to underline that non-linear soil behaviour is “more persuasive than seismologists used to think”, mainly based on the data set from Loma Prieta earthquake. In his paper published in 1996 and clearly entitled “Nonlinear Soil Response: A Reality?”, Beresnev (I.A Beresnev & Wen, 1996) reviewed all the papers showing either evidence or lack of evidence of the impact of non-linear soil behaviour in earthquake recordings. The latest data collected indicate that there is direct evidence of those effects. In 1998 a workshop on this specific subject was organized and led to a paper that involves most of the main occidental specialists in that field (E. H. Field et al., 1998). Six main questions were raised and discussed and some of them still remain. – Do lab studies reflect in-situ behaviour? Did non-linear codes based on physical models exist? Is equivalent linear model adequate? What are the new methods to analyse data? Is nonlinearity in rock or very stiff soil significant? Is sediment nonlinearity significant at long periods? The last paper was published in 2001 by Elgamal (Elgamal et al., 2001). An impressive collection of analysis of vertical arrays has been achieved in that paper site after site. The conclusions of the authors were mainly oriented toward solving technical issues related to the installation of the vertical arrays, the processing of the seismological data before any analysis and the future installations that could include dense 3D arrays and wide implementing of vertical arrays on the whole territory.

### **Evolution of the PGA threshold in the literature for non-linear significance**

As shown in figure 1 the PGA threshold from which non-linear soil behaviour has been observed in seismological data tends to decrease year after year. Why ?

I will give five suggestions to explain this decrease. They will be detailed in the next paragraphs.

- The evolution of the consideration of non-linear soil behaviour. Before the 90's the seismological community (in general) was not yet convinced by the significance of the impact of soil non-linear behaviour on seismological recordings and most papers concluded that non-linear behaviour was not significant.
- The better quality of the recordings.
- The increasing number of recordings.
- The increasing capacity of exchange, storage and computation.
- The evolution of the analysis methods.
- The signature of the non-linear soil behaviour in seismological data assessed by the seismological community.

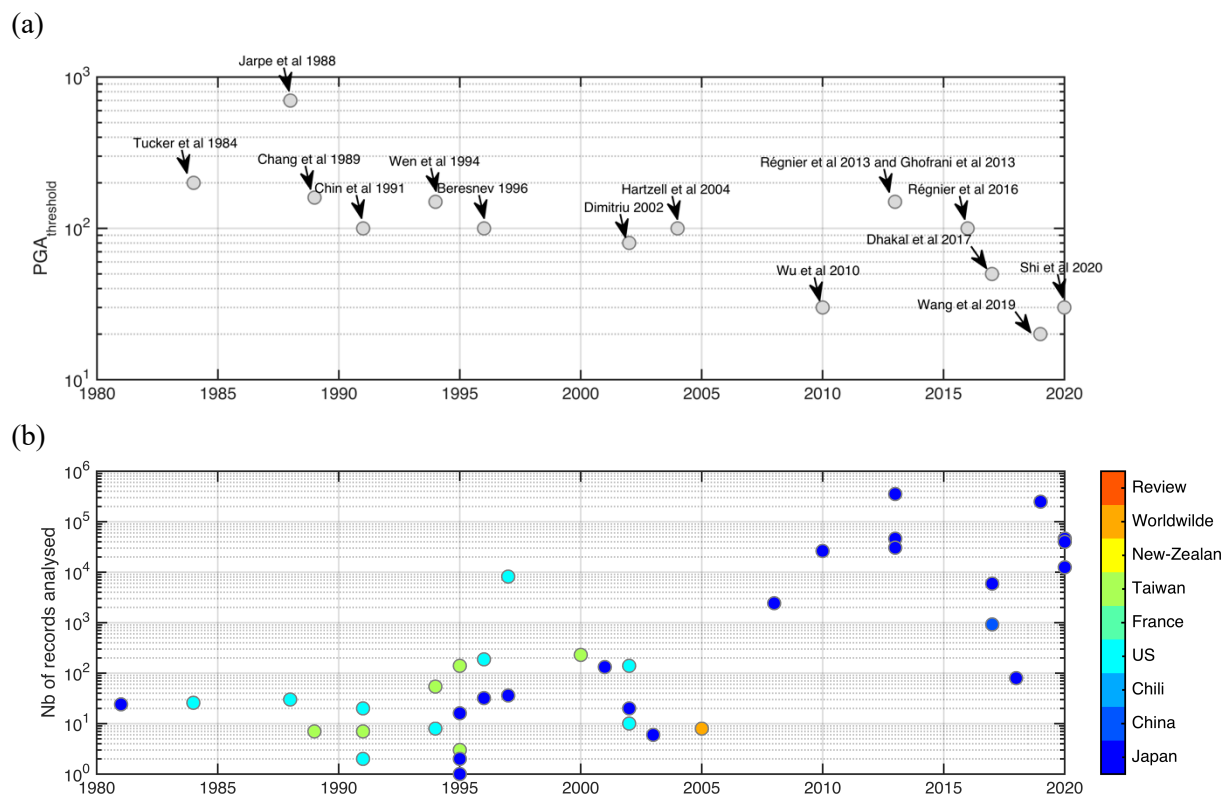


Figure 1: (a) Evolution of the PGA threshold from which non-linear behaviour is observed in seismological data, reported in the papers and (b) number of recordings used to analyse non-linear soil behaviour with date of publication. The colour scale indicates the countries where the data come from to perform the analysis.

### ***Illustration of the evolution of the consideration of non-linear soil behaviour***

It was noticed in a large number of papers that while the geotechnical community was aware of the non-linear soil (and rock) behaviour through the laboratory tests, the seismological community were not considering that this behaviour could significantly impact the surface motion. Therefore, in some of the first studies performed before the 90's, most of the conclusions were that non-linear soil behaviour does not have a significant impact. In the paragraph below 3 examples are given to illustrate this explanation:

- In 1984, Tucker et al (Tucker & King, 1984) investigated the site response at Chusal valleys and compared the site responses obtained from weak motions (PGA below 10<sup>-3</sup> g) with stronger motions (PGA between 0.04 g to 0.2 g), which is a low PGA bandwidth to describe strong motion. The comparison was only performed visually. The authors concluded that no discrepancy between these two groups of site responses could be seen. However, looking into the site responses of the EW component (Figure 2-a), a shift of the fundamental resonance frequency between these 2 groups can be observed today. It can be interpreted as an impact of soil non-linear behaviour.
- Jarpe et al., (1988) also compared weak and strong motion site responses with quantification of the variability. From figure 2-c, the authors concluded that there is no evidence of soil non-linearity because the 95% confidence limit of the strong motion site response include the weak motion 95% cond-fident limit below 10 Hz. Today my interpretation would be different. In figure 2-d non-linear soil behaviour can be observed through a shift of the site resonance frequency. The shifts are from 10 to 9 Hz for the events having a PGA of 0.22g and 0.54g, from 10 to 7 Hz for the event characterized by a PGA of 0.47g and finally a shift from 10 to 3.5Hz for the strongest event with a PGA of 0.7g. The interpretation of the data can be subjective and also depend on the type of impact the author is looking at.
- In 1991, Darragh et al (1991), compares weak and strong site responses, in figure 2-b, the solid line corresponds to the strong event, the shift of the resonance frequencies: from 1.1 to 0.9 Hz

for the fundamental resonance frequency and from 2.1 to 1.3 Hz for the predominant frequency, with the decrease of the amplification at the predominant frequency are quite clear in this figure.

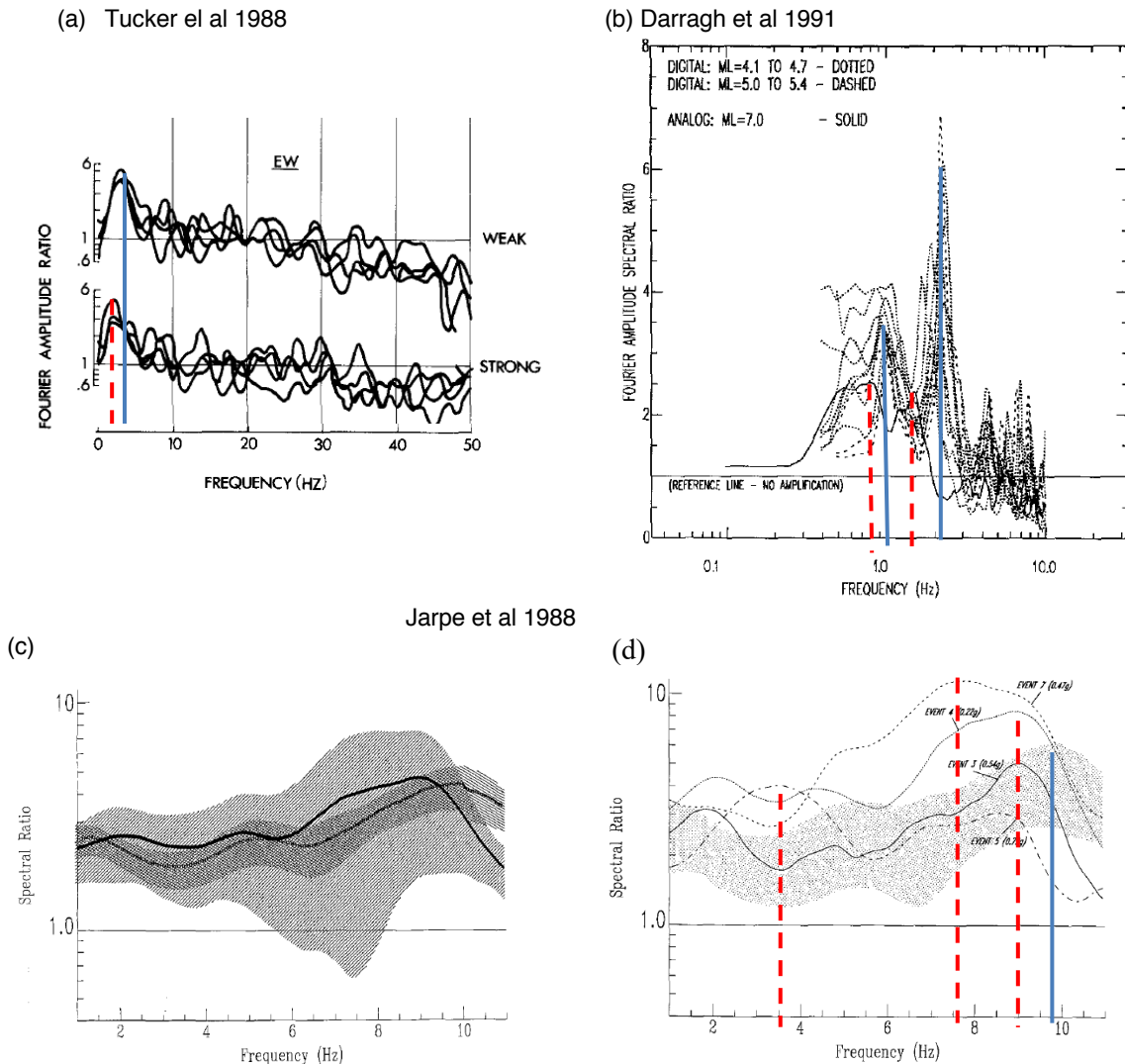


Figure 2 : (a) Comparison between weak and strong motion site responses at Chusal valleys (from Tucker et al 1984). The red dotted line refers to the fundamental resonance frequency obtained using the strong events while the blue solid line corresponds to the weakest motions. (b) Comparison between weak and strong motion site responses at Coalinga (from Darragh et al 1991) (c) and (d) Comparison between weak and strong motion site responses at Coalinga (from Jarpe et al 1988). (c) average and 95% confidence limit.

### The improvement of the quality of the recordings

During the 80's and the 90's the stations were modified to provide recordings from analogic to digital. In the last two decades, most of the stations were upgraded to transmit first, triggered signals and nowadays continuous recordings. The spreading of vertical and dense arrays (provided in the figure 3) has largely participated in increasing the number of recordings available to analyse non-linear soil behaviour. Figure 3 illustrates the location of the vertical arrays with the colour scale indicating the year of installation (or the year corresponding to the first earthquake recorded at the station when the information were not available). 85% of the vertical arrays were deployed between 2000 and 2003.

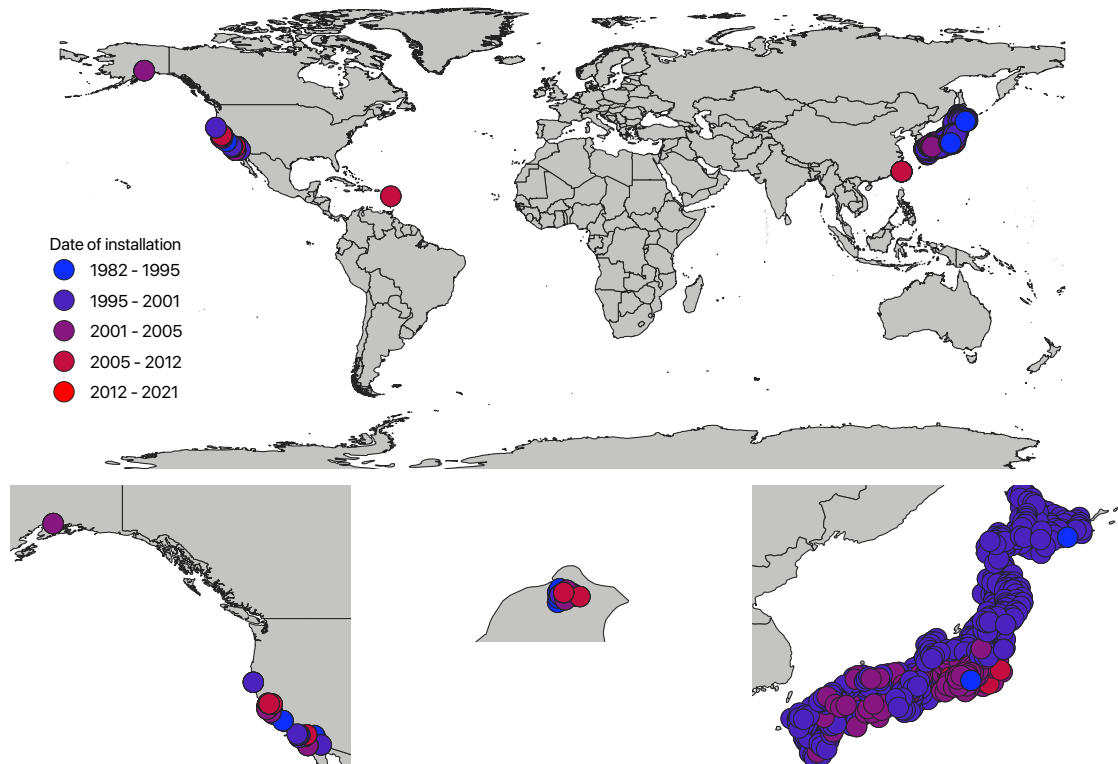


Figure 3: Location of vertical arrays used in the reviewed papers. The colour scale provides information on the dates of installation. When those information were not available the date of the first earthquake recorded was used.

### ***The number of recordings has increased***

With the deployment of stations, especially in vertical array for the study of wave propagation in the subsurface soil layers, the number of recordings has also increased. From figure 1 we can see that the recent studies on non-linear soil behaviour use more and more data and are mainly focused on zones where these data are freely available such as Kik-net and K-net.

The increasing number of recordings for one site offers the possibility to analyse the whole panel of ground motion intensity and frequency content. It is therefore possible to provide a more accurate value of PGA Threshold for such sites. In Régnier et al., (2013) a parameter called  $PGA_{th}$  is defined. It provides a site-specific value of PGA from which we observe more than 10% difference between the linear and the non-linear site responses.

The large number of recordings from vertical arrays opens the possibility to use statistical tools on site responses:

- **Single parameter correlation:** In Dimitriu et al. (2000) a negative correlation between resonance frequency and ground acceleration was found using the Smart 1 data. In Noguchi et al (2008) a correlation was found between the DNL (Degree of Non Linearity, see below for more details) parameter and the observed PGA at 67 K-net and 54 Kik-net sites. In 2010, Wu et al made a correlation between frequency drop and PGA at 6 Kik-net sites. In 2013, Ghofrani et al correlate the decrease in the predominant frequency ( $f_{MS}/f_{ref}$ ) and/or amplification amplitude ( $A_{MS}/A_{ref}$ ) as a function of  $PGA_{ref}$ . in 2017, Yang et al categorized the back calculated shear modulus curves as a function of confining pressure at 18 sites subjected to 165 ground motions. Ren et al (2017) tested and defined new parameters that characterized the effect of non-linear soil behaviour on site responses on 33 strong motion stations that recorded the Ms 8 Wenchuan earthquake in China. In 2020 Castro et al defined a new parameter called  $f_{sp}$  (that is a frequency shift, see below for more

details) that has a non-linear correlation with intensity parameters of ground motion. The same year Shi et al suggested a non-linear correlation between the non-linear soil behaviour observed in the vertical component of motion with a strain proxy at 8 Kik-net sites.

- **Multivariable canonical correlation:** in 2013 Régnier et al worked on Kik-net data. A multivariable canonical correlation was applied to 54 KiK-nets sites to find the site parameters that influence most of the non-linear soil behaviour of a site. It was found that the maximal amplitude of the linear borehole transfer function was well correlated with the non-linear soil behaviour.
- **Neural network:** in 2020, Derras et al published a model based on observation of ground motions at Kik-net sites that propose a correction of the linear transfer function to account for non-linear soil behaviour.

### ***Signature of non-linear soil behaviour on seismological data***

The seismologists were looking at different signatures of non-linear soil behaviour in accelerometric data. The main effects of soil non-linear behaviour are a decrease of the shear modulus and an increase of the attenuation with the increase of strain. Therefore, in site response we expect to see a decrease of the resonance frequencies through a decrease of the shear wave velocity and a decrease of the amplification due to the increase of the attenuation. However, the soil behaviour is more complicated according to the type of soil (sandy or clayey) with or without water, to the density/porosity and to the contracting or dilatant behaviour of the soil. In Wu et al (2010) and Pavlenko & Irikura (2006) a differentiation of type of non-linearities is suggested to explain the differences of effects on seismological data: “Concerning the influence of the soil non-linearity on the amplification of seismic waves in subsurface soil layers, we should distinguish two cases, namely “soft” and “hard” types of nonlinearity”. The signature in seismological data can be different as well. From the overview performed, four main effects have been mainly studied:

- **The first signature was mainly the decrease of the amplification.** The method used to show this impact varies from one paper to another, we can distinguish (a) Comparison of PGA at sedimentary sites with PGA at rock sites (Seed et al., 1991) or PGA predicted with linear computation Aki (1993) (b) Comparison of amplification at frequency peak (Darragh and Shakal, 1991) (c) Comparison of site response computed with weak motions or pre/post-event data with strong ground motions (Igor A. Beresnev et al., 1995; Iwasaki & Tai, 1996; E. Field et al., 1997; Aguirre & Irikura, 1997; Frankel et al., 2002) and (d) Comparison with predictive models like GMPEs (Ground Motion Prediction Equation) to highlight low values of PGA at sedimentary sites (Chin & Aki, 1991; Trifunac & Todorovska, 1996).
- **Later on papers also looked at the frequency shift of the resonance frequencies** (Chang et al., 1991; Yu et al., 1993; Iai et al., 1995; Satoh et al., 1995; Sato et al., 1996; Igor A. Beresnev et al., 1998; Aguirre & Irikura, 1997; P. Dimitriu et al., 2000; P. P. Dimitriu, 2002; Wu et al., 2010; Johnson et al., 2009; Luis Fabian Bonilla et al., 2011; Ghofrani et al., 2013; Régnier et al., 2013; Dhakal et al., 2017; Régnier et al., 2016; Luis Fabian Bonilla et al., 2019).
- A large number of studies indicate that the low frequency of the site response was not impacted by the non-linear soil behaviour. However, recent studies have shown that the shift of the resonance frequency to low frequency bandwidth can sometimes create **an amplification greater than the linear one at low frequency** (Luis Fabian Bonilla et al., 2011; Kawase, 2006; Olga V. Pavlenko & Irikura, 2006; Régnier et al., 2013, 2016).
- **Using back calculations the authors showed decrease of the shear wave velocity during strong motions** (Wen, 1994; Huang, 1995; Satoh et al., 1995; Sato et al., 1996; Aguirre & Irikura, 1997; Kokusho, 2004; K. Sawazaki et al., 2006; Lawrence et al., 2008; Kaoru Sawazaki et al., 2009; Chandra, 2014; Gassenmeier et al., 2016; Yang et al., 2017; Luis Fabian Bonilla et al., 2017; Goto et al., 2017; Wang et al., 2019; Shi et al., 2020) or back-calculated stress/strain curves (O. V. Pavlenko & Irikura, 2002, 2003; Lee et al., 2006)
- In sites prone to liquefaction or cyclic mobility the dilatant behaviour of soil can generate **spikes in the acceleration and create high PGA values** (Archuleta et al., 2000; Luis F. Bonilla et al., 2005; Frankel et al., 2002; Yu et al., 1993; Zeghal et al., 1995)

### Monitoring the non-linear signature

Using time-frequency domain, Dimitriu, (2002) and Wu et al., (2010), monitored the frequency shift during the main shock. With even more details, methods such as Stockwell decomposition monitors the slight modifications of resonance frequencies (Luis Fabian Bonilla et al., 2011) or using continuous data for several years Sawazaki et al., (2009, 2006) or just after the main shock (Aguirre & Irikura, 1997; O. V. Pavlenko & Irikura, 2002). From these studies the authors indicated a large variability of the recovery time which can be instantaneous, take 3 to 24 hours, several days or even several years. In Sawazaki (2006) the recovery time of the velocity was 69% over the first week, 83% over 1 month, 87% over 1 year and 97% over 4 years.

### Proxy parameters

To extract the dynamic soil properties from the seismological data, there are several possibilities. One solution is the use of direct information from the acceleration time series (either at a single surface station or more often at various depths in vertical arrays). Proxy of stress, strain, shear modulus degradation and attenuation are defined. In some studies we find a hybrid method in which the stress is extracted from the data but the strain is calculated with a numerical modelling. A second method is based on back calculations of the dynamic properties using inversion techniques. Those dynamic properties can be used in numerical simulations to predict a strong motion.

Finally, some authors defined proxy parameters that describe the effect of non-linear soil behaviour in seismological data and elaborated correlation with site and intensity measurement parameters. Some of these proxies are used in pure empirical approaches to correct the linear transfer function from the non-linear soil behaviour, without using numerical models (Castro-Cruz et al., 2020; Derras et al., 2020). In the following paragraph a review all those proxies is suggested.

### Proxy for shear modulus degradation curves with empirical evolution of strain

The dynamic parameters that have been mostly extracted from seismological data are the shear degradation curves:

- Tokimatsu and Midorikawa, (1981), suggested to extract these properties by using a single surface station with the following equations. A comparison between laboratory measurements and the  $\frac{G}{G_0} = f(\gamma_{eff})$  is then worked out.

$$\frac{G}{G_0} = \left(\frac{T}{T_0}\right)^2$$

eq. 1

T, predominant period of the surface motion.

$$\gamma(t, z) = \frac{1}{2v_i^*} \left( v_0 \left( t + \frac{z}{v_i^*} \right) - v_0 \left( t - \frac{z}{v_i^*} \right) \right)$$

eq. 2

$G_i^* = G(1 + 2\beta i)$ ,  $\beta$  damping factor from  $\frac{G}{G_0}$

$$\gamma_{eff} = \begin{cases} 0.65\gamma_{max} & (\text{whole record}) \\ 0.85\gamma_{max} & (\text{partial records}) \end{cases}$$

- Zeghal et al. (1995) proposed a determination of the stress/strain curves by using the shear beam theory. The stress is defined as shown in eq. 3

$$\tau_i(t) = \sum_{k=1}^{i-1} \rho \frac{\ddot{u}_k + \ddot{u}_{k+1}}{2} \Delta z_k, i = 2, 3, \dots$$

eq. 3

Where the subscript i correspond to different depth,  $\tau_i(t) = \tau(z, t)$  is calculated from the acceleration  $\ddot{u}_i = \ddot{u}(z, t)$  and  $\Delta z_i$  is the spacing interval. The strain is defined as shown in the following equation:

$$\gamma_i(t) = \frac{1}{\Delta z_{i-1} - \Delta z_i} \left[ (u_{i+1} - u_i) \frac{\Delta z_{i-1}}{\Delta z_i} + (u_i - u_{i-1}) \frac{\Delta z_i}{\Delta z_{i+1}} \right]$$



eq. 4

From the stress/strain curves, the authors extracted the shear modulus  $G$  and the damping ratio  $D$  as a function of the maximal shear strain ( $\gamma_m$ ):

$$G = \frac{\tau(\gamma_m)}{\gamma_m}$$

eq. 5

$$\eta = \frac{W_d(\gamma_m)}{2\pi W_c(\gamma_m)}$$

eq. 6

$W_d$  is the energy dissipated during the stress-strain loop,  $W_c$  is the elastic energy of an equivalent system. Cox et al. (2009) and Idriss (2009) suggested a strain proxy by using the PGV divided by the  $V_{s30}$  (Harmonic average of the shear wave velocity over the first 30 m of depth). This proxy was also used in Bonilla et al (2019).

- Chandra et al. (2015) use seismic interferometry to calculate the shear wave velocities in the soil layers of Garner valley and wildlife liquefaction arrays ( $V_{s^*}$ ). Instead of using PGA and PGV, the authors used the average peak particle velocity  $v^*$  and average peak acceleration  $a^*$ .  $v^*/V_{s^*}$  was used as a strain proxy.

### ***Proxy for shear modulus degradation curves with numerical evolution of strain***

- Chang et al. (1991) worked on the dense vertical array of Lotung, he suggested a procedure in which the ratio of the Fourier response spectra was calculated between each sensor depth, the frequency of each equivalent soil layer can be extracted. Then he suggested an analytical solution for the response of a two-soil layers model to retrieve the velocity of each layer. From equivalent linear calculation he found the shear strain at the middle of each soil layers and for each earthquake the shear modulus was obtained empirically by using the  $V_s$  value of each soil layer.

### ***Inversion techniques***

- Satoh et al., (1995) compared the theoretical and the empirical borehole transfer functions at KS2 site in the Ashigara valley in Japan. They found the minimum value of misfit between these two functions and back calculated the  $V_s$  profile and damping factor.
- Sato et al., (1996) performed inversion of the  $V_s$  profiles at 4 downhole arrays in Kansai.
- Aguirre & Irikura, (1997) analysed the recordings of the 1995 Hyogo-Ken Nambu earthquake before, during and after the main event. They used the Haskell-Thomson algorithm associated to a genetic algorithm to back calculated the  $V_s$  profile.
- Satoh et al., (2001) performed again an inversion of the  $V_s$  profiles at 3 vertical borehole arrays (Amagasaki, Takasago and Nanko) in Japan after the Hyogo-Ken Nambu earthquake.
- Pavlenko & Irikura, (2002 and 2003) inverted the stress/strain curves and were able to back calculate the shear modulus decrease in the different soil layers by using the surface and the borehole stations only.
- Kokusho, (2004) used an inversion technique based on a Bayesian approach. The shear modulus degradation curves were calculated, and the effective shear strain is corrected with the confining pressure.
- Kawase, (2006) used a general inversion technique on surface ground motion to retrieve the site response parameter.

### ***Proxy for non-linear signature in site response***

- E. Field et al., (1997) have suggested for the first time to use the ratio between the linear and the non-linear site responses.
- Satoh et al., (2001) have suggested for the first time to use a cross correlation between surface and down-hole station to find the average  $V_s$  of the soil column.
- P. P. Dimitriu, (2002) suggested the ratio of the fundamental resonance frequency. The numerator of the ratio is the fundamental resonance frequency peak of an H/V calculated on moving windows and the denominator is a reference weak motion fundamental resonance frequency. The square of this frequency ratio is a proxy of the shear modulus degradation.

- Noguchi & Sasatani, (2008) suggested a new parameter to describe the degree of non-linearity of a site according to the equation. He applied this technique on a single station by calculating the Horizontal-to-Vertical spectral ratio (H/V) or by using the surface to downhole spectral ratio (On Kik-net and K net data)

$$DNL = \sum_{eq. 7} \left| \log \left( \frac{R_{strong}}{R_{ref}} \right) \right| \Delta f$$

Where  $R_{strong}$  can represent the H/V or the borehole transfer function of a strong event and  $R_{ref}$  is the average H/V or the borehole transfer function of the weak motions.

This parameter was also used in Wen et al., (2011) using the 2010 Darfield (New-Zealand) data and in Dhakal et al., (2017) on the seismographs located at the bottom of the oceans.

- Ghofrani et al., (2013) used the ratio between the ratio of the fundamental resonance frequency obtained from strong and weak motions.
- Régnier et al (2013), defined 6 proxy parameters, two that depend on the event ( $PNL_{ev}$  and  $SH_{ev}$ ) and four characterized the site non-linear soil behaviour ( $PNL_{site}$ ,  $Sh_{site}$ ,  $PGA_{th}$  and  $f_{NL}$ ). Compared to the DNL suggested by Nogushi et al. (2008), the  $PNL_{ev}$  took into account the variability of the linear site-response curve and is normalized by the average linear site-response curve in order to give an absolute estimation of the nonlinear behaviour of the soil independently of the linear site-response amplitude.  $Sh_{ev}$  is the shift between the average weak ground motion resonance frequency and the one calculated for a specific event.  $PNL_{site}$  corresponds to the value of  $PNL_{ev}$  at a threshold value of PGA (here  $50 \text{ cm/s}^2$  at the downhole station).  $PGA_{th}$  is the threshold value of PGA at  $PNL_{ev}$  of 10%.  $Sh_{site}$  is the value of  $Sh_{ev}$  when the PGA is  $50 \text{ cm/s}^2$ . Eventually,  $f_{NL}$  is the frequency that characterized the non-linear to linear site response ratio
- Régnier et al., (2016) suggested the  $RSR_{NL-L}$  which is the ratio between non-linear and linear site responses.
- Ren et al., (2017), compared proxy parameters defined in Nogushi et al. (2008) and in Régnier et al (2013) with two new parameters ADNL and  $RF_p$  on the data of the Wenchuan earthquake. ADNL considers the linear site response variability and  $RF_p$  is the frequency ratio between strong and weak motions.
- Castro-Cruz et al., (2020) defined a frequency shift parameter ( $fsp$ ) that illustrates the shift of the resonance frequencies toward low frequency bandwidth and is a proxy for shear modulus degradation.

## PERSPECTIVES

Most of the papers aim at drawing attention to the large impacts soil non-linear behaviour can have on site responses. With the increasing number of seismological observations it becomes clear that this effect is significant even at a quite moderate level of solicitations. Even in moderate seismicity countries it is of importance to provide accurate predictions of non-linear site responses. This is even more essential for critical facilities that are designed to resist strong motions. In the following paragraphs proposals for future work are provided.

### Densification of the instruments in vertical arrays:

Vertical arrays represent a natural laboratory in which in-situ characterisation of the dynamic parameters can be performed. The in-situ site response captures all the complexities of the site (geometrical, anisotropy, heterogeneities) and the complexities of the soil nature in its environment, in its scale which are the main advantages relative to the laboratory tests. The precision of the estimation of the soil dynamic characteristics is linked to the spatial distribution of the instruments along the array. One of the next developments is increasing the number of instruments with idealistically, the accelerometers at the bottom of the soil layers and strain meters at the middle. An interesting perspective is the use of continuous spatial recordings of the soil deformation with optical fiber as strain meters. These new technology become a reality for a lot of seismological applications: measurements of microearthquakes,

regional earthquakes, teleseisms, and infrastructure signals with Distributed acoustic sensing (DAS) (Lindsey & Martin, 2020).

### **Correlation between site parameters and dynamic properties or constitutive models:**

For engineering purposes and especially in moderate seismicity area it is not feasible to install temporary vertical arrays to be able to have an in-situ evaluation of the non-linear soil behaviour. It justifies the use of numerical models that include the soil constitutive model to accurately predict the seismic motion of a strong earthquake. The non-linear soil parameters are obtained with site-specific studies involving laboratory tests or most of the time with the use of empirical relationship that have been defined from data obtained with laboratory tests (Darendeli, 2001; Dobry & Vucetic, 1987; Ishibashi & Zhang, 1993). One improvement would be to design empirical relationship between non-linear soil properties derived from accelerometric data and in-situ site parameters. We have observed from the previous review that a large number of analysis provided new evaluation of non-linear soil behaviour whereas parameters characterizing the site are missing.

Therefore, the next step is also to improve the site characterisation at the instrumented sites. To unfold all the in-situ characterisation available involving classical geotechnical tests (such as SPT, CPT, downhole suspension logging) and innovative ones (Cyclic pressiometer) in combination with geophysical measurements of soil properties using ambient vibration individual and in network. Soil samples of all characteristic soil layers must be analysed as well with the laboratory tests used to measure strain dependent dynamic properties and soil rupture properties. The in-situ measurements aim at characterizing the spatial variability of the soil around the seismic station that influence the seismic site response.

### **Assessment of the uncertainties:**

Many developments to define soil constitutive models have been performed in the last decades (Nuth & Laloui, 2008), but few studies have analysed the uncertainties of input parameters and their impacts in the seismic site response evaluation and liquefaction. The uncertainties come from the soil parameters, the input motion variability and all intrinsic uncertainties related to calculations and models. We can distinguish two type of uncertainties. The first type is the site-specific uncertainty: part of the soil parameters obtained can be compared from one type of measurements to another. For example, the maximal shear modulus, the shear modulus reduction curves, the shear wave velocities. This can provide a first site parameter variability estimation. Then, using in-situ measurements, an estimation of the soil spatial variability can be performed. The second type is the generic soil parameters uncertainties: the uncertainties about the soil input parameters can be evaluated by using existing databases of laboratory tests and earthquake recordings. The uncertainties of dynamic non-linear soil parameters and parameters controlling the volumetric behaviour can be defined from the statistical analysis of existing soil measurements databases.

### **Cooperation**

As shown in the first figure, the last papers that published a large overview of non-linear soil behaviour worked with Japanese data. This dataset is large in terms of number of sites and panel of level of solicitations recorded, with a homogeneous site characterisation. Besides the access to the database is made very easy through the website ([www.kyoshin.bosai.go.jp](http://www.kyoshin.bosai.go.jp)). The semiologist community is one of the communities with the most developed international cooperation. One great improvement would be sharing worldwide data and encourage common work.

In order to be complete this review will need additional iterations and would deeply beneficiate from a common sharing of ideas. I would like to thank the committee who organized this conference and thus made it achievable.

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