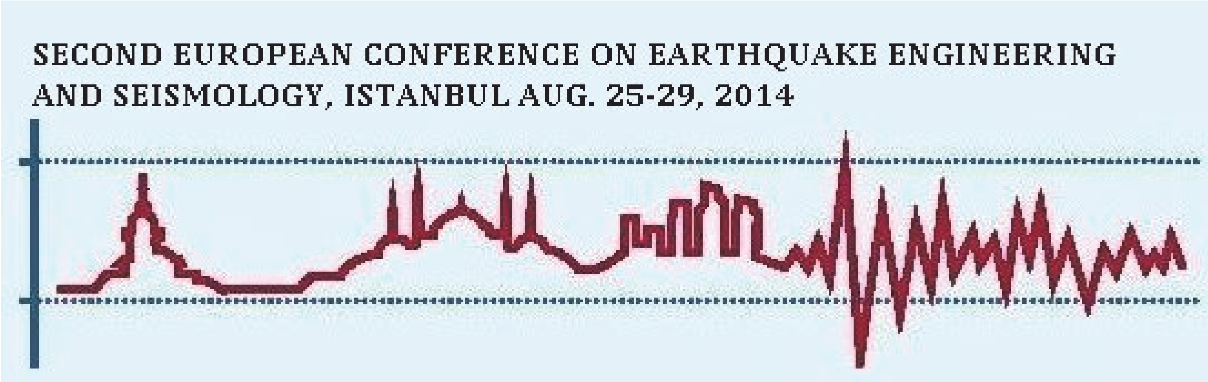


APPLICATION OF PGV/VS PROXY TO ASSESS NONLINEAR SOIL RESPONSE: FROM DYNAMIC CENTRIFUGE TESTING TO JAPANESE K-NET AND KIK-NET DATA

Johanes CHANDRA[1], Philippe GUEGUEN[2] and Luis Fabian BONILLA[3]

ABSTRACT

In this paper the soil nonlinear response is studied using dynamic centrifuge test and the Japanese K-NET and KiK-net data. The seismic interferometry by deconvolution method is first applied to extract the instantaneous shear wave velocity (*Vs*) profile of the vertical array. The soil nonlinear behavior is observed by monitoring the variation of shear wave velocity of the dynamic centrifuge test results. The variation of shear wave velocity is observed by considering weak and strong input motions at the base of the centrifuge's laminar container. Furthermore, the nonlinear soil response is assessed using the *PGA–PGV/Vs* proxy that is considered as a proxy of the stress-strain. We show that *PGA-PGV/Vs* is an effective stress-strain proxy, hence, demonstrate well the nonlinear behavior of the soil. Classical two-parameter hyperbolic model is inverted and we show that it fits well the data. Finally, these proxies are applied to the Japanese K-NET and KiK-net data, using Vs_{30} rather than the instantaneous *Vs*. The Vs_{30} is used for practical application on the related soil classification recommendation.

INTRODUCTION

The difficulty to predict the nonlinear response of soil is a key issue in seismic risk assessment, especially for site effects assessment and ground motion prediction. The observation of site nonlinear behavior became more apparent after the 1989 Loma Prieta earthquake (Chin and Aki, 1991), and is observed mostly in soft sediment site (e.g., Field et al., 1998; Bonilla et al., 2005), and less significant in hard rock site. The nonlinear response depends on the soil properties and the dynamic excitations such as earthquake motion. The nonlinear behavior is characterized by shear modulus (*G*) degradation, and variation of damping (ζ) during excitation. The nonlinearity produces site amplification reduction through increased damping and frequency response shifting towards lower frequencies related to *G* reduction. Thus, one way to observe the in-situ nonlinear behavior is by monitoring the variation of *G* and ζ over time.

In this paper, the soil nonlinear behavior is assessed by observing the shear wave velocity (*Vs*) variation. This can be done since *Vs* is directly related to *G* by the formula $Vs = \sqrt{G/\rho}$. We use the seismic interferometry by deconvolution method (Snieder and Şafak, 2006) rather than the traditional cross-correlation method to extract the shear wave velocity of the vertical array. Since the soil column

[1] PhD Candidate, Institut des Sciences de la Terre (ISTerre), Université Joseph Fourier, CNRS/IFSTTAR, Grenoble (France), johanes.chandra@ujf-grenoble.fr
[2] PhD, ISTerre, Université Joseph Fourier, CNRS/IFSTTAR, Grenoble (France), philippe.gueguen@ujf-grenoble.fr
[3] PhD, Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR), Paris (France), fabian.bonilla@ifsttar.fr

can be considered as a resonant system having a shear deformation (Dobry, 2013), this method can be applied to analyze the soil column response. The simplest way to observe nonlinear behavior is to trace the stress-strain curves. In this paper we use the stress-strain proxy proposed using *PGA* (Peak Ground Acceleration) as stress proxy, and *PGV* (Peak Ground Velocity)/*Vs* (Hill et al., 1993) and PGV/Vs_{30} (Idriss, 2011) as strain proxy. In this paper we use both instantaneous *Vs* and Vs_{30} which has different advantage that will be discussed in the following.

Although laboratory measurement can hardly exhibit the real site condition, it is still considered as the benchmark results considering the lack of real site data recording, especially in low-to-moderate seismic regions. The use of advanced dynamic laboratory centrifuge test is expected to recreate closer the initial mechanical properties of the soil and to maintain its boundary condition. After validation of the methods on the experimental laboratory data, we apply the same process to the dense Japanese K-NET and KiK-net data. The results of the nonlinear proxy and material model will be presented.

SEISMIC INTERFEROMETRY BY DECONVOLUTION

Seismic interferometry is used to extract the Green's function by cross-correlating the seismic responses between different receivers. By doing it, wave propagation from source to the reference receiver is removed, thus allowing the extraction of seismic response from receiver array (Wapenaar et al., 2010). We apply seismic interferometry by deconvolution rather than the cross-correlation method, such as expressed in Eq.(1).

$$D(\omega) = \frac{A_i(\omega)A_{ref}^*(\omega)}{\left|A_{ref}(\omega)\right|^2 + \varepsilon} \tag{1}$$

where $D(\omega)$ is the deconvolved waves, the ω symbol means that the process is done in frequency domain, $A_i(\omega)$ is the time history accelerogram recorded in the receiver *i*, and $A_{ref}(\omega)$ is the time history accelerogram recorded in the reference receiver. In this paper, we consider the top receiver of the vertical array as the reference receiver. The * symbol indicates the complex conjugate of the signal, and ε is the water level/stabilization parameter, and is set to be 10% of the average spectral power. This method has previously used, for example by Clayton and Wiggins (1976) on teleseismic bodywaves, and Nakata and Snieder (2012) on the Japanes KiK-net borehole data. The advantage of this method is the source independency and the capability of demonstrating the causal and acausal shear deformation propagation within the system. It also gives a more accurate estimation of time arrival between receivers. On the other side, it often has mixed between the causal and acausal waves on the first layer. Extracting the estimated time arrival using the deconvolution, the instantaneous shear wave velocity can be calculated directly by $Vs = \Delta h / \Delta t$, where Δh and Δt are the distance and estimated time propagation between two successive receivers, respectively.

PGA-PGV/VS AS STRESS-STRAIN PROXY FOR NONLINEAR ASSESSMENT

PGV/Vs has been used as strain proxy based on wave propagation (Hill et al., 1993). Idriss (2011) proposed the use of $PGA\text{-}PGV/Vs_{30}$ as a stress-strain proxy. This can be done since shear stress and shear strain are the spatial derivative of PGA and PGV/Vs following Eq.(2-3).

$$\tau = PGA \times \rho \times z \tag{2}$$

where τ is the shear stress, ρ is the mass density and z is the depth.

$$\gamma = \frac{du}{dx} = \frac{du/dt}{dx/dt} = \frac{PGV}{Vs} \tag{3}$$

where γ is the shear strain. In the first part to assess the effectiveness of the proxy, we focus on the use of *PGV/Vs*. Since *Vs* is the instantaneous shear wave velocity that changes depending on the excitation, the shear strain computed is the actual deformation and not the average velocity such is given by Vs_{30}. However, for practical engineering application the use of Vs_{30} is conformed to the recommended soil classification.

The data is then inverted to fit the classic two-parmeter nonlinear hyperbolic model (Seed et al., 1984) following Eq.(4).

$$\tau = \frac{G_0 \gamma}{1 + \frac{\gamma}{\gamma_r}} \quad (4)$$

where G_0 is the initial shear modulus correspond to the maximum shear modulus, and γ_r is the strain reference.

DYNAMIC CENTRIFUGE TESTING: BACKGROUND AND RESULTS

On the first application we use the previous explained methods to our dynamic centrifuge data. The dynamic centrifuge test is a scaled-down model that is expected to recreate the actual behavior of soil by increasing the gravity-scaled acceleration fields. The properties of scaled model can be scale easily to the real object's properties using the scaling factors in Table. 1, with N is the gravity scale used on the experimentation.

Table 1. Scaling factors from model to real object for centrifuge test

Parameter	Real Object/Model
Length, Displacement	N
Area	N^2
Volume, Mass	N^3
Velocity	1
Stress	1
Acceleration	1/N
Time	N
Frequency	1/N

The centrifuge test was performed at the French IFSTTAR (Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux) facility (Chazelas, 2010) at the 60 g scale. The typical model, dimensions and sensor distribution of the setups are presented in Fig. 1. We use equivalent shear-beam (ESB) containers to maintain the boundary condition of the soil. The dimension of the box is 800x350x416mm, which equivalent with 48x21x25m of real soil mass. We used two laminated containers in our experiments. The experiments were reproduced several times for each excitation set.

The material used is the standard dry Fontainebleau sand. The soil mass was constructed using the dry pluviation method and the sensors were placed manually along the pluviation in the desired positions. This soil filling technique is used to recreate the initial stress in granular soil. Piezoelectric horizontal accelerometers (PCB type 200 A1 and Bruel & Kjaer type 4317) were used, attached to a thin plate to ensure direction and position. The repeatability and stability of the tests have been discussed by Chandra et al. (2014), and proved to be stable. A bit variation is found for low level excitation due to the difficulty to control the weak input motion. It however can be neglected, and thus the results of analysis is not affected by the test setup variation.

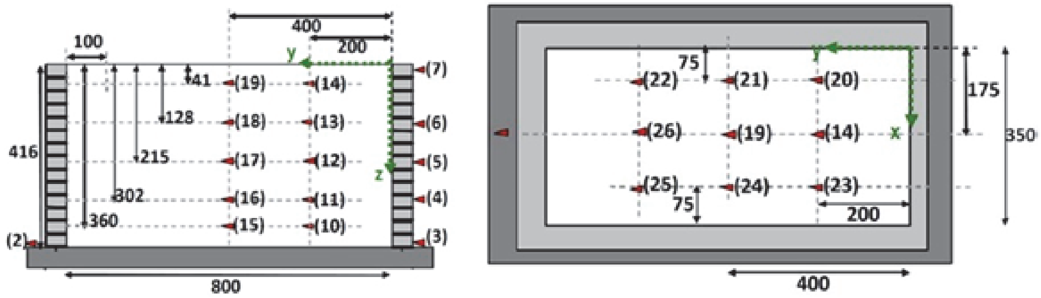


Figure 1. Typical model, dimension and sensor distribution of the centrifuge test. Sensor numbers are in brackets and the numbers without bracket are model dimensions in mm. (left). Y-Z plan view (right). X-Y plan view. (modified from source: Chazelas, 2010)

Two different input signals are used, referring to weak and strong excitation (Fig. 2). The first accelerogram is a strong synthetic ground motion having a PGA of around 0.43g (dominant frequency close to 1.86Hz). The second motion is a weak real accelerogram with PGA corresponds to around 0.07g and dominant frequency is close to 2.70Hz. We did pre-processing to our signal including mean and trend removal, a 5% Tukey taper window and filtering within frequency band between 0.33 and 13.8Hz (3-order Butterworth filter). The filter frequency band corresponds to the area where the signal-to-noise (S/N) ratio is over 3.

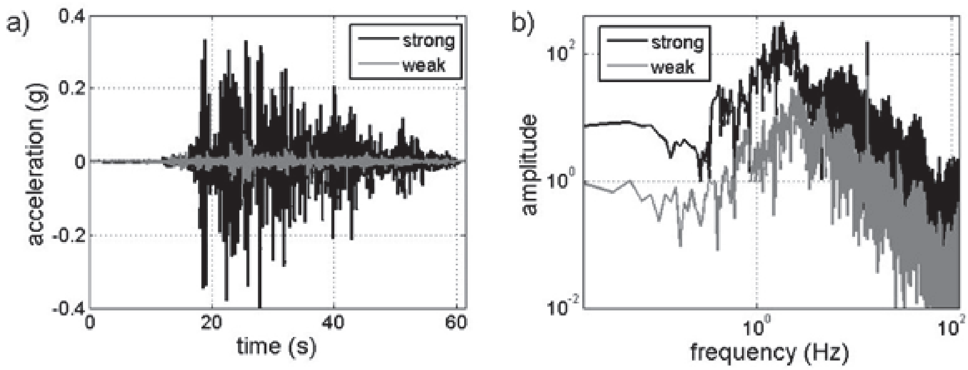


Figure 2. a. Time History of Input Signals; b. Fourier Spectra of Input Signals

The seismic interferometry by deconvolution method is applied to extract the instantaneous shear wave velocity. An example of the deconvolved waves is shown in Fig. 3.

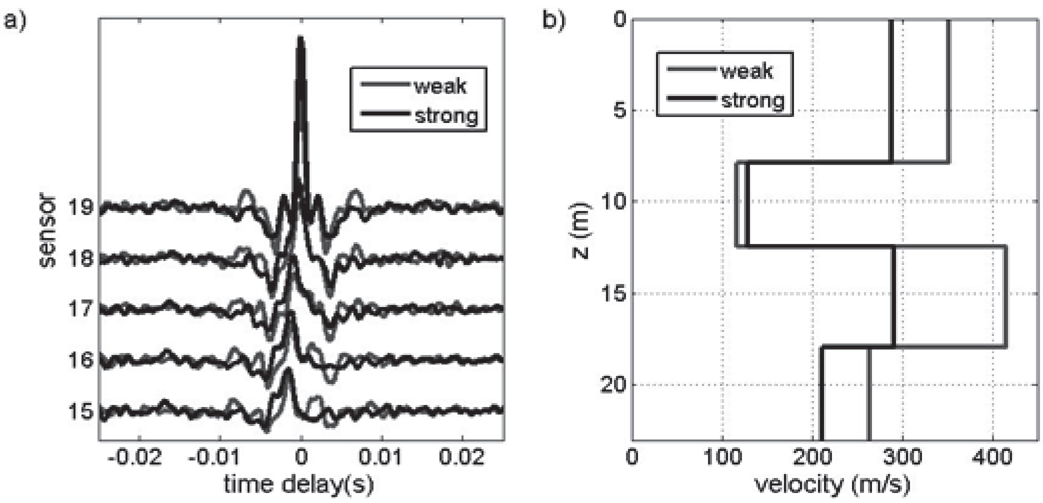


Figure 3. a. Interferogram of the deconvolved waves for weak and strong excitation of the centrifuge test; b. Velocity profile extracted based on the deconvolved waves

We see in Fig. 3, the deconvolved waves, although a little bit noisy, show the upgoing and downgoing waves for the weak and strong events. Thus, it allows the estimation of *Vs* by setting the time-delay between two successive sensors. The amplitude reduction of the downgoing waves is observed related to the increased damping, which corresponds to the nonlinearity signature. The average shear wave velocities obtained are 242m/s and 197m/s for weak and strong motions respectively. This reduction of shear wave velocity gives further indication of nonlinear response of the soil. The data is collected for both soil columns (sensor 15-19 and 10-14 of Fig. 1).

The *PGA–PGV/Vs* curves for all centrifuge data, including all containers, all trials, all vertical arrays, all depths measurement and for all levels of excitation are constructed in Fig. 4. We group the nonlinear curve based on its instantaneous *Vs*, ranging from less than 150m/s (softer soil) to more than 400m/s (stiffer soil), rather than soil initial *Vs*. This represents the real nonlinear evolution of the soil which changes during time. We show that for the lower velocity group (soft soil) we have higher nonlinearity, and for the higher velocity group (stiff soil), lesser nonlinear behavior is observed. In addition we put the PGV/Vs_{25} of the data which corresponds to the 150-200 m/s velocity group for practical purpose. The Vs_{25} is used instead of the common Vs_{30} since the maximum depth of soil column is 25m.

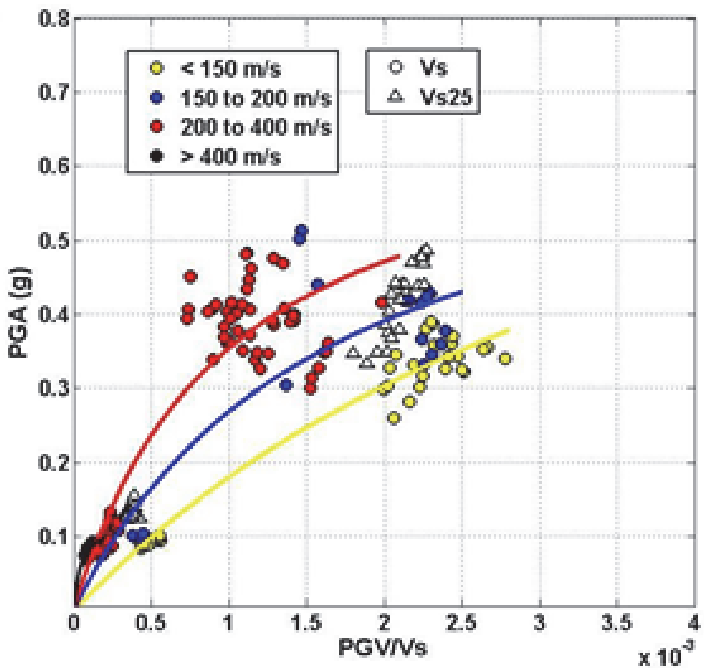


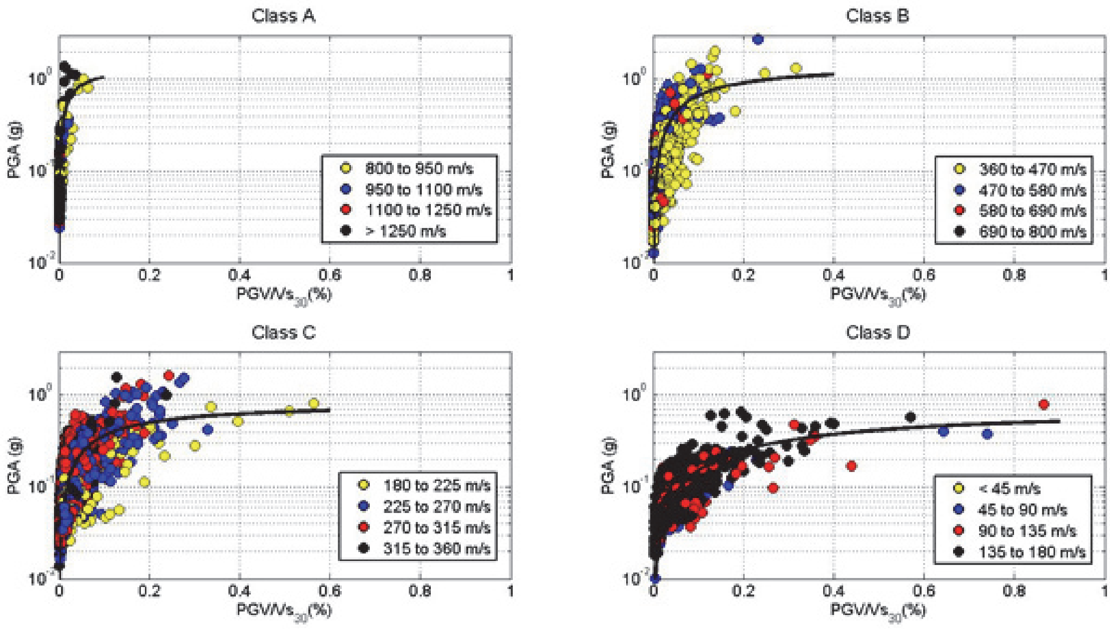
Figure 4. Centrifuge test: nonlinear behavior using *PGA–PGV/Vs* representation as a stress-strain proxy. Data are taken from all centrifuge analysis results. The solid line represents the hyperbolic model for observed data using Eq. 4.

The inverted hyperbolic model from the data using Eq. 4 is shown by the solid line in fig. 4. We observe that the hyperbolic model fits well the data. Using more parametric-refined model, the nonlinear behavior can be estimated and possibly predicted.

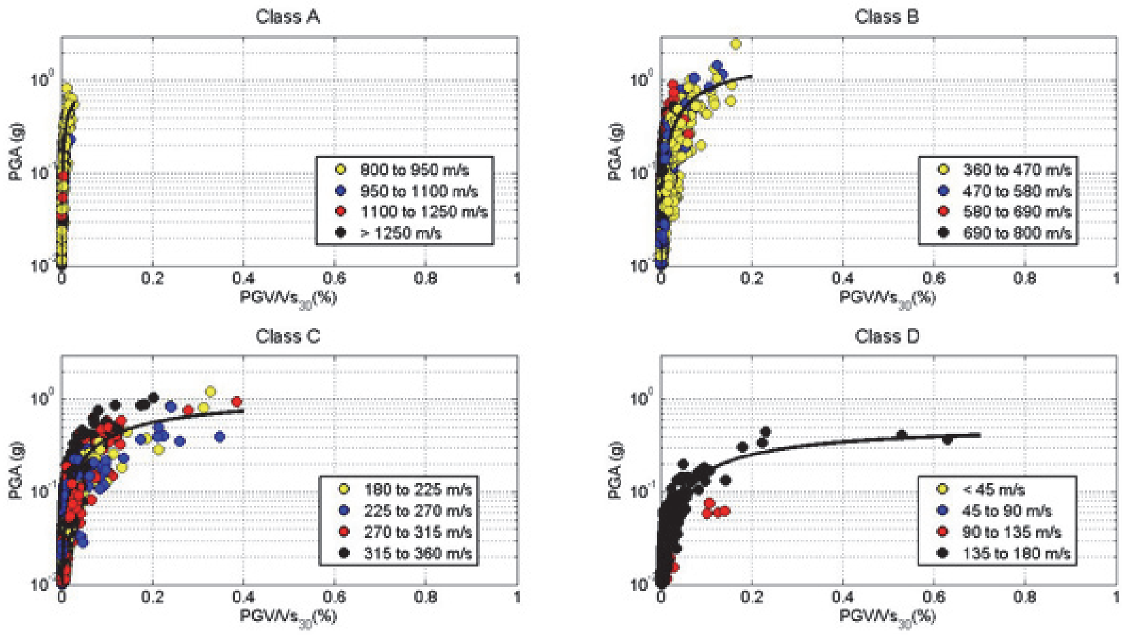
JAPANESE K-NET AND KIK-NET DATA: BACKGROUND AND RESULTS

We apply the same procedures to the Japanese K-NET and KiK-net data. Having high seismicity, Japan has installed several dense seismic networks covering the country. The network has a good quality data and is accessible to public. Among these dense networks are the K-NET and KiK-net strong motion networks (Okada et al., 2004). The K-NET stations are mainly instrumented on sedimentary sites, while KiK-net stations are on weathered rock and/or on thinner sediment sites (Aoi, et al., 2004). The site characterization was performed homogeneously (downhole measures). For the K-NET, the surveys were made down to 20 m in depth, the Vs_{30} is then extrapolated (Boore et al., 2011). As for the KiK-net, the sites are characterized by velocity profiles from 30 to 200 m. In the present study, the KiK-net and K-NET strong-motion records were collected up to the end of 2009. For both networks, only data with a PGA larger than 0.01 m/s^2 are retained with no regards on distance and magnitude. Detailed data processing is provided by Regnier et al. (2013).

For practical engineering purpose, the nonlinear observation will only be made using the *PGA-PGV/Vs$_{30}$*. The *PGV* is obtained by integrating the recorded accelerograms following the procedure from Boore (2005). We classified the *Vs$_{30}$* following the Eurocode 8 (CEN, 2003), which are: Soil Class A (*Vs$_{30}$* > 800m/s), Soil Class B (*Vs$_{30}$* of 360 to 800 m/s), Soil Class C (*Vs$_{30}$* of 180 to 360 m/s), and Soil Class D (*Vs$_{30}$* < 180 m/s). The results are shown for K-NET (Fig. 5a) and KiK-net (Fig. 5b) data for each soil class, as well as the corresponding hyperbolic model.



(a)



(b)

Figure 5. Nonlinear behavior of Japanese sites according to the EC8 site classification, using *PGA–PGV/Vs$_{30}$* as the stress-strain proxy (a. K-Net data; b: Kik-Net data). The solid line represents the hyperbolic model for observed data using Eq. 4.

We found that our proxy describes well the nonlinear response according to the site classification. For the stiffer soils (Classes A and B), the nonlinear behavior appears for high value of PGA (or stress) corresponding to low *PGV/Vs*$_{30}$ (strain) values, while for soft soil (Classes C and D), the nonlinear behavior starts at very early stage on the stress-strain curve. The hyperbolic model represents well the data. In addition, the K-NET data appear to be more non-linear than the KiK-net data, which in agreement with the site conditions discussed by Aoi et al. (2004). This observation should be confirmed in the future with more specific comparison.

CONCLUSIONS

The soil nonlinear response related to near-surface geology effects are a key issue to ground motion hazards. The nonlinear behavior of the soil depends on the variation of shear wave velocity related to shear modulus degradation and the increase damping during excitation.

In this paper we use the *PGA-PGV/Vs* and *PGA-PGV/Vs*$_{30}$ proxy to show the evolution of soil shear stress-strain, depicting the nonlinear response during excitation. First observation is done by dynamic centrifuge experiment. This test enables the recreation of a scaled-down model that reproduces the actual object behavior by applying gravity-scaled acceleration field to the laminated box. The laminated box is important to conserve soil's initial stress-strain boundaries condition. The shear wave velocity firstly calculated using the seismic interferometry by deconvolution method. The estimated time arrival is extracted and the corresponding velocity profile is constructed. Moreover, we applied the stress-strain proxy based on different velocity group. The *PGA-PGV/Vs* is proved to demonstrate well the nonlinear behavior for different soil velocity groups. It is shown that for lower velocity group (softer soil) the nonlinearity appears more rather than the higher velocity group (stiffer soil). Furthermore, the classical two-parameter hyperbolic model is fitted and it represents the data well.

These proxies are then applied to the Japanese K-NET and KiK-net strong motion networks, and proved to demonstrate well the evolution of soil nonlinear behavior for different Eurocode 8 soil classification groups. We observe similar phenomenon as the centrifuge results. We observe that the K-NET data appears more nonlinear to the KiK-net data in accordance with the site descriptions and their velocity group.

REFERENCES

Aoi S, Kunugi T, Fujiwara H (2004) "Strong-motion seismograph net- work operated by NIED: K-NET and KiK-net," *Journal of Japan Association for Earthquake Engineering*, 4(3): 65–74

Bonilla LF, Archuleta RJ, Lavallée D (2005) "Hysteretic and dilatant Behavior of Cohesionless soils and their Effects on Nonlinear site Response: Field Data Observations and Modeling," *Bulletin of the Seismological Society of America,* 95(6): 2373-2395

Boore D (2005) "On Pads and Filters: Processing Strong-Motion Data," *Bulletin of the Seismological Society of America,* 95(2): 745–750

Boore D, Thompson E, Cadet H (2011) "Regional correlations of VS30 and velocities averaged over depths less than and greater than 30 meters,".*Bulletin of the Seismological Society of America*, 101(6): 3046–3059

Chazelas J-L (2010) Program de recherché ANR ARVISE - Rapport Interne Final de la Contribution du LCPC. (in French)

Chin B, Aki K (1991) "Simultaneous study of the source, path, and site effects on strong ground motion during the 1989 Loma Prieta earthquake: A preliminary result on pervasive nonlinear site effects," *Bulletin of the Seismological Society of America*, 81: 1859-1884

Clayton RW, Wiggins RA (1976) "Source shape estimation and deconvolution of teleseismic bodywaves," *The Geophysical Journal of the Royal Astronomy Society*, 47: 151-177

Dobry R (2013) "Radiation damping in the context of one-dimensional wave propagation: A teaching perspective," *Soil Dynamics and Earthquake Engineering*, 47: 51-61

Field EH, Kramer S, Elgamel A-W, Bray JD, Matasovic N, Johnson PA, Cramer C, Roblee C, Wald DJ, Bonilla LF, Dimitriu PP, Anderson JG (1998) "Nonlinear Site Response: Where We're at (A report from a SCEC/PEER seminar and workshop)," *Seismological Research Letter*, 69(3): 230-234

Hill DP, Reasenberg PA, Michael A, Arabaz WJ, Beroza G, Brumbaugh D, Brune JN, Castro R, Davis S, dePolo D, Ellsworth WL, Gomberg J, Harmsen S, House L, Jackson SM, Johnston MJS, Jones L, Keller R, Malone S, Munguia L, Nava S, Pechmann JC, Sanford A, Simpson RW, Smith RB, Starks M, Stickney M, Vidal A, Walter S, Wong V, Zollweg J (1993) "Seismicity Remotely Triggered by the Magnitude 7.3 Landers, Caliornia, Earthquake," *Science*, 260: 1617-1623

Idriss IM (2011) "Use of Vs30 to represent Local site Condition" *4th IASPEI/IAEE International Symposium. Effects of Source Geology on Seismic Motion*, University of Santa Barbara California, August 23-26th, 2011

Nakata N, Snieder R (2012) "Estimating near-surface wave velocities in Japan by applying seismic interferometry to KiK-net data," *Journal of Geophysical Research*, 117: B01308.

Okada Y, Kasahara K, Hori S, Obara K, Sekiguchi S, Fujiwara H, Yamamoto A (2004) "Recent progress of seismic observation net- works in Japan-Hi-net, F-net, K-NET and KiK-net," *Earth Planets Space*, 56: xv–xxviii.

Régnier J, Cadet H, Bonilla LF, Bertrand E, Semblat J-F (2013) "Assessing Nonlinear Behavior of Soils in Seismic Site Response : Statistical Analysis on KiK-net Strong-Motion Data," *Bulletin of the Seismological Society of America*, 103(3):1750-1770

Seed HB, Wong RT, Idriss IM, Tokimatsu T (1984) "Moduli and Damping Factors for Dynamic Analyses of Cohesionless Soils," *Earthquake Engineering Research Center*, Report No. UCB/EERC-84/14, September 1984.

Snieder R, Şafak E (2006) "Extracting the Building Response Using Seismic Interferometry: Theory and Application to the Milikan Library in Pasadena, California," *Bulletin of the Seismological Society of America*, 96(2): 586-598

Wapenaar K, Draganov D, Snieder R, Campman X, Verdel A (2010) "Tutorial on seismic interferometry: Part 1 – Basic principles and applications," *Geophysics*, 75(5): 75A195-75A209