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NUMERICAL MODELLING OF SITE RESPONSE AT THE LSST DOWNHOLE ARRAY IN LOTUNG

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Abstract: The acceleration records of the downhole LSST array located in Lotung (Taiwan) were analyzed to study the seismic response of a deep cohensionless soft soil site. Two earthquakes characterized by maximum PGA respectively equal to 0.08 and 0.15g were considered to investigate the soil response to different levels of input motion. Three computers programs were used, i.e STRATA, DEEPSOIL and FLAC. The study focused on the relative reliability of the three codes with respect to the variations of the input soil parameters and differences in nonlinearity implementation. It has been found that, due to the dominant nonlinear behaviour at the site, the greatest uncertainties lie in the selection of the strain-dependent stiffness and damping soil properties.

Introduction

Over the past 40 years several observations from earthquakes worldwide have shown the paramount importance of subsoil conditions in modifying the ground motion characteristics at a given site with respect to a nearby rock site. A plethora of computer codes are nowadays available to simulate the propagation of seismic waves from the bedrock to the ground surface. The prediction of the site response at the ground surface and/or within the soil profile depends on the reliability of the geotechnical model, including the strain dependencies of cyclic material properties, and on the capability of the numerical code in modelling the cyclic soil behavior, which is nonlinear even at small strains. It is well known that, in general, the two approaches conventionally used to model cyclic soil response are the equivalent linear and the nonlinear.

The most valuable way to validate the numerical predictions is to make use of the acceleration recordings measured at downhole arrays, which can reveal the actual nature of the cyclic soil behavior under earthquake shaking. An increasing number of measurements from several arrays deployed worldwide are nowadays available and provide a unique opportunity for validating site response analysis programs and testing the performance of equivalent linear and nonlinear analyses for different levels of shaking, under total or effective stress conditions (e.g. Elgamal *et al*., 1996; Kwok *et al*., 2008; Stewart *et al*., 2008; Tsai and Hashash, 2009; Ziotopolou *et al*., 2012; Yee *et al*., 2013).

This paper presents the outcomes of a numerical study of one-dimensional seismic response analyses carried out at the downhole LSST (Large Scale Seismic Test) array in Lotung (Taiwan). A number of numerical studies were conducted to investigate the recorded downhole seismic response at LSST array where significant nonlinearity occurred even for small levels of input motions (EPRI, 1993a). In these studies different shear wave velocity profiles and strain-dependent stiffness and damping ratio curves were used. Chang *et al*. (1990) showed that the computed nonlinear responses were closer to the recorded results than the equivalent linear responses, especially in the small-amplitude higher-frequency part of motion. A better agreement between equivalent linear and nonlinear results was found by Borja *et al*. (1999, 2002) using SHAKE and STRATA, with both codes predicting quite satisfactorily the recorded surface motions. Lee *et al*. (2006) investigated the linear, equivalent linear and nonlinear soil response using the records of 13 earthquakes with

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horizontal PGA varying from 0.01 to 0.19g. A consisted picture emerged with simulated motions from linear model matching well the records for small input motions and simulated motions from equivalent linear/nonlinear models matching satisfactorily the records for large input motions. Stewart *et al*. (2008) compared predictions from several nonlinear computers programs with data recorded in terms of acceleration response spectra. They found that the predictions from all codes were generally similar each other and underpredicted the recorded response at periods below about 1 s. Similar trends were found at the ground surface and at all depths along the array. A more recent numerical investigation was conducted by Amorosi *et al*. (2011) which showed a satisfactory agreement between the recorded motions and those simulated by equivalent linear and more sophisticated advanced nonlinear analyses.
In this paper, investigation of nonlinear site response at the Lotung site was conducted using three well-known computer codes (STRATA, DEEPSOIL and FLAC) in which different methods are implemented to model soil nonlinearity. The recorded and predicted responses, in terms of acceleration response spectra, are compared to evaluate the capability of the codes to reproduce soil amplification along the vertical array.

Lotung array and earthquake data
In the framework of a Large-Scale Seismic Test (LSST) program at a site near Lotung, a seismically active region in northeast Taiwan, the construction of ¼ and ½ scale models of a nuclear plant containment structure was carried out for soil-structure interaction research. The instrumentation installed (Figure 1) included three linear surface arrays (arms 1, 2 and 3) and two downhole arrays (DHA and DHB). The location of the two downhole arrays, with respect to the edge of the ¼ scale model, is indicated in Figure 1. Extensive instrumentations was deployed to record seismic structural and ground response and to monitor soil pore-water pressure build-up. More specifically, the arrays were equipped with three-component accelerometers located at the ground surface and approximately at depths of 6, 11, 17 and 47 m; in addition, a total of 27 pore pressure transducers have been installed. In this paper, the free-field site response was studied using the downhole array DHB and the overlying surface accelerometer FA1-5 (Figure 1b).

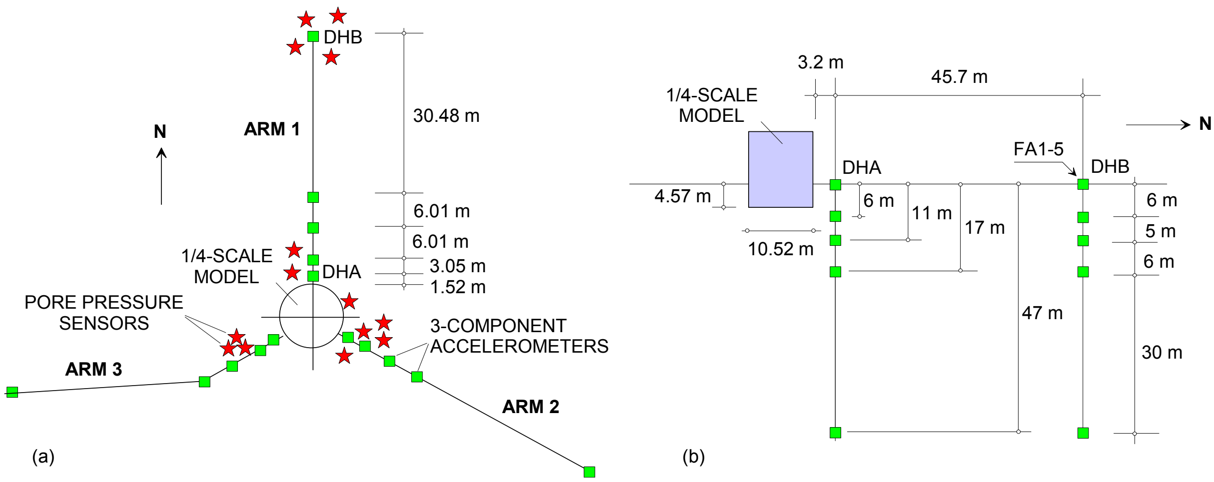

Figure 1. Plain view and schematic cross-section of the site with the deployment of instruments at the ground surface and at the depths of 6, 11, 17 and 47 m

During a 6-year operation from 1985 to 1990, 30 earthquakes of magnitude comprised between 4.0 and 6.5 triggered this array. In order to explore different levels of shaking, two events were considered: one weak event (LSST#8) and one strong event (LSST#7) to investigate small and high strain soil behaviour, respectively. Parameters of the events selected for the analysis are listed in Table 1. Maximum acceleration (PGA) recorded at the ground surface (FA1-5) along the EW component is 0.158 g and 0.035g for the strong and weak motion events, respectively.

Table 1. Earthquake data used in the analyses

Earthquake #	Date	Epicenter		Depth (km)	Magnitude	Distance (km)	PGA – EW	
		Long. (E)	Lat. (N)				DHB47	FA1-5
LSST07	5/20/1986	2404.90	12135.49	15.8	6.2	66.1	0.081	0.158
LSST08	5/20/1986	2402.89	12137.04	21.8	5.8	69.2	0.015	0.035

Site properties and geotechnical model

The local geology at the Lotung site consists of recent alluvium and Pleistocene materials overlying Miocene basement. The alluvium is approximately 40-50 thick and the underlying Pleistocene formation is approximately 350 m thick. Soil profile at the site (Fig. 2) is composed of an upper layer about 30-35 m thick consisting of predominantly silty sand and sandy silt with some gravel. Underneath this layer, between about 30 and 50 m, interlayered sandy silts, clayey silts and silty clays can be found (Tsai, 1990). The water table is located at 0.6 m from the ground surface. The soil profile and parameters assumed in the geotechnical model, summarized in Table 2, are taken from Lee *et al*. (2006). These Authors demonstrate the reliability of the Vs profile by comparing the computed and recorded surface/47m linear transfer function. The recorded transfer function was obtained from a weak motion event with PGA~0.008g at 47 m depth. The viscoelastic (D_0=3%) linear transfer function computed using the Vs profile (Figure 2a) of the Lee *et al*. (2006) model is reported in Figure 2b. The numerical fundamental frequency f_0=1.4 Hz (T_0=0.714 s) is in good agreement with the experimental one in the linear range. In Figure 2a the Vs profiles used by Chang *et al*. (1990), EPRI (1993a), Borja *et al*. (2000) and Stewart *et al*. (2008) are also reported.

Table 2. Soil profile and parameters of the geotechnical model assumed for the analyses

Layer #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Thickness (m)	1.21	1.52	1.52	1.52	1.52	1.21	2.42	1.82	1.52	1.21	1.52	6.06	6.06	5.91	12.0
Depth (m)	1.21	2.73	4.24	5.76	7.27	8.48	10.9	12.7	14.2	15.5	16.9	23.0	29.1	35	47
γ (kN/m^3)	16.2	16.5	20.4	18.6	17.8	17.9	19.3	18.6	19.7	22.5	19.3	19.3	19.3	19.3	19.3
Vs (m/s)	115	126	137	148	159	167	179	193	201	210	218	234	244	312	262

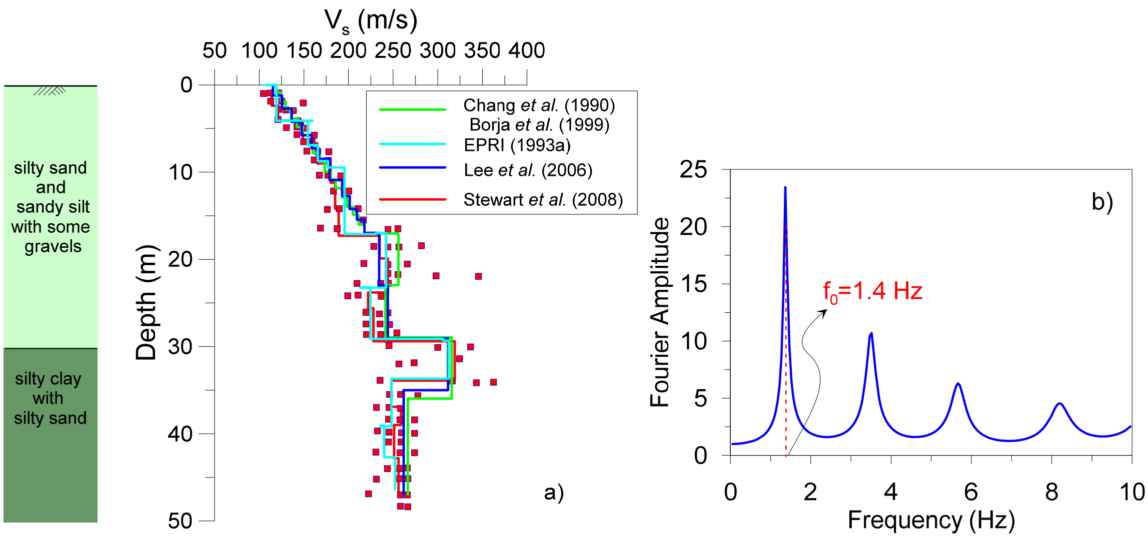

Figure 2. a) Vs profiles from various studies and b) numerical viscoelastic linear transfer function

A compilation of normalized shear modulus reduction (G/G_0) and damping ratio (D) curves for Lotung site is illustrated in Figure 3. Stiffness and damping curves were obtained from laboratory testing reported in Tsai (1990) and EPRI (1993b). In this latter work resonant column and torsional shear tests were conducted at the University of Texas at Austin on eight “undisturbed” samples of silty sands and silts. For the silt samples the PI was generally about 7-8% suggesting dynamic soil properties closer to sands rather than clays. This is reflected in the normalized modulus reduction and damping curves from all samples represented as a grey region in Figure 3. Chang *et al*. (1990) developed two set of curves that were assumed for the equivalent linear analyses, respectively for depths of 0-6 m and 6-17 m. These curves were more recently used by Lee *et a*l. (2006) in the nonlinear simulation analyses of the Lotung site. Zeghal *et al*. (1995) proposed three material curves inferred from the in situ recorded seismic response at the Lotung site. Separate curves were assumed for depths of 0-6 m, 6-11 m and 11-17 m. Because data were only available to a depth of 17 m, the soil properties from 17 to 47 m were assumed to be the same as those from 11-17 m depth. The curves by Zeghal *et al*. (1995) were also adopted by Borja *et al*. (2000) and Stewart *et al*. (2008) in their seismic response verification studies. As may be observed, the Zeghal *et al*. (1995) shear modulus curves fall within the range proposed for sandy soils by Seed and Idriss (1970) whereas the curves proposed by Chang *et al*. (1990) and also used by Lee *et a*l. (2006) fall along the lower bound. Analogously, damping curves by Zeghal *et al*. (1995) fall along the upper bound of the Seed and Idriss range while curves from Chang *et al*. (1990) exhibit much lower damping. Therefore, a great variation in the stiffness and damping curves is evident which, in turn, reflects a large uncertainty in the selection of an appropriate set of curves. In this study, as a first approximation, the unique set of curves suggested by Lee *et al*. (2006) was used for the whole alluvial layer.

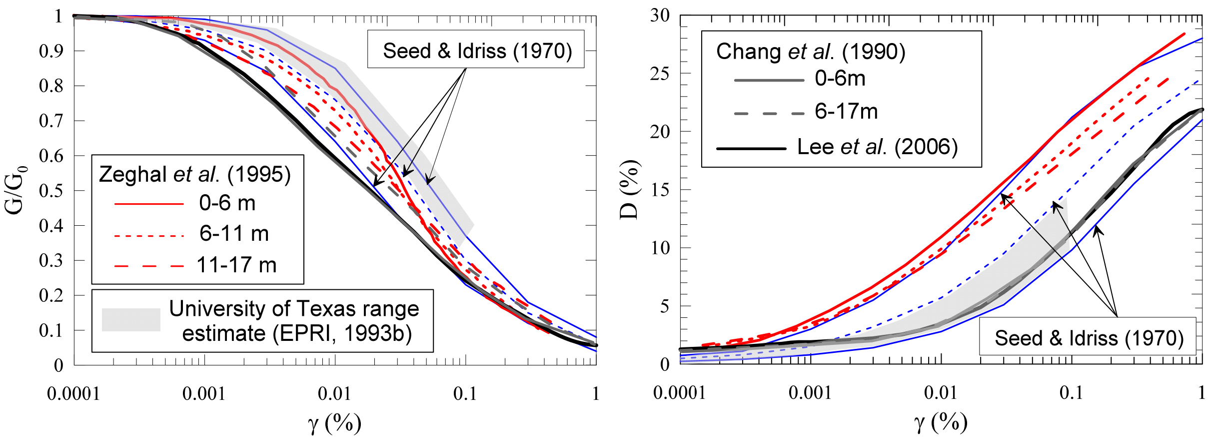

Figure 3. Normalized modulus reduction and damping curves for the Lotung site from various literature studies

Computer programs used

Three computer codes were used to conduct the 1D site response analyses, i.e. STRATA, DEEPSOIL and FLAC. The code STRATA (Kottke and Rathje, 2008) is a frequency domain code, like the well-known SHAKE. It uses a closed form solution of the 1D wave equation, as described by frequency domain transfer functions, to compute the dynamic response of a soil deposit. Nonlinearity is simulated through the equivalent linear method which consists in performing linear analyses with equivalent stiffness and damping properties progressively adjusted to the shear strain amplitude experienced by the soil.

The program DEEPSOIL (Hashah *et al*., 2011) computes the response of the soil deposit using a 1D lumped-mass system. Stiffness properties are modelled through nonlinear springs. Additional viscous damping is included through viscous dashpots. The analysis is performed in time domain and requires a time stepping method that solves the differential equations of motions incrementally between time steps..The soil behaviour is represented by a nonlinear backbone curve coupled with extended Masing rules describing unloading-reloading behaviour. To define the initial backbone curve, the MKZ (Modified Kondner and Zelasko) model is used. Simplified, full and extended Rayleigh damping formulations, as well as a frequency independent damping scheme, are implemented in the code.

The computer program FLAC (Itasca, 2011) uses a finite difference formulation to idealize the 1D soil column. The program solves the dynamic stress-strain problem using an explicit

time-stepping procedure. The soil nonlinearity can be modelled according to user-defined nonlinear models or to the hysteretic damping formulation available in the code library. According to this latter model, employed in the present study, the backbone curve is built by adjusting the tangent shear modulus for each zone in the model as a function of the strain amplitude; in addition, Masing rules are used to specify the behaviour at reversal points thus modelling the unloading-reloading loops. In addition to the hysteretic damping, FLAC allows to specify Rayleigh damping according to the full formulation with one control frequency.
In the present study, the nonlinear site response analyses were carried out according to the following: i) the recorded (within) input motion was taken as input without modification and was used as rigid base; (ii) a small amount of damping was added to provide a non-zero damping at very small strains, namely 1.3% and 0.2% for DEEPSOIL and FLAC respectively; in particular for DEEPSOIL the frequency-independent damping option was used whereas for FLAC the Rayleigh damping scheme with control frequency set at 1 Hz was adopted iii) curve fitting was performed to match the nonlinear backbone curve to the specified G/G_0-γ curve by Lee *et al*. (2006). This procedure produced a misfit between the D-γ curves effectively used in the analyses and that by Lee *et al*. (2006), as shown in Figure 4. The actual D-γ curves lay approximately around the Seed and Idriss (1970) mean curve. This was deemed as a reasonable compromise considering that the Seed and Idriss mean damping curve lay between the available curves in Figure 3. For this reason, the equivalent linear analyses with STRATA were performed with the Seed and Idriss mean curves. It should be highlighted that for FLAC two sets of parameters were employed for the sigmoidal4 hysteretic damping model (sigm4-a and sigm4-b in Figure 4). In particular, in order to reduce the overestimation of damping as compared to the reference curve, the sigm4-a model was developed by relaxing the constrain on G/G_0-γ curve; in this way, the normalized stiffness curve falls significantly above the reference one, at least at medium and high shear strains.

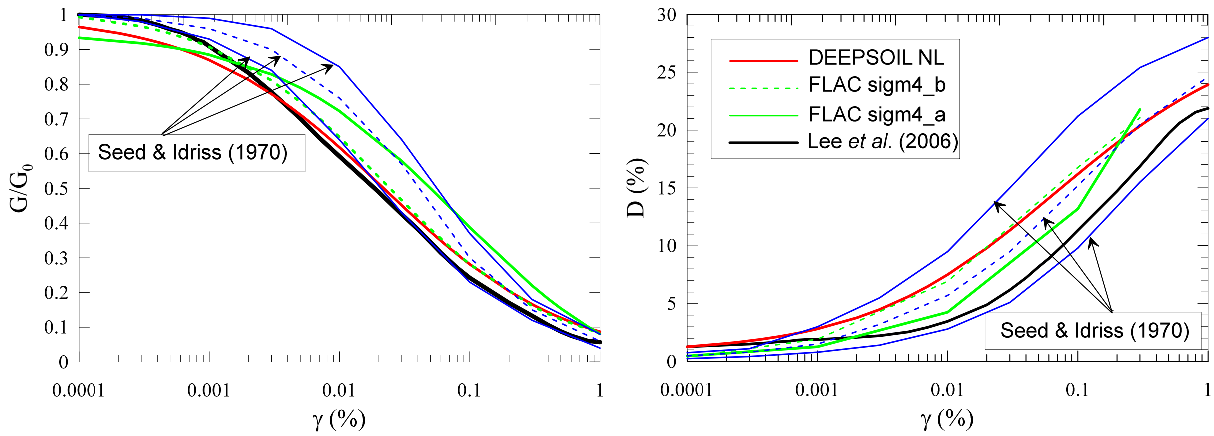

Figure 4. Modulus reduction and damping curves effectively used in the codes.

Prediction results

Site response analyses were performed with the three codes for both seismic events reported in Table 1. Two cases were analysed: one used the motion recorded at 47 m depth as input motion and the other used the motion recorded at 17 m as input motion. Prediction results were then compared at various depths with recorded data. Furthermore, the performance of equivalent linear analyses and nonlinear analyses was also investigated.
Figures 5 and 6 show 5% damped acceleration response spectra of the recorded motions and predictions for events LSST#7 and LSST#8, respectively. The results are shown for the ground surface and depths of 6, 11 and 17 m; the response spectrum of the input acceleration taken at depth of 47 m is also reported. The comparisons show that for the higher input motion (LSST#7) the simulated results using the FLAC sigm4_a model, match the recorded data very well at all periods and all depths; some discrepancy can be noted at periods shorted than 0.3 s, especially for the surface recording (Fig. 5). On the other hand

DEEPSOIL and FLAC sigm4_b model, provide comparable results at all depths but generally quite lower than the recorded motions. This is presumably a consequence of similar modulus reduction and damping curves effectively used by the codes which are less linear (lower shear modulus and higher damping) that those used by FLAC sigm4_a. This results in a general overdamping at all depths and especially at the fundamental site period of about 1 s. Similar results have been obtained using STRATA, even if the underestimation of the recorded is slightly less pronounced. Previous research using seven different codes (Stewart *et al.*, 2008) has highlighted a general under-prediction in the same period range.
For the lower input motion (LSST#8) the nonlinear simulations are very similar one each other (Figure 6), presumably because of minor degree of nonlinearity experienced during shaking. Larger peaks are generally exhibited by the FLAC sigm4_a model, probably due to the smaller damping ratio values in the small-to-medium strain range. The comparisons between recorded and simulated values are generally satisfactory at all depths. At the ground surface a good prediction is obtained up to 0.2 s whereas the computed motion is generally lower than the recorded one between 0.2 and 0.7 s; at higher periods a local "bump" is evident in the calculated values which is not reflected in the recorded data. At other depths the prediction is satisfactory in the whole period range with the exception of the "bump" at around 0.8 s. A similar trend may be observed in the simulation results by STRATA; overall these results are very similar to those obtained with the nonlinear codes.
Figure 7 shows the comparison between recorded and simulated response spectra for both events (LSST#7 and LSST#8) for the input motion applied at 17 m depth. As compared to the previous case, a different picture results. In fact, it can be seen that for both input motions the recorded response is generally in satisfactory agreement with the DEEPSOIL and FLAC sigm4_b results, especially for input LSST#7, at all depths. Conversely, the results using FLAC sigm4_a and STRATA exhibit larger discrepancies, especially at the ground surface and at 6 m depth, where a significant over-prediction is apparent.
The above results indicate that if the input motion is applied at 47 m, the computed results are consistent with observed ones when the more linear (FLAC sigm4_a) G/G_0-γ and D-γ curves are used. On the contrary, if the input motion is applied at 17 m, a better agreement between predicted and recorded motions is obtained using the more nonlinear curves (FLAC sigm_4b and DEEPSOIL). This apparent contradiction may be due to the choice of a unique curve for stiffness and damping curves for the whole soil deposit. Most probably, the upper part of the soil profile would be better characterized by nonlinear G/G_0-γ and D-γ curves like those corresponding to FLAC sigm_4b and DEEPSOIL models, as shown by the good prediction obtained with input motion at 17 m. A more linear behaviour, associated to the increasing confining pressure, should be assigned to the deeper soil layers.

Conclusions

A numerical investigation on the seismic response of the deep cohensionless soft soil deposit at Lotung array in Taiwan has been carried out with three different codes, i.e. the nonlinear FLAC and DEEPSOIL and the equivalent linear STRATA. Two seismic events characterized by different levels of input motion were considered in order to investigate the performance of the codes under nonlinear soil behaviour. Moreover, two cases were analysed using as input the motion recorded at 47 m and 17 m depth, respectively. Prediction results were then compared at various depths with recorded data.
The comparisons showed encouraging results. The relatively simple constitutive models here employed captured in a satisfactory way the highly nonlinear response of the site during shaking. In particular, the hyperbolic and hysteretic damping models implemented in DEEPSOIL and FLAC respectively, which can be easily calibrated based on standard stiffness and damping curves, provided in general a slightly better performance of the equivalent linear approach employed by STRATA. This demonstrates that a valuable site response prediction can be obtained even for high nonlinear shear strain levels with simple constitutive models.

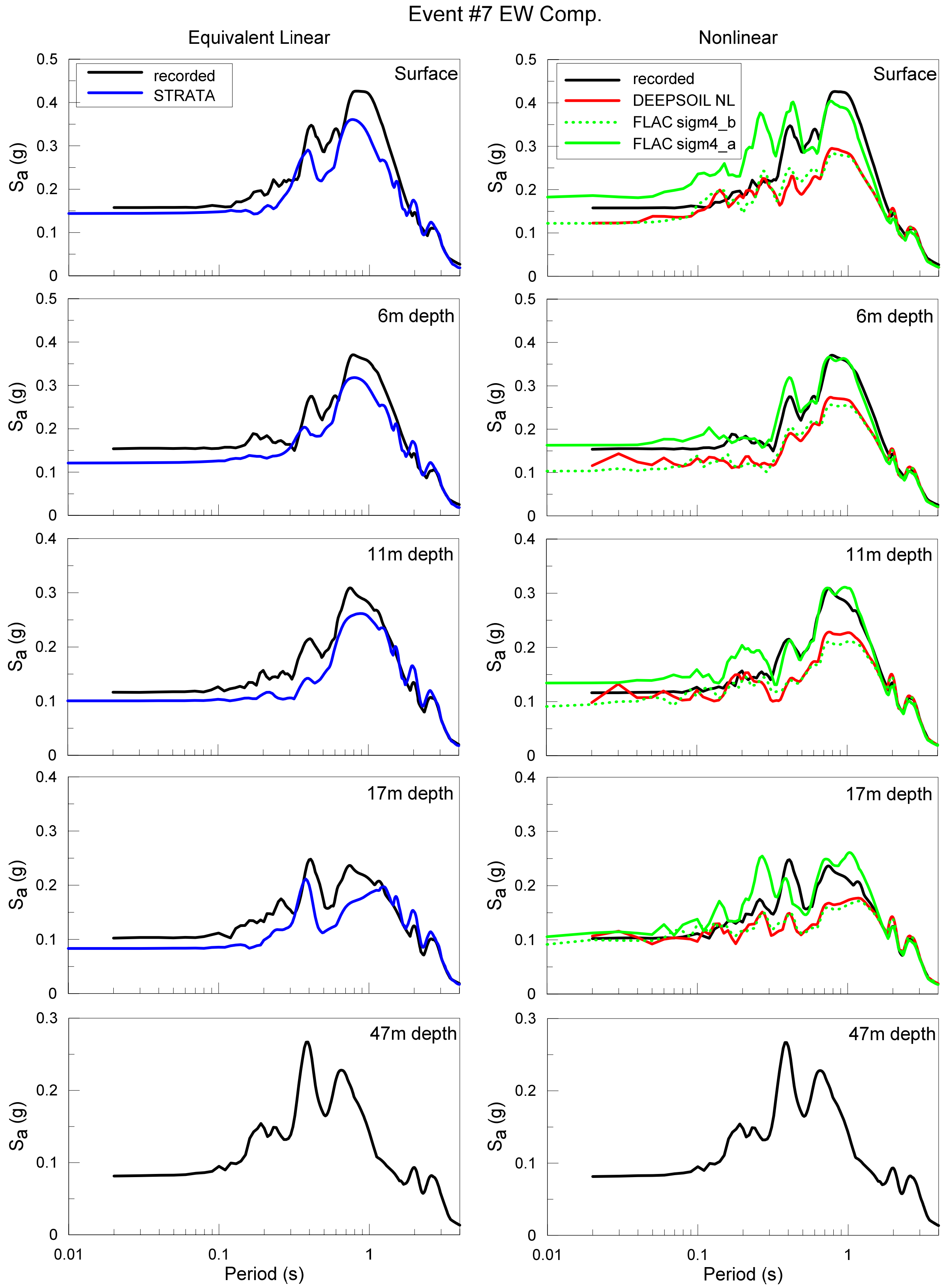

Figure 5. Acceleration response spectra (ξ=5%) from records and numerical analyses using motion at 47 m as input: equivalent linear (left side) and nonlinear (right side) analyses for LSST#7 event

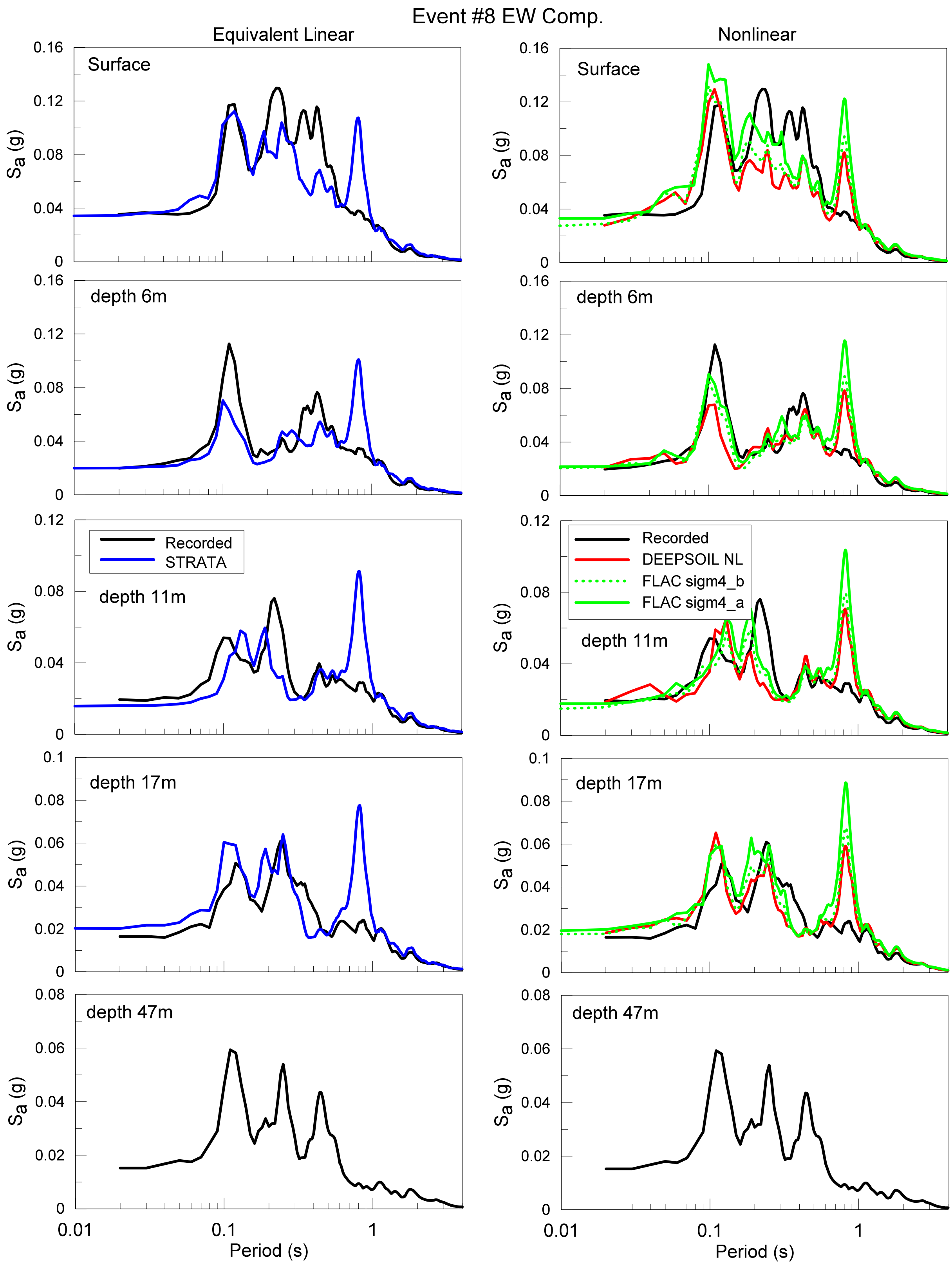

Figure 6. Acceleration response spectra (ξ=5%) from records and numerical analyses using motion at 47 m as input: equivalent linear (left side) and nonlinear (right side) analyses for LSST#8 event

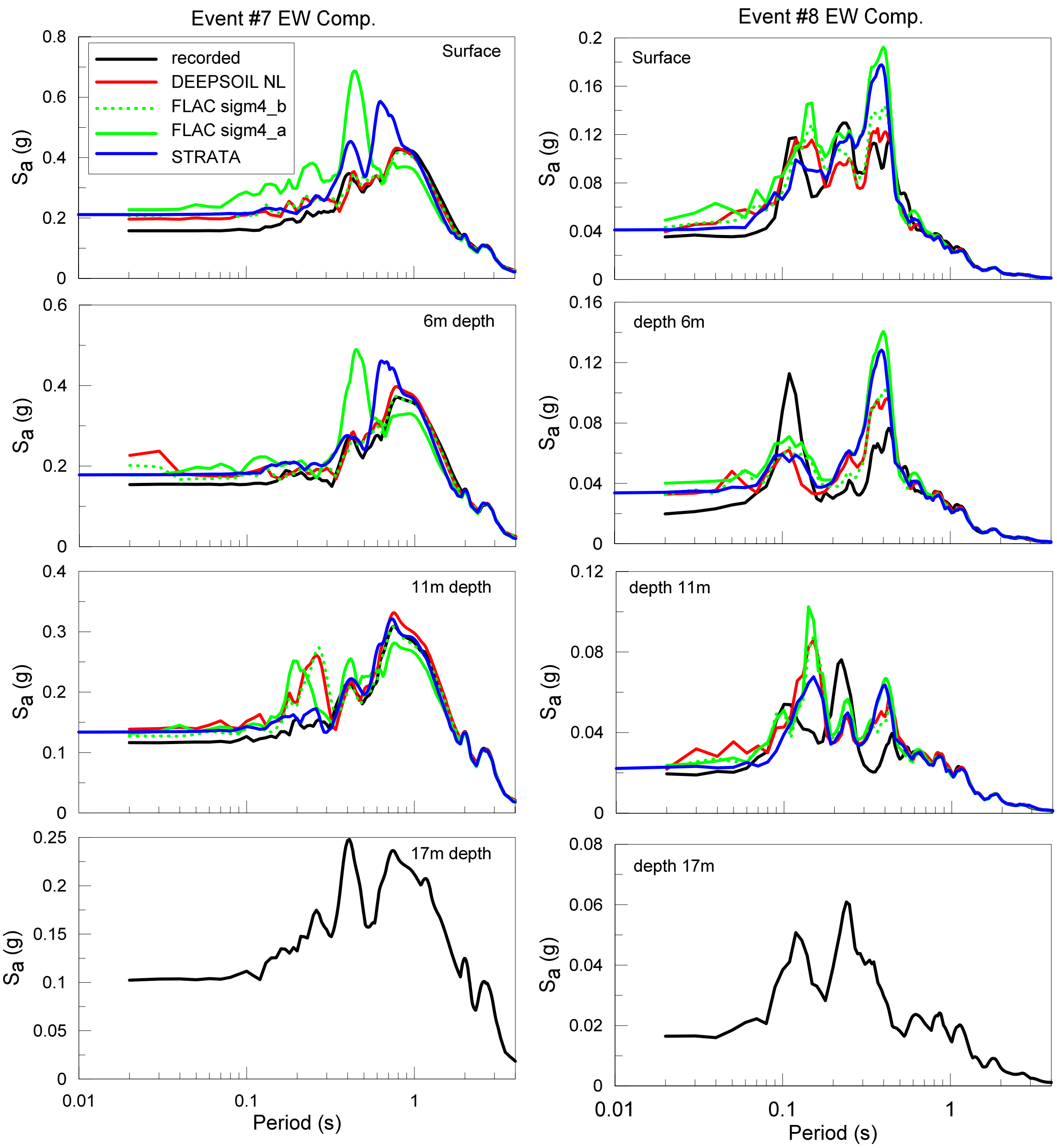

Figure 7. Acceleration response spectra (ξ=5%) from recorded data and numerical analyses using motion at 17 m as input: LSST#7 event (left side) and LSST#8 event (right side)

It should be emphasised that in the present study, as a first approximation, a unique set of stiffness and damping curves was assumed for the whole deposit as reference to calibrate the nonlinear parameters of the constitutive models. This calibration produced curves effectively assumed in the analyses that differ each other and with the reference one. This misfit is due to the difficulties in matching simultaneously both stiffness and damping curves. The results showed that, depending on the curves assumed by codes, the matching between predicted and recorded response can be more or less satisfactorily. In particular, if the input motion is applied at 47 m, the computed results are consistent with those observed when the more linear curves are used. On the contrary, if the input motion is applied at 17 m, a better agreement between predicted and recorded motions is obtained using the more nonlinear curves. This apparent contradiction may be due to the choice of a unique curve for stiffness and damping properties. A more realistic subsoil model assuming nonlinear curves variable with depth is the subject of an ongoing research.

ACKNOWLEDGMENTS
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