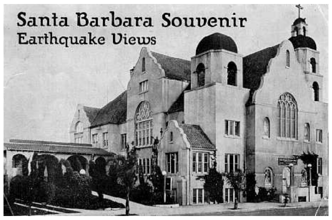


*4th IASPEI / IAEE International Symposium:*

**Effects of Surface Geology on Seismic Motion**

August 23–26, 2011 · University of California Santa Barbara

# THE CHALLENGE OF NONLINEAR SITE RESPONSE: FIELD DATA OBSERVATIONS AND NUMERICAL SIMULATIONS

**Luis Fabian Bonilla**
Universite Paris-Est, IFSTTAR
58 Bd Lefebvre
75732 Paris Cedex 15
France

**Celine Gelis**
Institut de Radioprotection et de Surete Nucleaire
IRSN/DEI/SARG/BERSSIN
BP 17, 92262 Fontenay-aux-Roses
France

**Julie Regnier**
CETE - Mediterrannee
56 Bd Stalingrad
06359 Nice Cedex 4
France

## ABSTRACT

Seismologists acknowledged nonlinear site response during strong motion in the aftermath of the Loma Prieta earthquake. Yet, it is the earthquake engineering community that conducts exclusively most nonlinear studies in practice. These are performed either by using linear-equivalent approximations or using complex constitute models that require a detailed soil characterization. Indeed, the problem of estimating nonlinear site response is the number of parameters needed to describe the dynamic material properties. For this reason, the majority of nonlinear analyses remain to one-dimensional computations. The well-recorded Mw9 Tohoku earthquake of March 11, 2011 shows widespread nonlinear effects on stations close to the rupture, even at sites having Vs30 larger than 400-600 m/s. Sites having lower values of Vs30 showed cyclic mobility and liquefaction. This event shows that if we want to correctly assess the ground motion for future large earthquakes, large-scale nonlinear analyses are needed. These observations represent a constraint when developing nonlinear constitutive models as well as a challenge for numerical computations. Furthermore, this mega-earthquake shows the need to team together seismologists and engineers because we need simple, yet robust, soil models able to reproduce these observations with few parameters than can be used in numerical predictions of near-field ground motion that include nonlinear site effects.

## INTRODUCTION

The near surface geological site conditions in the upper tens of meters are one of the dominant factors in controlling the amplitude and variation of strong ground motion, and the damage patterns that result from large earthquakes. It has long been known that soft sediments amplify the earthquake ground motion. Superficial deposits, especially alluvium type, are responsible for a remarkable modification of the seismic waves. The amplification of the seismic ground motion basically originates from the strong contrast between the rock and soil physical properties (e.g. Kramer, 1996). At small deformations, the soil response is linear: strain and stress are related linearly by the rigidity modulus independently of the strain level (Hooke's law). Mainly because most of the first strong motion observations seemed to be consistent with linear elasticity, seismologists generally accept a linear model of ground motion response to seismic excitation even at the strong motion level. However, according to laboratory studies (e.g. Seed and Idriss, 1969), Hooke's law breaks down at larger strains and the nonlinear relation between strain and stress may significantly affect the strong ground motion at soil sites near the source of large earthquakes.

Since laboratory conditions are not the same as those in the field, several authors have tried to find field data to understand nonlinear soil behavior. In order to isolate the local site effects, the transfer function of seismic waves in soil layers is estimated by calculating the spectral ratio between the motion at the surface and the underlying soil layers. Variation of these spectral ratios between strong and weak motion has actively been searched in order to detect nonlinearity. For example, Darragh and Shakal (1991) observed an amplification reduction at the Treasure Island soft soil site in San Francisco. Beresnev and Wen (1996) also reported a decrease of amplification factors for the array data in the Lotung valley (Taiwan). Such a decrease has also been observed at different Japanese sites including the Port Island site (e.g. Satoh et al., 1997, Aguirre and Irikura, 1997). On the other hand, Darragh and Shakal (1991) also reported a quasi-linear behavior for a stiff soil site in the whole range from 0.006 g to 0.43g. Following these results, there is a need to precise the thresholds corresponding to the onset of nonlinearity and the maximum strong motions amplification factors according to the nature and thickness of soil deposits (Field et al., 1998; Bonilla et al., 2003).

However, nonlinear effects can also directly be seen on acceleration time histories. This is the case when pore pressure takes place during liquefaction. In addition, Iai et al., (1995), Archuleta (1998), and Bonilla et al., (2005) showed that the appearance of large acceleration peak values riding a low frequency carrier is an indicator of soil nonlinearity known as cyclic mobility. Laboratory studies show that the physical mechanism that produces such phenomenon is the dilatant nature of cohesionless soils, which introduces the partial recovery of the shear strength under cyclic loads. This recovery translates into the ability to produce large deformations followed by large and spiky shear stresses. The spikes observed in the acceleration records are directly related to these periods of dilatancy and generation of pore pressure. These examples indicate that nonlinear soil phenomena are complex.

With the increasing computer power, it is possible to perform large-scale (i.e. dozens of kilometers) simulations of the ground motion that includes the complexity of the source, the propagation media, and site effects (e.g. Cui et al., 2010). Yet, it is still difficult to assess large-scale nonlinear site response, namely due to the lack of knowledge of the dynamic properties of the media as well as the necessity of broadband simulations so that nonlinear effects can be triggered. It is well known that 3D elastic properties are already expensive to obtain; 3D soil characterization with dynamic parameters needed by nonlinear rheologies could easily become prohibitive. For these reasons, large-scale 3D nonlinear simulations performed by the engineering community basically comprehends well-characterized sites of few dozens of meters such as earth dams, bridges, wharfs, among others that may include soil-structure interaction (e.g. Lu et al., 2011). These studies share the same name, large-scale analyses; however, they differ in several orders of magnitude of the studied area dimensions.

On the afternoon of March 11th, 2011, an earthquake of magnitude Mw 9 occurred off the Pacific coast of Tohoku, Japan (Japan Meterological Agency, JMA hereafter, 2011). This event is one of the largest earthquakes in the world that has been well recorded in the near vicinity of the source (NIED, 2011). The estimated fault plane is 500 km along strike in the northeastern part of Japanese mainland and 200 km along dip (Simons et al., 2011). This event brought devastating damages especially by the tsunami that took place after the main shock. Yet, the recorded ground motions were also very large. The observed PGA values from K-NET and KiK-net showed large accelerations for many sites (19 sites having PGA values larger than 1 g) and strong motion duration longer than 80 s (time interval between 5% and 95% of the Arias intensity). This event produced a wealth of data showing different types of nonlinear soil behavior, going from traditional high frequency deamplification to liquefaction. These phenomena could be seen on the records of sites at soft soils over a large area along the fault's rupture including Miyagi, Chiba and Tokyo prefectures (Bonilla et al., 2011). This event brings the necessity of studying a large area that suffered not only traditional site effects, but also strong nonlinear soil response, with the aggravating factors of near field and finite fault effects. Therefore, we need to team seismologists and earthquake engineers to study events like this, and eventually be able to predict, reasonably well, ground motion incorporating earthquake physics and soil dynamics in a realistic way.

In this paper we show site-specific examples of the complexity of dynamic soil characterization that is needed to perform nonlinear site response studies. We revisit the 1994 Northridge earthquake to see what large-scale nonlinear effects were encountered and 2D numerical simulations that may explain the observations. Finally, we show some results from the 2011 Tohoku earthquake displaying other nonlinear signatures. We expect to demonstrate, through these examples, the complexity of these phenomena and the need to study them for a better seismic hazard assessment.

## SITE CHARACTERIZATION TO STUDY NONLINEAR SITE RESPONSE

Site characterization studies have different goals for seismologists and earthquake engineers. Traditionally, seismologists work on elastic and viscoelastic wave propagation in complex media. This means, that P and S wave speeds, density, $Q_P$ and $Q_S$ values characterize the media (e.g. Magistrale et al., 2000). In addition to these parameters, earthquake engineers also need information about the dynamic properties of the different materials. To name a few, lithology composition to see the type of material (e.g. sand, clay, silt); water content (dry, saturated or partially saturated material); cohesion and friction angle (material strength); liquefaction resistance laboratory tests; shear modulus reduction and damping ratio curves (e.g. Heuze et al, 2004). The type and number of geotechnical parameters depend on the constitutive soil model used in the numerical simulations. Figure 1 shows acceleration records, surface and down-hole, of the 1995 Kobe earthquake at Port Island (left) and the 1993 Kushiro-Oki earthquake at Kushiro Port (right). Both sites have shear wave velocity profiles relatively close each other, except in the first 30 meters depth. Yet, their response is completely different. Port Island is a man-made site composed of loose sands that liquefied during the Kobe event (Aguirre and Irikura, 1995). Practically there is no energy after the S-wave train in the record at the surface. Conversely, Kushiro Port is composed of dense sands and shows, in the accelerometer located at ground level, large acceleration spikes that are even higher than their counterpart at depth. Iai et al. (1995) studied the Kushiro Port records and they showed that this type of behavior comes from dilatant properties of dense sands. They used triaxial laboratory tests on frozen samples to determine the dynamic characteristics of the material. A linear or equivalent-linear model will never reproduce such behavior. For this reason, nonlinear site analyses are quite expensive. Needless to say that such kind of site characterization in two and three dimensions makes these studies prohibitive. Before going into the details of nonlinear simulations, we can still use the "traditional" properties to detect nonlinear effects. This will be done with examples using KiK-net stations.

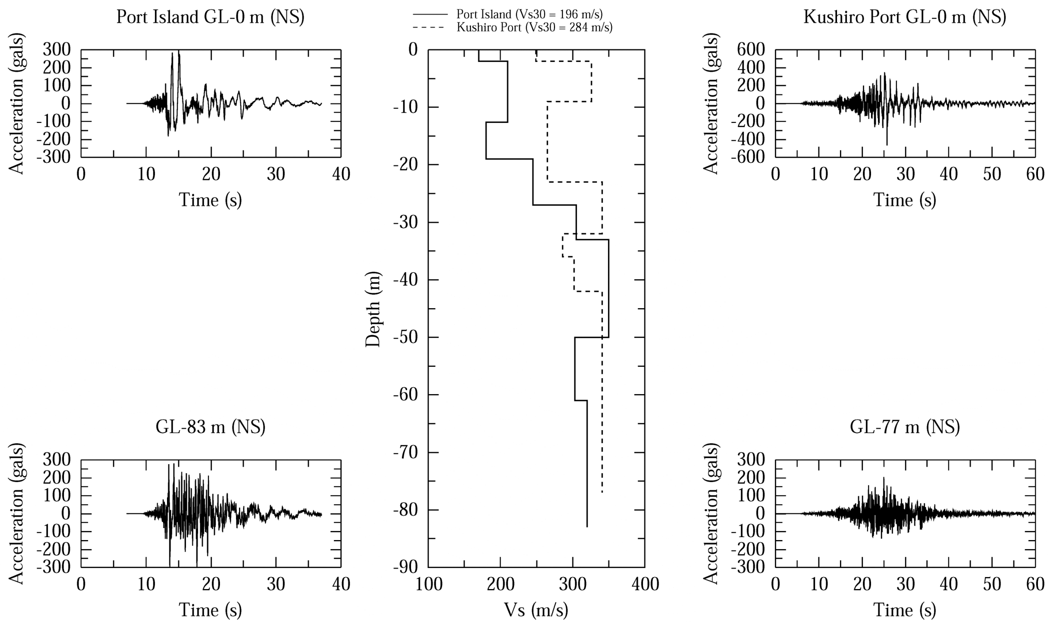


*Fig 1. Surface and borehole records of the 1995 Kobe earthquake at Port Island (left), and the 1993 Kushiro-Oki earthquake at Kushiro Port (right). The middle panel shows the shear wave velocity distribution at both sites.*

The Kiban-Kyoshin Network (KIK-net), in Japan, is composed by about 700 stations with surface and borehole high sensitivity triaxial accelerometers (Aoi et al., 2000). Most of the KiK-net sites have borehole stations 100 m or 200 m below the surface; however, there are about 20 exceptions where depths of boreholes are deeper than a few hundred meters. In addition, geological information and borehole logging are available.

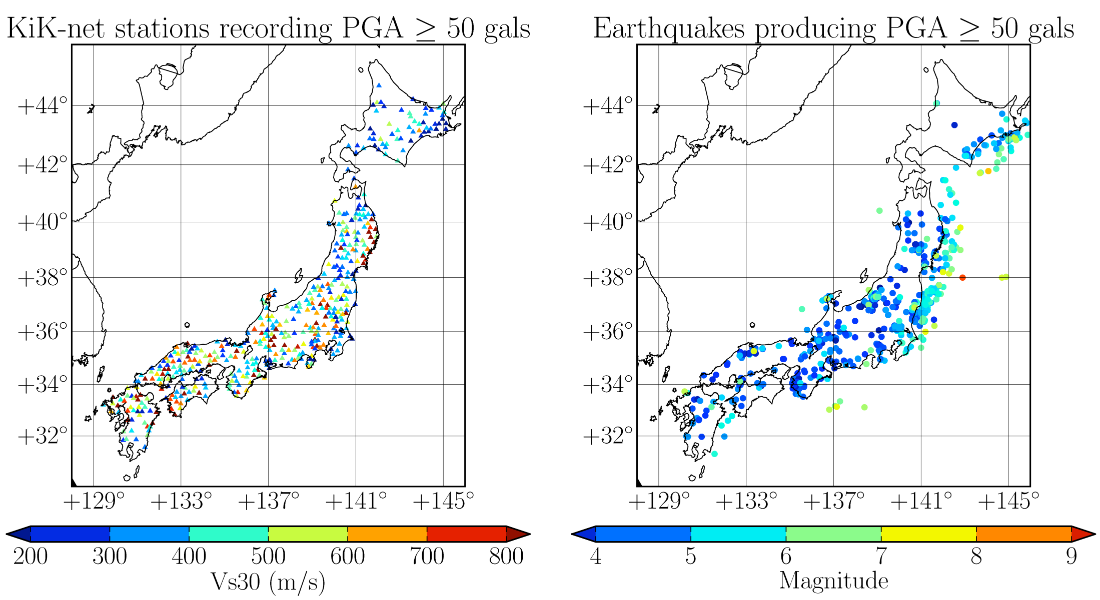


*Fig. 2. Map showing the location of KiK-net stations that recorded a PGA greater than 50 gals (left) and the related events (right).*

Figure 2 shows the location of KiK-net stations that recorded a PGA grater than 50 gals (left) and the corresponding events (right). This figure illustrates the wealth of data that potentially could be used to study nonlinear site response. Indeed, this network is exceptional because it has site characterization, high quality data, and the site effect can be isolated by simple surface-to-borehole spectral ratios (Kawase, 2006). Figure 3 shows the statistics of Vs30 of KiK-net stations as a function of the maximum and minimum shear wave speeds, $Vs_{max}$ (left) and $Vs_{min}$ (right), respectively. The distribution of Vs30 indicates that most of stations have values less than 500 m/s; whereas the maximum shear wave speed is almost uniformly distributed between 500 and 3000 m/s. Furthermore, the majority of stations have a minimum shear wave speed less than 200 m/s. These two plots suggest that it is likely to find places with a combination of strong impedance contrast and a superficial layer with low shear wave speed.

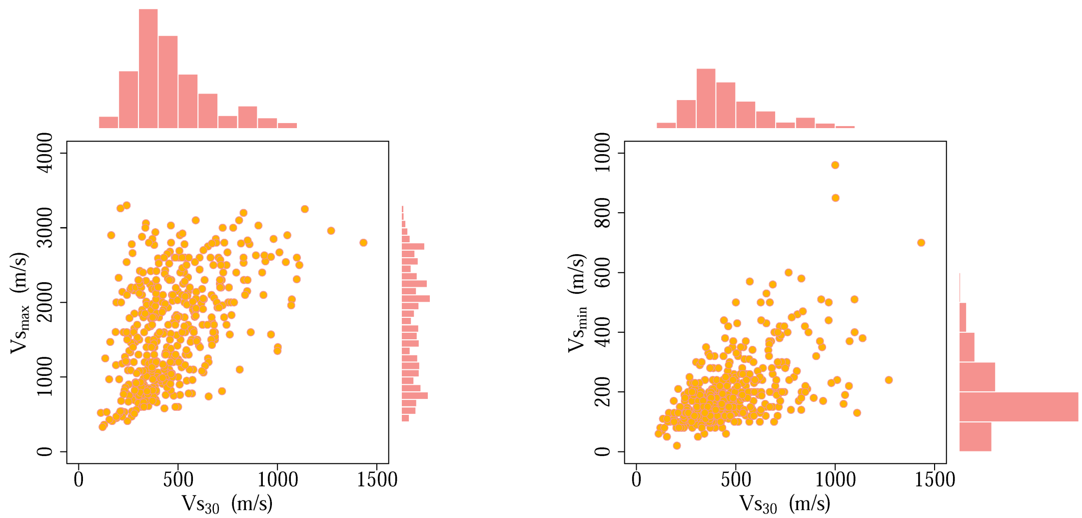


*Fig. 3. Distribution of Vs30 as a function of maximum (left) and minimum (right) shear wave speeds for the KiK-net stations.*

Figure 4 shows an example of nonlinear soil behavior at station TTRH02 ($Vs_{30}$ = 340 m/s), KiK-net station that recorded the $M_{JMA}$ 7.3 October 2000 Tottori in Japan. The orange shaded region represents the 95% borehole transfer function computed using events having a PGA less than 10 cm/s$^2$. Conversely, the solid line is the borehole transfer function obtained using the data from the Tottori main shock. One can see the difference between these two estimates of the transfer function, namely a broadband deamplification and a shift of resonance frequencies to lower values. The fact that the linear estimate is computed at the 95% confidence limits means that we are confident that this site underwent nonlinear at a 95% probability level.

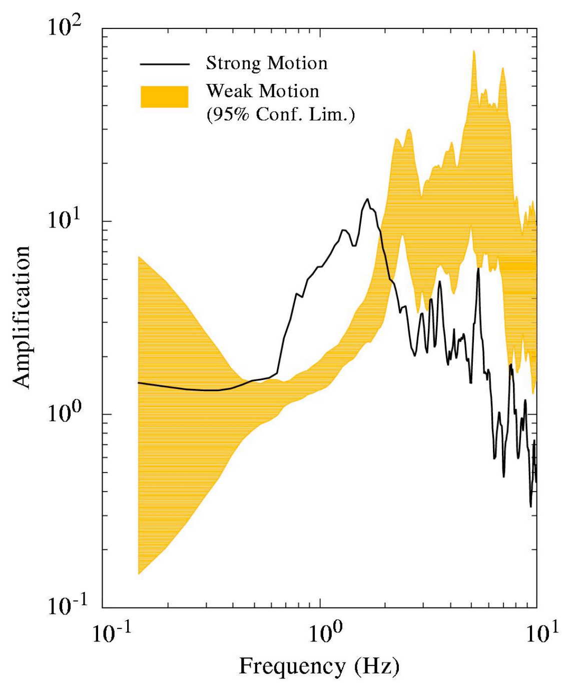


*Fig. 4. Borehole transfer functions computed at KiK-net station TTRH02 in Japan. The orange shaded area represents the 95% confident limits of the transfer function using weak-motion events (PGA < 10cm/s$^2$). The solid line is the transfer function computed using the October 2000 Tottori main shock data.*

In addition, another kind of analysis is the study of the statistical distribution of recorded PGA or spectral accelerations at depth and at the surface (Bonilla et al., 2003). The idea is that under nonlinear soil behavior, the observed acceleration at the surface will become less and less amplified. From Fig. 4, we expect that this effect will be greater at higher frequencies. Figure 5 shows the results for two spectral accelerations at 1 and 3 Hz and the PGA, respectively. The data corresponds to Fig. 2 and includes the 2011 Tohoku earthquake. Figure 5 shows surface-to-borehole acceleration relation depending on event magnitude and Vs30 bins.

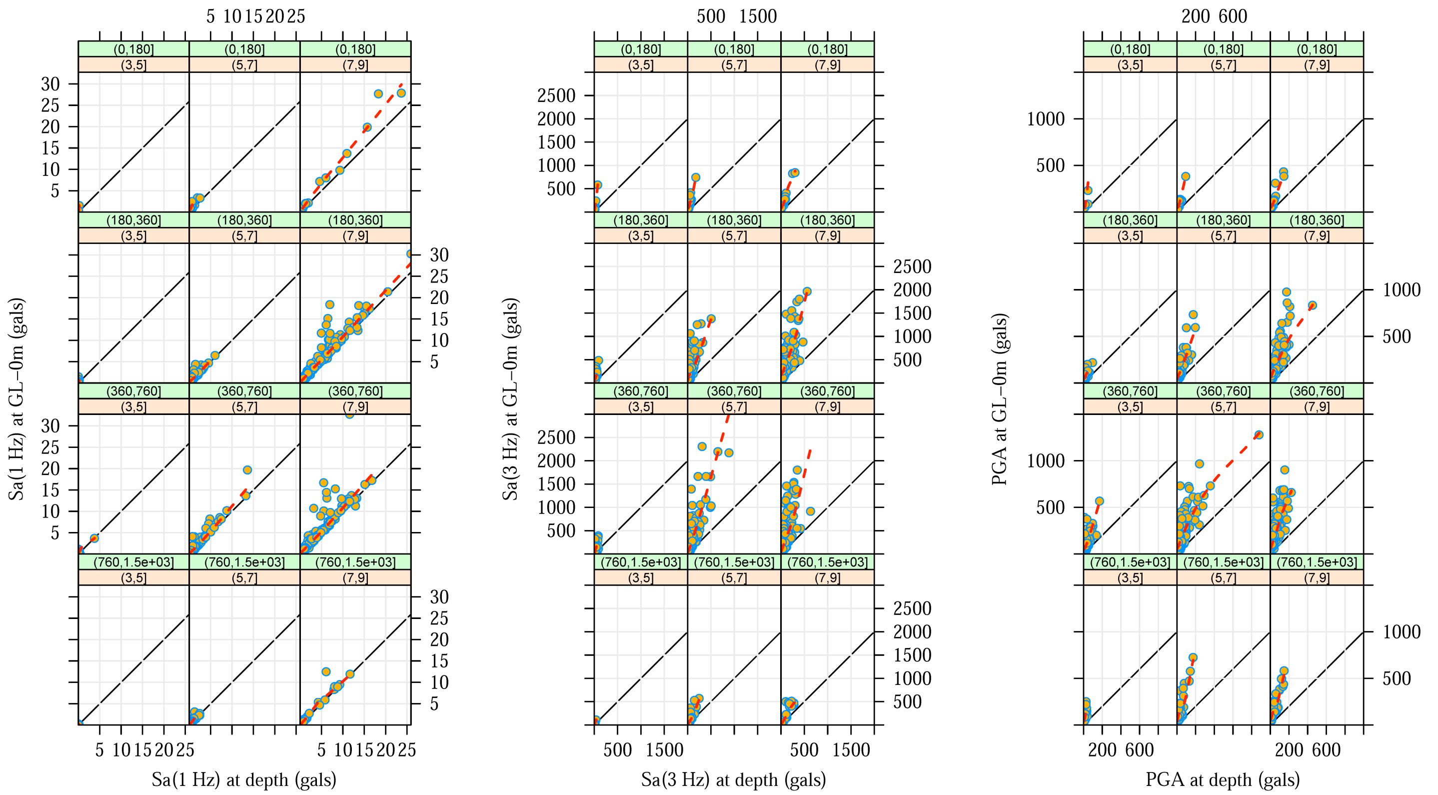


*Fig. 5. Observed acceleration at depth and at the surface as a function of event magnitude and Vs30 values. The accelerations are at 1 Hz (left), 3 Hz (middle), and the PGA (right).*

Can nonlinear effects be seen? It is quite difficult to answer this question. For example, the PGA shows some signs of nonlinear behavior for events having a magnitude between 5 and 9 and sites having a Vs30 between 180 and 760 m/s (2 bins of magnitude and Vs30 combined). In addition, there is amplification for the 2011 Tohoku earthquake spectral accelerations at 1 Hz at stations having a Vs30 less than 180 m/s. This is different for lower magnitude events, where the spectral accelerations are almost the same at surface and depth at this particular wavelength. These two facts may suggest that nonlinear phenomena took place. Yet, the most interesting feature is that both PGA and accelerations at 3 Hz, recorded at the surface, are always amplified with respect to the observations at depth. Because of this, such kind of representation is not enough to clearly reveal nonlinear effects compared to the frequency domain representation as shown in Fig. 4. Nonetheless, this kind of analyses is worthy in the sense that we still need to find a simple index of material nonlinearity, and PGA is not very conclusive. Finally, these observations constitute empirical constraints for nonlinear simulations.

## SITE-SPECIFIC STUDIES: THE 1987 SUPERSTITION HILLS EARTHQUAKE

On 24 November 1987, the $M_L$ 6.6 Superstition Hills earthquake was recorded at the Wildlife Refuge station. This site is located in southern California in the seismically active Imperial Valley. In 1982, the U.S. Geological Survey instrumented this site with downhole and surface accelerometers and piezometers to record ground motions and pore water pressures during earthquakes (Holzer et al., 1989). The Wildlife site is located in the flood plain of the Alamo River, about 20 m from the river's western bank. *In situ* investigations have shown that the site stratigraphy consists of a shallow silt layer approximately 2.5 m thick underlain by a 4.3 m thick layer of loose silty sand, which is in turn underlain by a stiff to very stiff clay. The water table fluctuates at about 2 m depth (Matasovic and Vucetic, 1993).

This site shows historically one direct *in situ* observation of nonlinearity in borehole data. The Wildlife Refuge liquefaction array recorded acceleration at the surface and 7.5 m depth, and pore pressure on six piezometers at various depths of the Superstition Hills earthquake (Holzer et al., 1989). Figure 6 (left) shows the acceleration time histories at GL-0 m and GL-7.5 m, respectively. Note how the acceleration changes abruptly for the record at GL-0 m after the S wave. Several sharp peaks are observed; they are very close to the peak acceleration for the whole record. In addition, these peaks have lower frequency than the previous part of the record (the beginning of the S wave, for instance).

Zeghal and Elgamal (1994) used the Superstition Hills earthquake to estimate the stress and strain from borehole acceleration recordings. They approximated the shear stress and the mean shear strain at GL-2.9 m through linear interpolation (Fig. 6). This figure shows the large nonlinearity developed during this event. The stress-strain loops form an S-shape and the strains are as large as 1.5%. At this depth, there is a piezometer (P5 according to Holzer et al., 1989). With this information it is also possible to reconstruct the stress path (bottom right of Fig. 6). Note that some of the pore pressure pulses are correlated with episodes of high shear stress development. The stress path shows a strong contractive phase followed by dilatancy when the effective mean stress is close to 15 kPa. Nowadays, there are several vertical arrays installed in different parts of the world, which couple accelerometers and pore pressure transducers that will help to better capture nonlinear effects. Examples of these arrays are the Lotung array in Taiwan (Abrahamson et al., 1987); Garner Valley array in Southern California (Archuleta et al., 1992), CORSSA array in the Aegean region in Greece (Pitilakis et al., 2004), Llolleo array in Chile (Verdugo, 2009), Belleplaine array in the French Lesser Antilles (Gueguen et al., 2011) to name a few.

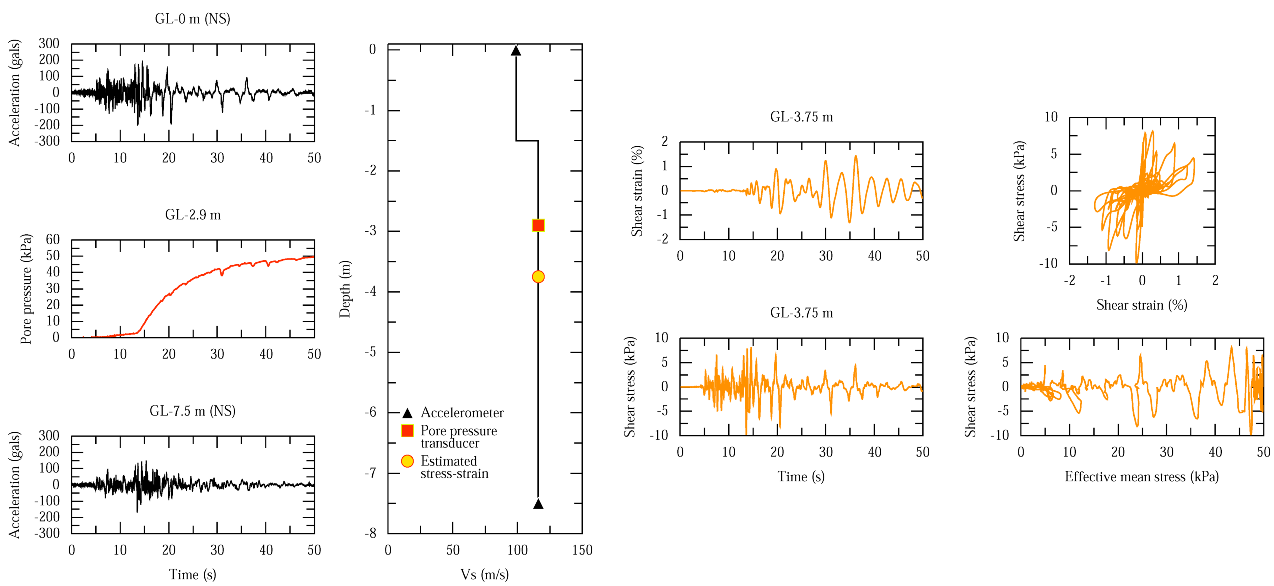


*Fig. 6. Wildlife Refuge station that recorded the 1987 Superstition Hills earthquake both acceleration and pores pressure time histories (left). Computed stress and strain time histories according to Zeghal and Elgamal (1994), stress-strain loops and stress path history reconstitution (right).*

Using the stress and stress time histories at GL-2.9 m computed earlier, Bonilla et al. (2005) performed a trial-and-error procedure in order to obtain the dilatancy parameters that best reproduce such observations. Figure 7 compares the computed shear stress time history with the observed shear strain at GL-2.9 m. The stress-strain hysteresis loops are also shown. We observe that the computed shear stress is well simulated; the stress-strain space also shows the same dilatant behavior (S-shape hysteresis loops) as the observed data. Once the model parameters were determined, they proceeded to compute the acceleration time history at GL-0 m using the north–south record at GL-7.5 m as input motion. Figure 8 shows the accelerograms (left) and the corresponding response spectra (right). The observed data are shown with no filtering, whereas the computed data are low-pass filtered at 10 Hz. The computed accelerogram shows the transition from high-frequency content between 0 and 15 sec to the intermittent spiky behavior after 15 sec. The response spectra show that the computed accelerogram accurately represents the long periods; yet, the short periods are still difficult to model accurately. This is one of the challenges of nonlinear simulations; the fit should be as broadband as possible.

## EMPIRICAL EVIDENCE OF WIDESPREAD NONLINEAR RESPONSE: THE 1994 NORTHRIDGE EARTHQUAKE

The M 6.7, January 1994, Northridge earthquake in southern California stimulated studies on the extent of nonlinear soil behavior in the epicentral area (Field *et al.,* 1997; Beresnev *et al.,* 1998a,b; Field *et al.,* 1998; Hartzell, 1998; Su *et al.,* 1998; Cultrera *et al.,* 1999). These studies were facilitated by the fact that this event was well recorded by many of the permanent strong-motion stations as well as to a rapid deployment of portable instruments after the main shock. The Northridge aftershock database allowed calculation of site-specific weak-motion responses at the sites that also recorded strong ground motions with accelerations exceeding several hundred gals. Therefore, accurate responses at the same soil sites to both weak and strong motions could have been compared, with implications for ground nonlinearity. These studies suppose that weak-motion will excite linear response as opposed to strong-motion where nonlinear effects may take place.

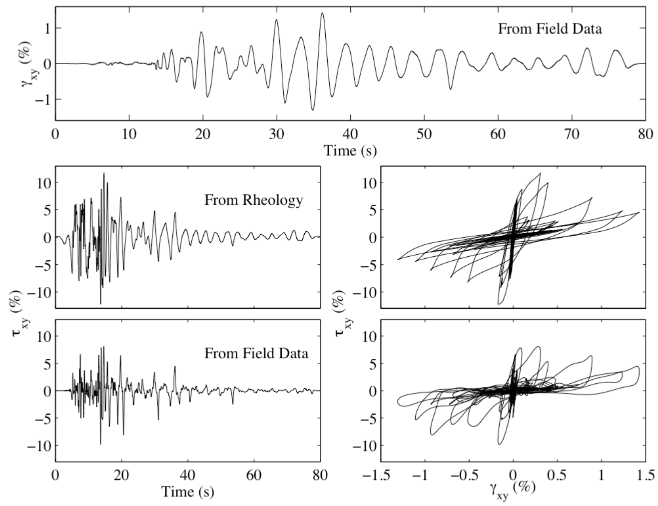


*Fig. 7. The top panel shows the computed strain time history at the middle of the borehole. Middle panels show the computed stress by trial-and-error using the Iai et al. (1990) model in order to find the best dilatancy parameters. Bottom panels indicate the computed stress time history from acceleration records (after Bonilla et al., 2005).*

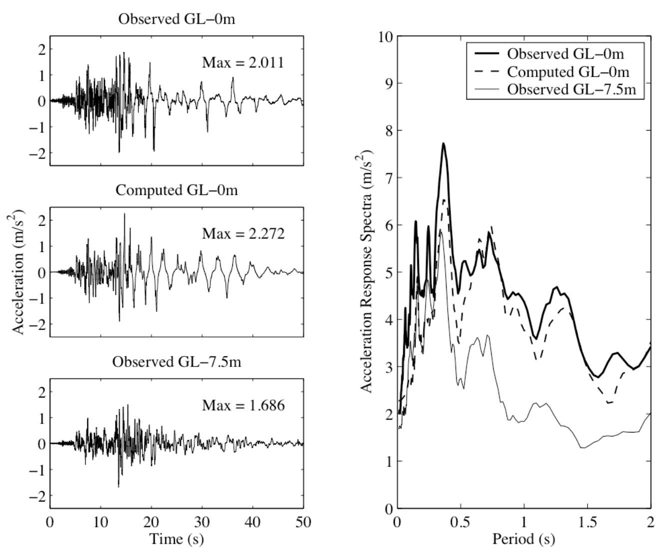


*Fig. 8. Observed and computed acceleration time histories of the 1987 Superstition Hills earthquake (left) and their corresponding response spectra (right) (after Bonilla et al., 2005).*

Field et al. (1997) used the linear-to-nonlinear response ratio to statistically infer nonlinear effects in the sediment sites that recorded both the main shock and aftershock data from the Northridge sequence. Since nonlinear response is usually lower than linear response, this ratio should be greater than one. Figure 9 (left) shows their result, where the mean (red line) and the 95% confidence limits (yellow shaded area) are displayed. As shown in previous sections, nonlinear effects deamplify high frequencies, thus we should expect that the linear-to-nonlinear response ratio should be greater than one at higher frequencies. This is not the case, Fig. 9 shows that the affected frequency band lies between 0.8 and 5.5 Hz. This was one of the first studies showing widespread nonlinear effects in the epicentral area. Yet, why sediment nonlinearity was affected at such intermediate frequencies?

An attempt to answer this question is by studying the 2D response of a small basin with inclined incident wavefield. Indeed, Fig. 9 (right) shows that the aftershocks may not necessarily arrive to the seismic stations with vertical incidence because they are quite close to the receivers. In order to reduce the model's size we propagate a plane wave with three angles of incidence into a relatively small basin in Nice, France, which has a 3D velocity model and whose soil nonlinear dynamic parameters have been estimated from literature (GEMGEP, 2000).

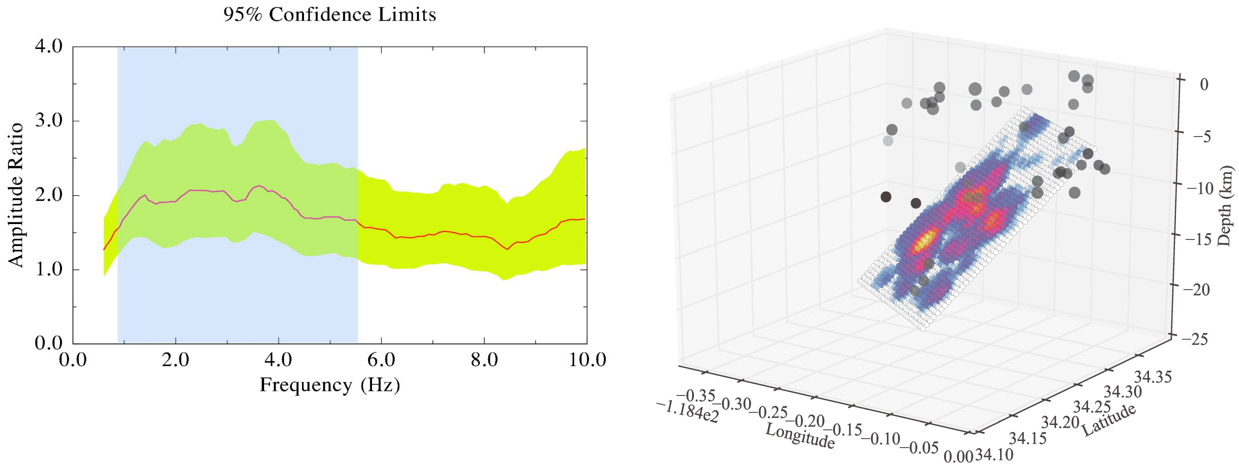


*Fig. 9. Mean and 95% confidence region of all the weak- to strong-motion site response ratios (left) (modified from Field et al., 1997). Northridge's aftershocks and slip distribution on the fault plane according to Zeng and Anderson (2000) (right).*

From the 3D model, we extract a 2D profile of 125 m deep and 2.5 km length. The minimum and maximum shear wave velocity is 180 and 1400 m/s in the sediments (obtained from SPT-Vs correlations) and bedrock, respectively. In the absence of information regarding P wave speed, we assume a Poisson's coefficient of 0.4. The quality factor values $Q_P$ and $Q_S$ are estimated as one tenth of the P and S wave speeds, respectively. The computations are carried out up to 10 Hz and the numerical spatial and time steps are 0.5 m and $10^{-4}$ s. We use a 2D P-SV finite differences scheme with Saenger et al. (2000) stencil. The nonlinear soil behavior is the one proposed by Towhata and Ishihara (1985) and Iai et al. (1990). For the source, we use a synthetic accelerogram simulating a M6 earthquake located at 8 km hypocentral distance and having a PGA of 0.2 g.

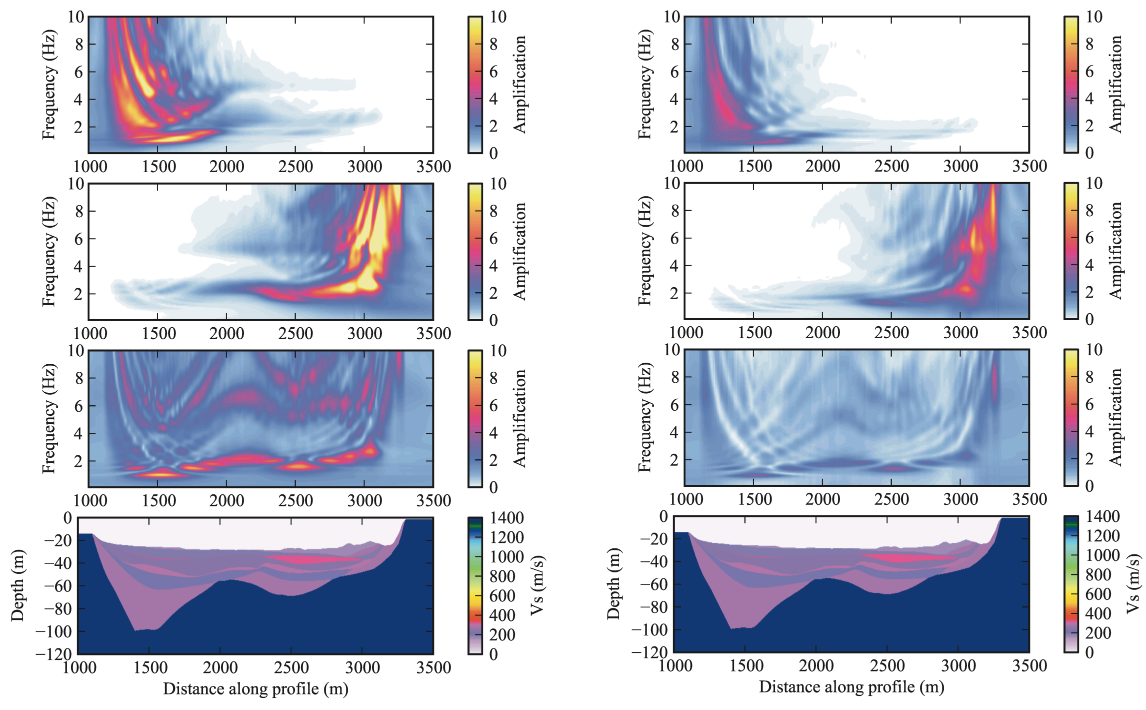


*Fig. 10. 2D linear (left) and nonlinear (right) basin response of Nice, France.*

Figure 10 shows the basin response for the linear (left) and nonlinear (right) cases. Top panels correspond to the basin amplification for an incident plane wave at $35^0$ to the right; the second panels show the results for an inclined wave at $35^0$ to the left; the third panels correspond to the case of vertical incidence, and the bottom panels display the S wave velocity model. The first thing that we observe is the deamplification of the ground motion for the nonlinear case. However, nonlinear basin responses for the inclined wavefield are not as much deamplified compared to the vertical incidence. This is due to the fact that inclined waves do not traverse the nonlinear media as if they were impinging vertically. In other words, the effective thickness for an inclined wave is smaller than the vertically incident case. Therefore, nonlinear effects are less pronounced.

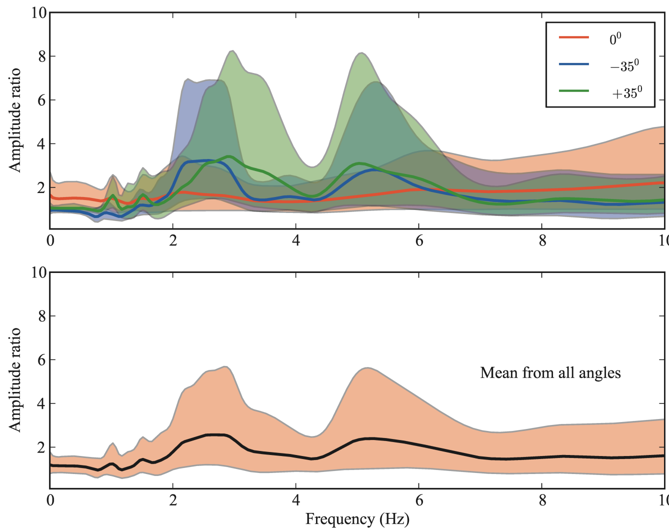


*Fig. 11. Geometric mean and 68% confidence limits of linear-to-nonlinear response ratio for receivers within the basin. The top panel shows individual results for each angle of incidence. Bottom panel shows the combined amplitude ratio for all angles.*

Following Field et al. (1997), we compute the linear-to-nonlinear response ratio for all receivers in the basin. First, we compute the geometric mean of these ratios for each angle of incidence. In a second time, we obtain the geometric mean of ratios for all angles (Fig. 11). This figure shows two things. The first is that linear-to-nonlinear response ratio is almost flat for vertical incidence. However, for the case of inclined wavefield, the linear-to-nonlinear response ratio shows two bumps at 2.5 and 4.5 Hz. When averaging all angles, these bumps are still present at these intermediate frequencies. These numerical tests suggest that the results from Field et al. (1997) may be due to the fact that they used aftershock data having angles of incidence different than the vertical. Furthermore, these results imply that 3D simulations may be needed if we want to correctly take into account the effect of the incident wavefield into the nonlinear sediments.

## THE 2011 TOHOKU EARTHQUAKE

On the afternoon of March 11th, 2011, an earthquake of magnitude Mw 9 occurred off the Pacific coast of Tohoku, Japan (JMA, 2011). This event is one of the largest earthquakes in the world that has been well recorded in the near field by numerous stations at the surface (e.g. K-NET and KiK-net) and in boreholes (KiK-net). Bonilla et al. (2011) selected 73 sites for which the recorded PGA at the surface (Euclidean norm of the horizontal components) of the Mw 9 Tohoku earthquake was higher than 50 gals (no criteria was imposed on the shear wave velocity at the borehole). Once these sites were identified, their linear response was computed using the data recorded between 1998 and 2009 having PGA's at the surface not exceeding 10 gals. Figure 12 (left) shows an example of four KiK-net stations having different Vs30 values where the linear borehole transfer function is characterized at 68% (dark gray area) and 95% (light gray area) confidence limits. The red line shows the nonlinear borehole transfer function computed using the main shock. The main shock is largely deamplified at high frequencies, and there is a shift of the predominant frequency to lower values. Furthermore, the frequency at which deamplification increases is proportional to the station's Vs30. For example, station IBRH16 (Vs30 = 626 m/s) deamplifies around 7 Hz; whereas station MYGH04 (Vs30 = 850 m/s) deamplifies around 12 Hz. In order to see the average nonlinear behavior for all KiK-net stations, we followed the same procedure as Field et al. (1997) for the Northridge earthquake. Figure 12 (right) shows the mean borehole response ratio as a function of Vs30. For this earthquake, nonlinear soil effects increase with decreasing Vs30 values. This figure indicates a broadband nonlinear behavior for soils having Vs30 < 800 m/s, from 3-6 to 30 Hz. Another interesting result is the presence of nonlinear behavior even at sites having Vs30 > 800 m/s following NEHRP (1994) soil classification. Their velocity profiles show that the first 10 m have a shear wave velocity ranging from 200 to 400 m/s, which may explain these observations. These are average results; more studies are needed to assess the uncertainties related to these observations. These results are quite different than those of Field et al. (1997). In this study the borehole transfer functions do not have source and path effects. In addition, the linear response is obtained from hundreds of events, including aftershocks, so particular path effects and angles of incidence are averaged and the resulting transfer functions are smoothed (Kawase, 2006). This represents an advantage to surface arrays. Yet, we need to reconcile the Northridge and the Tohoku studies, in order to better understand the origin of nonlinear soil behavior signature.

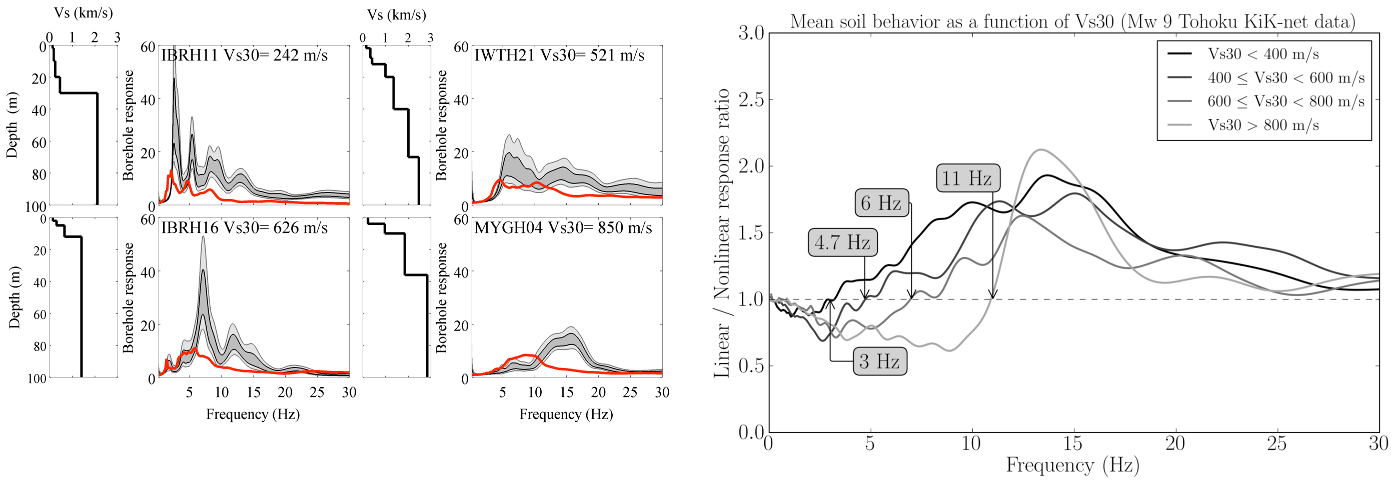


*Fig. 12. Example of KiK-net stations where linear borehole response is computed at 68% (dark gray area) and 95% (light gray area) confidence limits. Red line represents the nonlinear borehole response computed using the Mw 9 Tohoku data (left). Average linear-to-nonlinear borehole response ratios for all KiK-net sites for different Vs30 classes. Note the clear separation among classes and the broadband nonlinear response (3 to 30 Hz) for soils having Vs30 < 400 m/s (after Bonilla et al., 2011).*

## CONCLUSIONS

These are exciting times to study wave propagation in nonlinear media. The advance in earthquake physics and geotechnical earthquake engineering, plus the increasing computer power, make possible to tackle large-scale numerical simulations of realistic wave propagation including soil nonlinear behavior. Moreover, the densification of strong motion networks around the world help recording large events in the vicinity of the fracture zone. In some particular cases, coupled systems of accelerometers and pore pressure transducers help monitoring liquefaction and cyclic mobility prone areas. Most importantly, there is a lot of effort to make these data public; so various research groups could study these phenomena from different perspectives.

Nonlinear soil response depends on dynamic parameters that may be quite expensive to collect. However, in some cases they need to be obtained, for example when pore pressure takes place. This is a fundamental problem for handling large-scale studies. The cost of laboratory and *in situ* tests may become prohibitive. In addition, the number and type of test are correlated to the soil parameters needed for a given material rheology. In this sense, the analysis of recorded data for large events such as the Northridge and the Tohoku earthquakes is valuable to provide with empirical constraints to modelers. We advocate to the development of simple, yet robust constitutive equations that are able to reproduce these observations. This needs to be done by a close collaboration between the seismology and earthquake engineering communities.

Thus, what is the challenge of computing nonlinear soil response? There is no analytical solution to begin with. Indeed, every nonlinear observation is unique. The study of nonlinear soil physics, however, reveals the mechanisms that will be repeated in future earthquakes. This is already a major step. Second, as we have seen from the different examples presented before, soil nonlinearity has a broadband effect. Thus, there is a need of computing broadband time histories so that nonlinear effects can be triggered, which all seismologists know is not a trivial problem. Third, the analysis of the 2011 Tohoku records at KiK-net stations suggests that nonlinear behavior may be shallow. This is good news because there is no need to expensive material dynamic characterization up to the bedrock. Finally, since the resulting ground motion depends on the source and soil dynamic properties, there is a need to quantify the uncertainty of the numerical predictions. One-dimensional studies can be easily done, but 2D and 3D analyses present a challenge and there is still some work to be done.


## ACKNOWLEDGEMENTS

We would like to thank the organizers of the ESG4 conference for the opportunity to contribute this paper. We are indebted to the National Research Institute for Earth Science and Disaster Prevention (NIED) in Japan for providing K-NET and KiK-net data; especially for their efforts in spite of all human and technical difficulties they faced during the 2011 Tohoku earthquake's aftermath.

REFERENCES


Abrahamson, N.A., B.A. Bolt, R.B. Darragh, J. Penzien, and T.B. Tsai [1987]. "The SMART 1 accelerograph array (1980 – 1987): A review", Earthquake Spectra, Vol. 3, pp. 263-287.

Aguirre, J. and K. Irikura [1997]. "Nonlinearity, Liquefaction, and Velocity Variation of Soft Soil Layers in Port Island, Kobe, during the Hyogo-ken Nanbu Earthquake", Bull. Seism. Soc. Am., Vol. 87, pp. 1244-1258.

Aoi, S., K. Obara, S. Hori, K. Kasahara, and Y. Okada [2000]. "New Japanese uphole-downhole strong-motion observation network: KiK-net", Seis. Res. Lett., Vol. 72, p. 239.

Archuleta, R.J., S.H. Seale, P.V. Sangas, L.M. Baker, and S.T. Swain [1992]. "Garner Valley downhole array of accelerometers: instrumentation and preliminary data analysis", Bull. Seism. Soc. Am., Vol. 82, pp. 1592-1621. (Correction, Bull. Seism. Soc. Am., Vol. 83, p. 2039).

Archuleta, R. J. [1998]. "Direct observation of nonlinear soil response in acceleration time histories", Seism. Res. Lett., Vol. 69, p. 149.

Beresnev, I. A., and K. L. Wen (1996). "Nonlinear site response - a reality?", Bull. Seism. Soc. Am., Vol. 86, pp. 1964-1978.

Beresnev, I. A., G. M. Atkinson, P. A. Johnson, and E. H. Field [1998a]. "Stochastic finite-fault modeling of ground motions from the 1994 Northridge, California, earthquake. II. Widespread nonlinear response at soil sites", Bull. Seism. Soc. Am., Vol. 88, pp. 1402-1410.

Beresnev, I. A., E. H. Field, K. Van Den Abeele, and P. A. Johnson [1998b]. "Magnitude of nonlinear sediment response in Los Angeles basin during the 1994 Northridge, California, earthquake", Bull. Seism. Soc. Am., Vol. 88, pp. 1079-1084.

Bonilla, L.F., F. Cotton, and R.J. Archuleta [2003]. "Quelques renseignements sur les effets de site non-lineaires en utilisant des donnees de forage: la base de mouvements forts Kik-net au Japon", *Proceedings 6me Colloque National AFPS*, *1-3 Juillet, Ecole Polytechnique, Palaiseau.*

Bonilla, L.F., R.J. Archuleta, and D. Lavallee [2005]. "Hysteretic and Dilatant Behavior of Cohesionless Soils and Their Effects on Nonlinear Site Response: Field Data Observations and Modeling", Bull. Seism. Soc. Am., Vol. 95, pp. 2373-2395.

Bonilla, L.F., K. Tsuda, N. Pulido, J. Regnier, and A. Laurendeau [2011]. "Nonlinear site response evidence of K-NET and KiK-net records from the 2011 off the Pacific coast of Tohoku Earthquake", Earth Planets Space, Vol. 63, pp. 1-5.

Cui, Y., K. B. Olsen, T. H. Jordan, K. Lee, J. Zhou, P. Small, D. Roten, G. P. Ely, D. K. Panda, A. Chourasia, J. Levesque, S. M. Day, and P. J. Maechling [2010], "Scalable earthquake simulation on petascale supercomputers", in *Proceedings of the 2010 ACM/IEEE International Conference for High Performance Computing, Networking, Storage, and Analysis*, New Orleans, Nov. 13-19, doi:10.1109/SC.2010.45.

Cultrera, G., D. M. Boore, W. B. Joyner, and C. M. Dietel [1999]. "Nonlinear soil response in the vicinity of the Van Norman Complex following the 1994 Northridge, California, earthquake", Bull. Seism. Soc. Am., Vol. 89, pp. 1214-1231.

Darragh, R.B., and A.F. Shakal [1991]. "The site response of two rock and soil station pairs to strong and weak ground motion", Bull. Seism. Soc. Am., Vol. 81, pp. 1885-1899.

Field, E. H., P. A. Johnson, I. A. Beresnev, and Y. Zeng [1997]. "Nonlinear ground-motion amplification by sediments during the 1994 Northridge earthquake", Nature, Vol. 390, pp. 599-602.

Field, E. H., Y. Zeng, P. A. Johnson, and I. A. Beresnev [1998]. "Nonlinear sediment response during the 1994 Northridge earthquake: observations and finite-source simulations", J. Geophys. Res., Vol. 103, pp. 869-883.

Gueguen, Ph., M. Langlais, P. Foray, Ch. Rousseau, and J. Maury [2011]. "A Natural Seismic Isolating System: The Buried Mangrove Effects", Bull. Seism. Soc. Am., Vol. 101, pp. 1073-1080.

GEMGEP phase 1 [2000]. “Risque sismique sur Nice: étude de scénarios de gestion de crise sismique. Définition de l’aléa, de la vulnérabilité et des enjeux”, *CETE Méditerranée, laboratoire de Nice*.

Hartzell, S. [1998]. “Variability in nonlinear sediment response during the 1994 Northridge, California, earthquake”, Bull. Seism. Soc. Am., Vol. 88, pp. 1426-1437.

Heuze, F., R.J. Archuleta, L.F. Bonilla, S. Day, M. Doroudian, A. Elgamal, S. Gonzales, M. Hoehler, T. Lai, D. Lavallee, B. Lawrence, P.C. Liu, A. Martin, L. Matesic, B. Minster, R. Mellors, D. Oglesby, S. Park, M. Riemer, J.H. Steidl, F. Vernon, M. Vucetic, J. Wagoner, Z. Yang [2004]. “Estimating site-specific strong earthquake motions”, Soil Dyn. and Earth. Eng., Vol. 24, pp. 199-223.

Holzer, T.L., T.L. Youd, and T.C. Hanks [1989]. “Dynamics of liquefaction during the 1987 Superstition Hills, California, earthquake”, Science, Vol. 244, pp. 56-59.

Iai, S., Y. Matsunaga, and T. Kameoka [1990]. “Strain Space Plasticity Model for Cyclic Mobility”, Report of the Port and Harbour Research Institute, Vol. 29, pp. 27-56.

Iai, S., T. Morita, T. Kameoka, Y. Matsunaga, and K. Abiko [1995]. “Response of a dense sand deposit during 1993 Kushiro-Oki Earthquake”, Soils and Foundations, Vol. 35, pp. 115-131.

Japan Meterological Agency [2011]. http://www.jma.go.jp/jma/en/2011_Earthquake.html.

Kawase, H. [2006]. “Borehole observation for site effect studies”, *Third International Symposium on the Effects of Surface Geology on Seismic Motion Grenoble, France, 30 August - 1 September 2006.*

Kramer, S.L. (1996). *“Geothechnical Earthquake Engineering”*, Prentice Hall, New Jersey.

Lu, J, Ahmed Elgamal, Linjun Yan, Kincho H. Law, and Joel P. Conte [2011]. "Large scale numerical modeling in geotechnical earthquake engineering." ASCE International Journal of Geomechanics (IJOG), doi:10.1061/(ASCE)GM.1943-5622.0000042.

National Earthquake Hazards Reduction Program (NEHRP) [1994]. Recommended provisions for seismic regulations for new buildings, *Federal Emergency Management Agency Report FEMA 222A, Washington, D.C.*

National Research Institute for Earth Science and Disaster Prevention (NIED) [2011]. http://www3.kyoshin.bosai.go.jp/k-net/topics/TohokuTaiheiyo_20110311/nied_kyoshin2e.pdf.

Magistrale, H., S. Day, R.W. Clayton, and R. Graves [2000]. “The SCEC Southern California Reference Three-Dimensional Seismic Velocity Model Version 2”, Bull. Seism. Soc. Am., Vol. 90, pp. S65-S76.

Matasovic, J., and M. Vucetic [1993]. “Analysis of seismic records obtained on November 24, 1987 at the Wildlife Liquefaction Array”, *Research Report, Civil Engineering Department, University of California, Los Angeles*.

Pitilakis, K., K. Makropoulos, P. Bernard, F. Lemeille, H. Lyon-Caen, C. Berge-Thierry, Th. Tika, M. Manakou, D. Diagourtas, D. Raptakis, P. Kallioglou, K. Makra, D. Pitilakis, and L.F. Bonilla [2004]. “The Corinth Gulf Soft Soil Array (CORSSA) to study site effects”, C. R. Geoscience, Vol. 336, pp. 353-365.

Saenger E., N. Gold, and S, Shapiro (2000). “Modeling the propagation of elastic waves using a modified finite-difference grid”, Wave Motion, Vol. 31, pp. 77-82.

Satoh, T., M. Horike, Y. Takeuchi, T. Uetake, and H. Suzuki [1997]. “Nonlinear behavior of scoria soil sediments evaluated from borehole records in Eastern Shizuoka Prefecture, Japan”, Earthquake Eng. Struct. Dyn., Vol. 26, pp. 781-795.

Seed, H.B. and I.M. Idriss [1969]. “Influence of soil conditions on ground motions during earthquakes”, J. Soil Mech. and Found. Div., ASCE, Vol. 95 (SM1).

Simons, M., S. E. Minson, A. Sladen, F. Ortega, J. Jiang, S. E. Owen, L. Meng, J-P. Ampuero, S. Wei, R. Chu, D. V. Helmberger, H. Kanamori, E. Hetland, A. W. Moore, and F.H. Webb [2011]. “The 2011 Magnitude 9.0 Tohoku-Oki Earthquake: Mosaicking the Megathrust from Seconds to Centuries”, Science, 10.1126 science.1206731.

Su, F., J.G. Anderson, and Y. Zeng [1998]. "Study of weak and strong ground motion including nonlinearity from the Northridge, California, earthquake sequence", Bull. Seism. Soc. Am., Vol. 88, pp. 1411-1425.

Towhata, I., and K. Ishihara [1985]. "Modeling Soil Behavior Under Principal Axes Rotation", *Fifth International Conference on Numerical Methods in Geomechanics*, Nagoya, pp. 523-530.

Verdugo, R. [2009]. "Amplification phenomena observed in downhole array records generated on a subductive environment", Physics of the Earth and Planetary Interiors, Vol. 175, pp. 63-77.

Zeghal, M., and A.-W. Elgamal [1994]. "Analysis of Site Liquefaction Using Earthquake Records", Jour. Geotech. Engrg., Vol. 120, No. 6, pp. 996-1017.

Zeng, Y., and J. Anderson [2000]. "Evaluation of numerical procedures for simulating near-fault long-period ground motions using Zeng method", *Report 2000/01 to the PEER Utilities Program, available at http://peer.berkeley.edu*