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COMPARISON OF VARIOUS NUMERICAL ASSUMPTIONS FOR 1-D NONLINEAR SITE RESPONSE ANALYSIS ON REAL SITES.

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Abstract

In the framework of the PRENOLIN international benchmark, aiming at testing multiple numerical simulation codes capable of predicting non-linear seismic site response with various constitutive models, the validation phase has consisted in comparing the predictions of numerical estimations with actual strong motion recordings obtained at well-known Japanese sites, selected within the Japanese KiK-net and PARI (Port and Airport Research Institute) accelerometric networks, and being as close as possible to a 1D geometry (horizontal layers), with complete field and laboratory measurements.

In this paper, we present the results obtained with the CyberQuake computation code [1] for the deep Kushiro (KiK-net KSRH10) and shallow Sendai (PARI) sites. For each site, different input (field and lab) data were provided by the organizers: weak and strong input motions; degradation curves (shear modulus and damping ratio evolution with respect to the cyclic shear strain distortion), either selected in Darendeli's curves or derived from available cyclic tri-axial laboratory tests or considering an hyperbolic constitutive model.

Here, a comparison is shown between actual recordings available on these sites (including those from Tohoku earthquake 2011) with various 1D computing assumptions and methods, assuming vertical incidence for propagating waves: (1) the so-called "equivalent linear model", which consists in a linear iterative viscoelastic approach performed in the frequency domain; (2) the nonlinear transient dynamic approach, based on finite-element time-domain computations, considering an elastoplastic cyclic constitutive model [2] and either effective-stress approach (called "preferred soil model" as chosen freely by each PRENOLIN participant from the available geotechnical data) and total-stress approach (called "imposed soil model", as set by PRENOLIN organizers).

For the shallow site, the nonlinear effective-stress approach gives better results for all the selected input motions (waveform, amplitude and frequency content), whereas with the total-stress approaches (equivalent linear and nonlinear), the soil response is overestimated and strains are underestimated for strong motions. For the deep site, the soil response is globally overestimated and frequency content is not well captured, even for weak input motions. This case has raised questions about the 1D assumption and the vertical incidence of input motions. Further investigations and computations are still needed, but they could not be performed during the PRENOLIN benchmark duration.

Keywords: Nonlinear site effects; Elastoplastic cyclic constitutive modelling; Effective and total-stress approaches

1. Introduction

The prediction of local site conditions, leading to the so-called "site effects", is crucial in case of strong motion events in sedimentary basin, as nonlinear soil behavior strongly affects the seismic motion of near-surface deposits, resulting in shear-wave velocity reduction, irreversible settlements, increased duration and important amplification of ground motion, and in some cases, liquefaction due to pore pressure build-up. As a consequence, site effects are considered as a key parameter in local seismic hazard assessment to reduce possible structural damages. A number of worldwide test-sites have been dedicated to the observations of these local effects for decades (e.g. Turkey Flat in USA, Ashigara Valley in Japan or EUROSEISTEST in Greece), the analysis of the seismic response of natural soils being based on a detailed characterization of the subsoil structure, soil conditions and properties. However, accurate quantification and prediction using numerical modeling approaches are still a challenge, despite the commonly accepted practice, and this has been the subject of past international benchmarks (e.g. [3, 4, 5]).

The PRENOLIN project ("Improvement of PREdiction of NOnLINear effects caused by strong seismic motion"), is an international benchmark (2013-2015), which aimed at testing several numerical simulation tools currently used for nonlinear 1D site response evaluation and at assessing epistemic uncertainties. The first phase of the benchmark was dedicated to the verification of codes (i.e. comparison between numerical codes on simple, idealistic cases) and the validation phase was to compare the numerical predictions with the actual strong motion recordings obtained on three well-investigated (field and lab data) vertical-array sites belonging to the Japanese KiK-net and PARI (Port and Airport Research Institute) accelerometric networks. The criteria for selecting sites by the organizers were: (1) as close as possible to the 1D configuration (no lateral velocity variations); (2) recorded weak and strong motions; (3) observed nonlinear soil behavior.

In the next sections, we present the results obtained with the CyberQuake software [1] for the last iteration of the validation phase, on one shallow site (PARI-Sendai) and one deep site (Kik-Net Kushiro).

1. Input motions selection

Nine earthquake events were provided by the PRENOLIN organizing team for the Sendai (PARI) site and nine other for the Kushiro (KiK-net KSRH10) one (Fig. 1). In this paper, we have selected results for 4 events only on each site, which main features (locations, magnitudes, frequency contents) are detailed in Table 1. For Sendai site, TS1 event corresponds to the 2011 Tohoku earthquake.

Table 1 – Main features of the events selected in this study, with indicative frequency contents (Low LF, Intermediate IF and High HF)

Site	Event #	Name	Mw	Epicentral Distance (km)	Depth (km)	Frequency Content
SENDAI	1	TS1	9	162.7	23.7	LF
	2	TS2	7.1	81.3	72	IF
	3	TS3	6.4	19.1	11.9	HF
	7	TS7	5.9	94.7	41.2	HF
KUSHIRO	1	TS1	7.1	31.9	48	HF
	2	TS2	6.9	44.14	46	LF
	4	TS4	5.8	43.21	47	IF
	9	TS9	6.5	105.03	43	LF

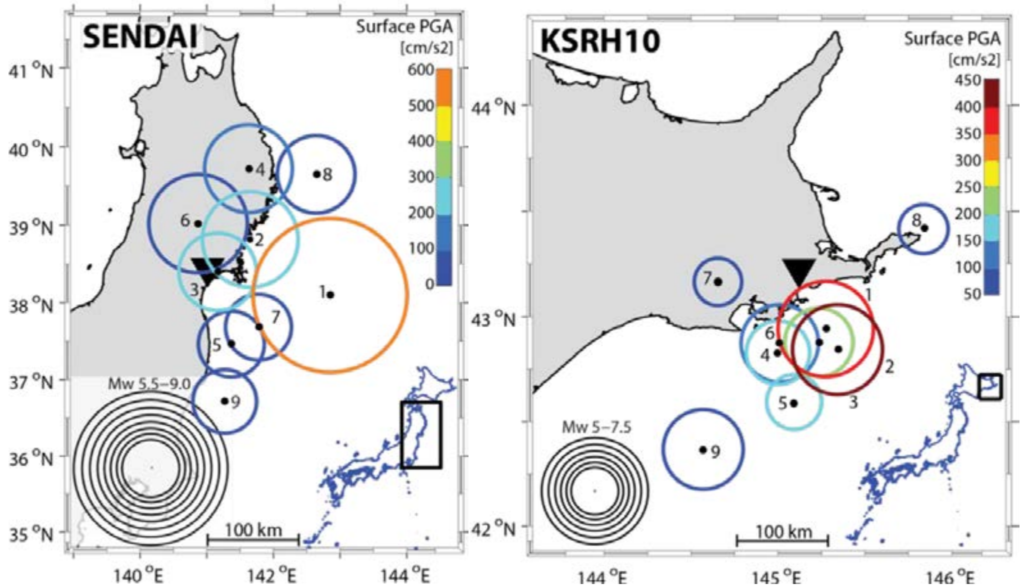

Fig. 1 – Maps of Sendai and Kushiro (KSHR10) earthquake events, selected by the PRENOLIN benchmark

2. Soil profiles definition

2.1 Shallow site: PARI-Sendai

The Sendai soil profile is composed of 3 main layers: a thin gravel fill (down to Ground Level GL-1m) and a sandy soil layer (down to GL-7m), both considered as nonlinear materials, and then a clayey rock layer (under GL-7m) with elastic behavior. A rigid bedrock condition is set at GL-10.4m, where downhole recorded motion was provided for computations. Various field and lab tests were available to characterize constitutive materials and related parameters were provided to participants: water content, particle size distributions, wave velocities V_S and V_P, bulk density ρ, quality factor Q_S, degradation curves, i.e. the evolution of shear modulus ratio (G/G_{max}) and damping ξ with respect to the maximum cyclic distortions γ.

There were two "imposed soil models", called SC1 and SC2, with total stress assumption (no water table) and degradation curves provided by the organizing team: SC1 curves were obtained by best fitting Darendeli's curves, whereas SC2 ones, from corrected cyclic triaxial lab tests curves. These curves were used for calibration of the Hujeux elastoplastic cyclic constitutive model [2] used in nonlinear simulations with CyberQuake (Fig. 2). SC1 curves were also used as input for the equivalent linear (SHAKE-like) approach in frequency domain (see §3.3.2). In this study (not during the benchmark), we have also performed simulations on a column (SCE) based on SC1 features, but considering an effective stress approach with water table set at GL-1.5m, instead of the total-stress approach for SC1. A constant permeability k of 10^{-5}m/s was set along the soil profile. Main features of soil columns are recalled in Table 2.

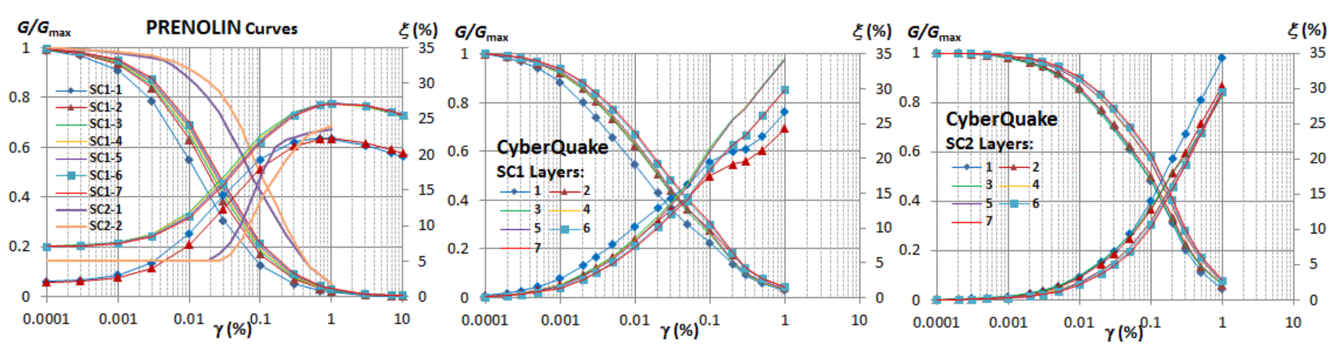

Fig. 2 – Degradation curves for Sendai soil columns: data (PRENOLIN) and calibration (CyberQuake)

Table 2 – Elastic and nonlinear properties provided for Sendai site

Layer		Elastic (L) properties					Nonlinear (NL) properties				
Num.	**GL (m)**	V_S **(m/s)**	V_P **(m/s)**	ρ **(kg/m³)**	Q_S	k **(m/s)**	**SC1/SCE column**	**SC2 column**	τ_{max} **(kPa)**	**C' (kPa)**	**ϕ' (°)**
1	0-1	120	610	1850	25	10^{-5}	SC1-1	SC2-1	5	0	44
2	1-2	170	870	1850	25	10^{-5}	SC1-2	SC2-1	5-11	0	44
3	2-3	200	1040	1850	7.14	10^{-5}	SC1-3	SC2-1	11-16	0	44
4	3-4	230	1180	1890	7.14	10^{-5}	SC1-4	SC2-2	16-21	0	44
5	4-5	260	1300	1890	7.14	10^{-5}	SC1-5	SC2-2	21-27	0	44
6	5-6	280	1420	1890	7.14	10^{-5}	SC1-6	SC2-2	27-32	0	44
7	6-7	300	1530	1890	7.14	10^{-5}	SC1-7	SC2-2	32-39	0	44
8	7-10.4	550	2800	2480	50	10^{-5}	L	L	-	-	-
Rigid bedrock											

2.2 Deep site: KiK-net-Kushiro

The soil profile on Kushiro site was composed of 5 main layers: a thin gravel fill (down to GL-1m) and a sandy soil layer (down to GL-7m), both considered as nonlinear materials, and then a clayey rock layer (under GL-7m) with elastic behavior. The rigid bedrock condition was set at GL-255m, where downhole motion was provided. Three "imposed soil models" (SC1, SC2 and SC3) with total stress assumption were provided by PRENOLIN, with SC1 degradation curves obtained by best fitting Darendeli's curves. SC2 and SC3 curves were obtained by fitting lab data and in-situ measurements, using a simple hyperbolic model [6]. Main features for the Kushiro site are given in Table 3 and PRENOLIN and calibrated degradation curves are shown in Fig. 3.

Table 3 – Kushiro soil profile: elastic parameters and constitutive model assumptions

Layer		Elastic (L) properties				Nonlinear (NL) properties					
Num.	**GL (m)**	V_S **(m/s)**	V_P **(m/s)**	ρ **(kg/m³)**	Q_S	**Degradation curves**			τ_{max} **(kPa)**	**C' (kPa)**	**ϕ' (°)**
						SC1	**SC2**	**SC3**			
1	0-6	140	1520	1800	25	1	1	1	5-20	0	38
2	6-11	180	1650	1800	25	2	2	2	20-30	0	38
3	11-15	230	1650	1500	25	3	3	3	30-40	0	43
4	15-20	300	1650	1500	25	4	3	3	40-50	0	43
5	20-24	250	1650	1600	25	5	4	4	50-60	0	43
6	24-28	370	1650	1600	25	6	5	5	60	0	38
7	28-35	270	1650	1800	25	7	5	5	60-80	0	38
8	35-39	460	1650	1800	25	8	6	6	80-40	259	16
9	39-44	750	1800	2500	75	L	L	L	-	-	-
10	44-84	1400	3400	2500	140	L	L	L	-	-	-
11	84-255	2400	5900	2500	240	L	L	L	-	-	-
Rigid bedrock											

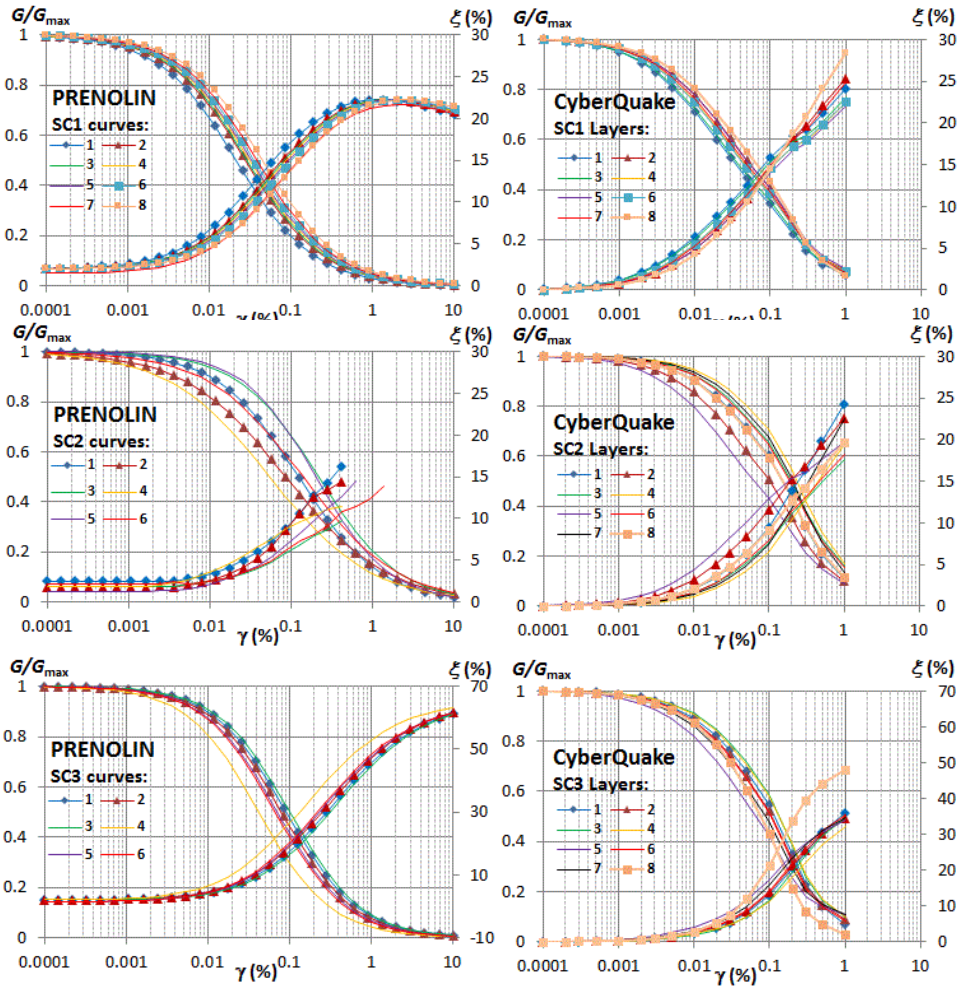

Fig. 3 – Degradation curves for Kushiro soil columns: data (PRENOLIN) and calibration (CyberQuake)

3. Comparison between natural recordings and numerical predictions

3.1 General methodology for a quantitative comparison

In this paper, the agreement between computed and recorded signals (acceleration, etc.) is performed by using the Anderson's methodology [7], which proposes to characterize the similarity by a goodness-of-fit (GOF) based on various ground-motion parameters commonly used in earthquake engineering. The agreement is quantified for each parameter by a GOF score ranging from 0 to 10, 10 meaning a perfect agreement: a GOF score below 4 means a "poor fit"; a score between 4 and 6 is a "fair fit"; a score between 6 and 8 is a "good fit", and above 8, it is considered as an "excellent fit".

Here, we will provide the GOF scores for seven parameters: the peak ground acceleration (PGA), a measure of the damage potential of ground motion (cumulative absolute velocity, CAV [8]), the time duration between 5% and 95% of the Arias intensity (relative significant duration, RSD [9]), the cross-correlation (COR), and the spectral acceleration over 3 frequency bands: between 0.5 and 1 Hz (B1); between f_0-0.5 and f_0+0.5 Hz with f_0, the resonant frequency of the site (B2); between 0.05 and 25 Hz (B3), where 25 Hz was the maximum target frequency for nonlinear computations. f_0 is close to 8 Hz for Sendai site and 2.5 Hz for Kushiro site.

3.2 Results for Sendai site

For each horizontal component of provided motions, participants had to provide nonlinear computation time-history results with prescribed time-step (0.01 sec) and locations: 8 for accelerations (ground surface, layer interfaces and bedrock), and 7 (middle of each soil layer) for stresses and strains. Here, we present a comparison between predicted / recorded quantities for the selected events (Table 1): GOF scores for all soil columns and earthquakes (Fig. 4); surface spectral accelerations (Fig. 5); surface accelerations obtained with the SCE soil column and all earthquakes (Fig. 6), with all soil columns (SCE, SC1, SC2) and the strongest motion TS1 only (Fig. 7); surface spectral accelerations considering various constitutive (nonlinear and equivalent linear) assumptions with the TS1 EW motion only (Fig. 8), as well as PGA and maximum shear strain profiles together with shear stress vs. shear strain curves (Fig. 9).

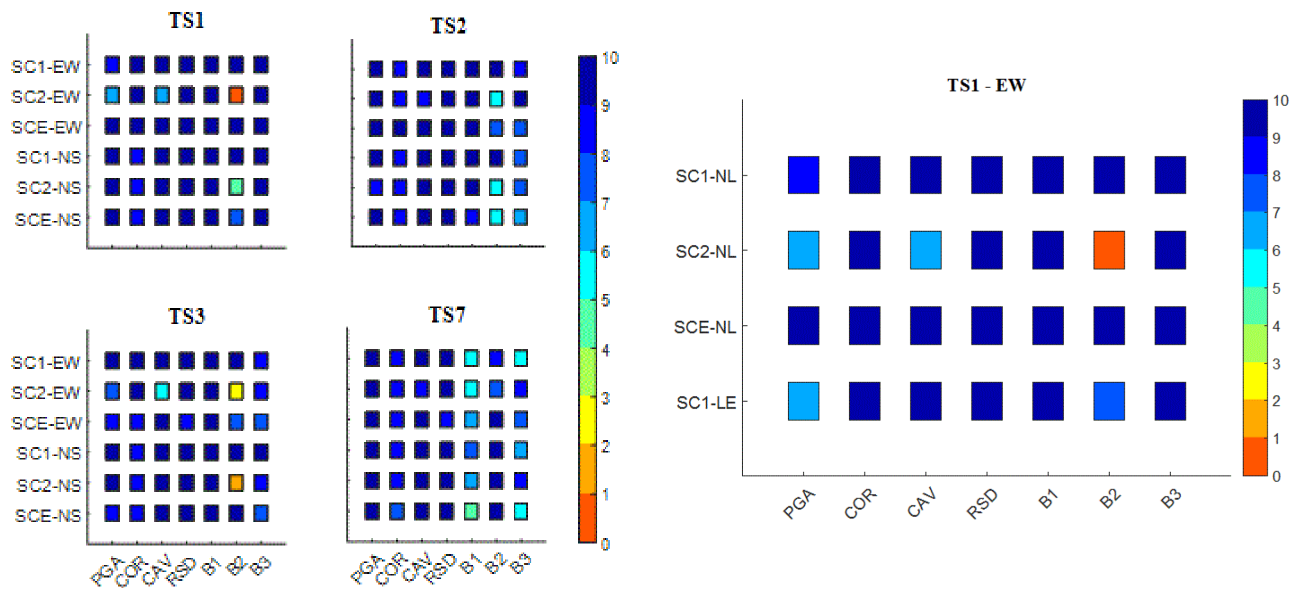

Fig. 4 –GOF scores for all Sendai soil columns: nonlinear predictions with all earthquakes (left); linear and nonlinear predictions for the strongest (TS1-EW) motion (right)

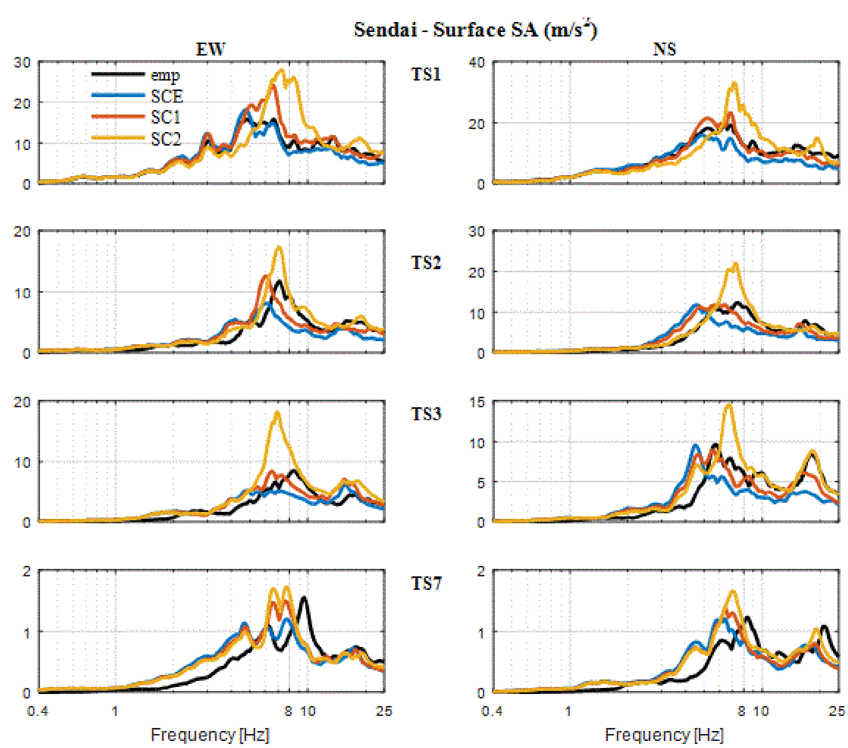

Fig. 5 –Surface spectral accelerations for Sendai selected earthquakes (black: records)

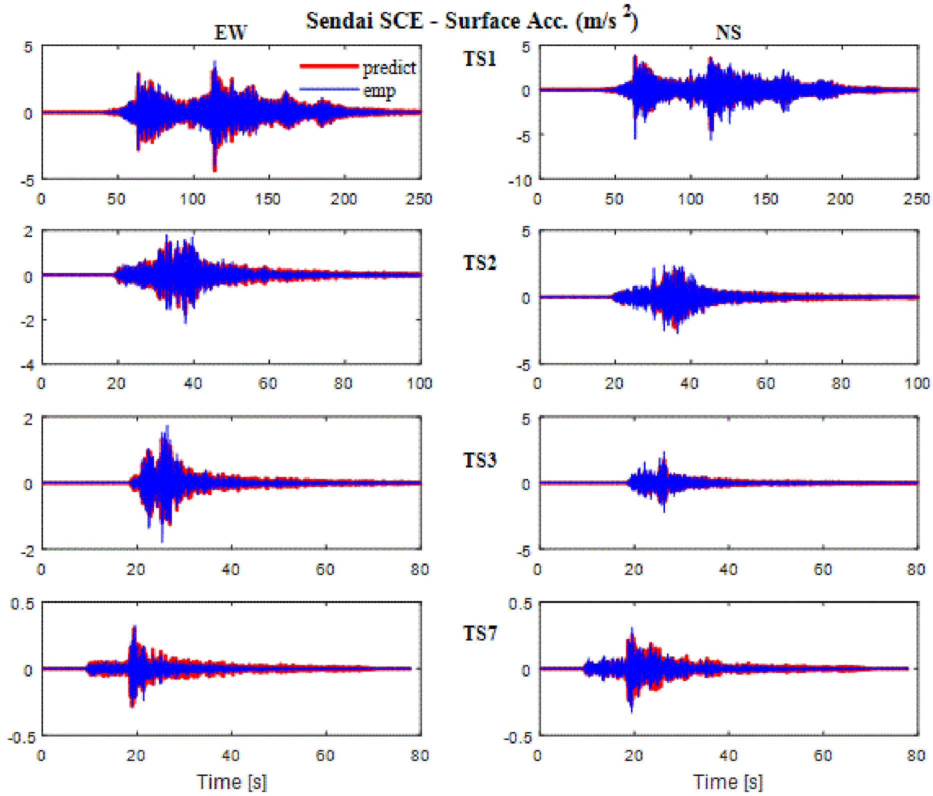

Fig. 6 – Surface accelerations obtained for Sendai selected earthquakes (blue: records; red: predictions)

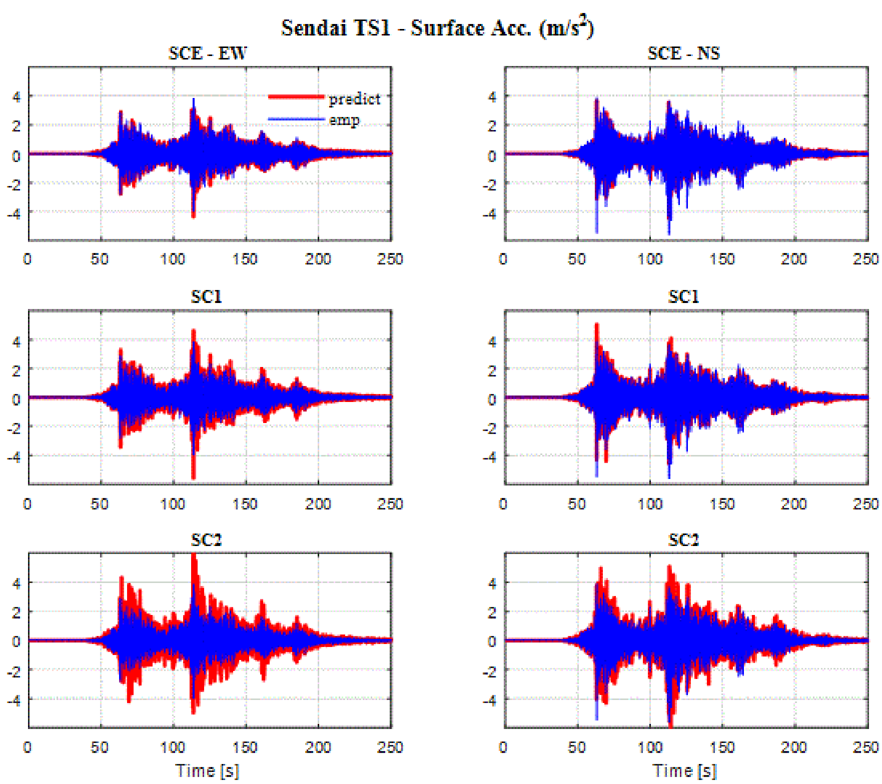

Fig. 7 –Surface accelerations obtained for Sendai TS1 motion (blue: records; red: nonlinear predictions)

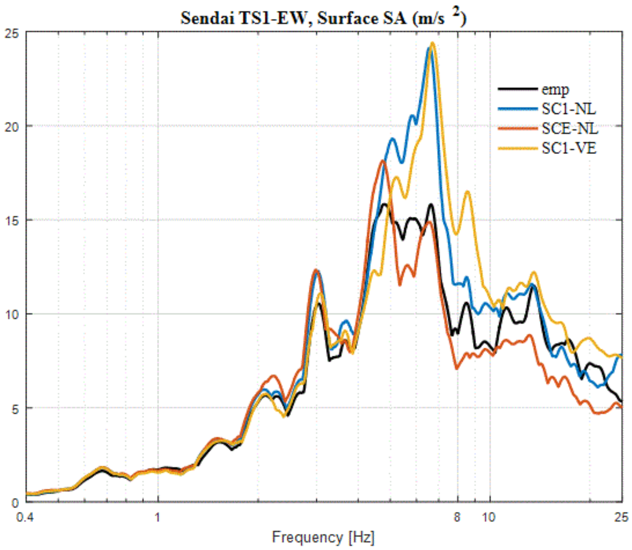

Fig. 8 –Surface spectral accelerations obtained for TS1 EW motion, using lin. equiv. (SC1-VE) and nonlinear (total-stress SC1-NL; effective-stress SCE-NL) approaches (black: records)

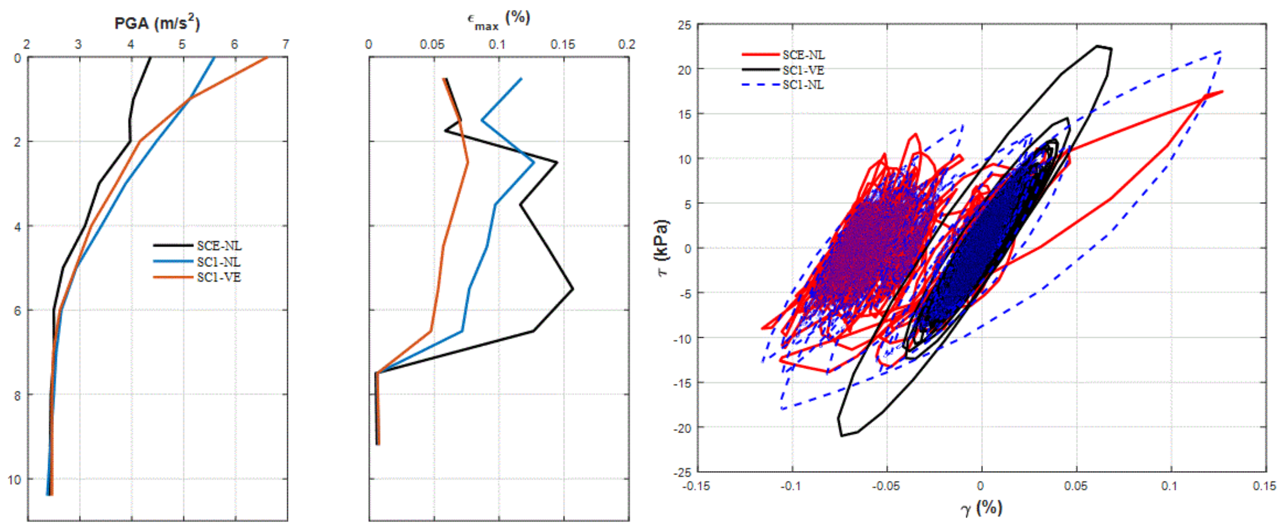

Fig. 9 – Computations for TS1 EW motion, using lin. equiv. (SC1-VE) and nonlinear (total-stress SC1-NL; effective-stress SCE-NL) approaches: PGA (left), maximum shear strain (middle) profiles and shear stress vs. shear strain curves obtained at GL-2.5m (right)

The SCE model (nonlinear effective stress approach) gives results in better agreement with observations, both in time and frequency domains, for weak and strong motions. As expected, we note that the soil response is overestimated with the total-stress approaches (either equivalent linear or nonlinear) when motion becomes strong (for TS1, observed PGA is close to 4 m/s^2), whereas shear strains are underestimated, due to stiffer materials.

3.3 Results for Kushiro site

For this site, participants had to provide results at 12 locations for accelerations (ground surface, layer interfaces and bedrock), and 11 (middle of each soil layer) for stresses and strains. Hereafter, we present the same type of comparisons as in §3.2, for the selected events of Table 2: GOF scores for all soil models and earthquakes (Fig. 10); surface spectral accelerations (Fig. 11); surface accelerations obtained with the SC1 soil model (Fig. 12), and with all soil models (SC1, SC2, SC3), for the strongest motion TS1 (Fig. 13).

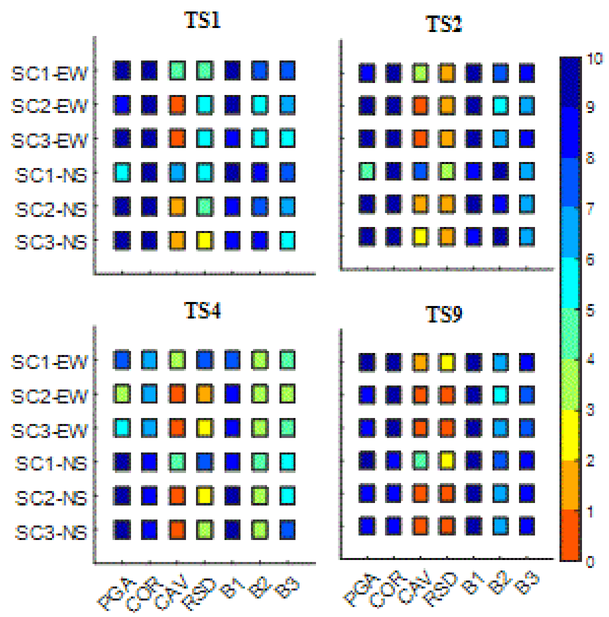

Fig. 10 – GOF scores for all Kushiro soil models and selected earthquakes

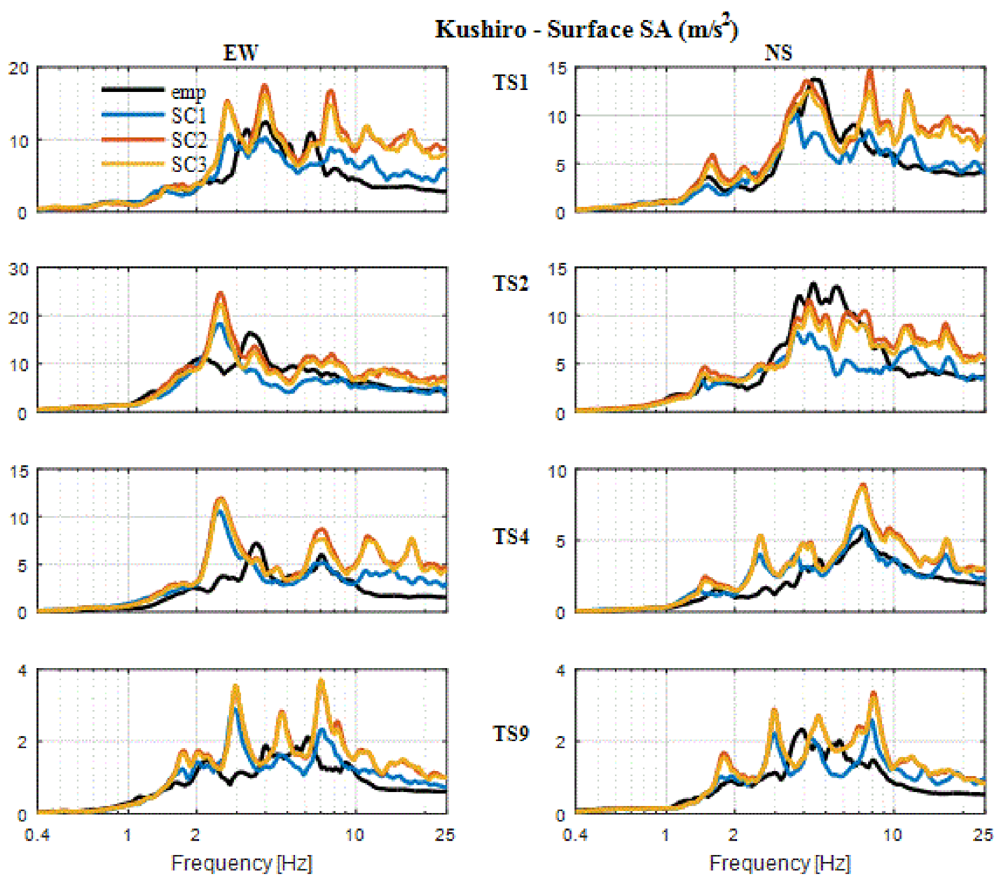

Fig. 11 – Surface spectral accelerations (SA) for Kushiro selected events (black: records)

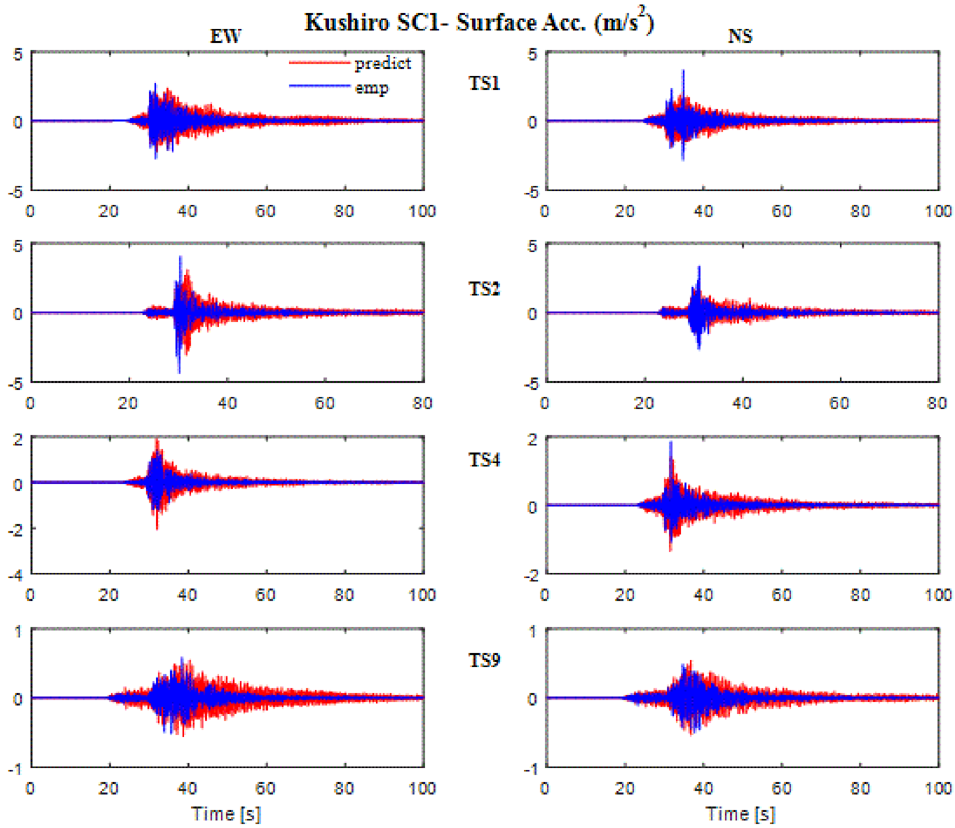

Fig. 12 – Surface accelerations for Kushiro selected events (blue: records; red: predictions)

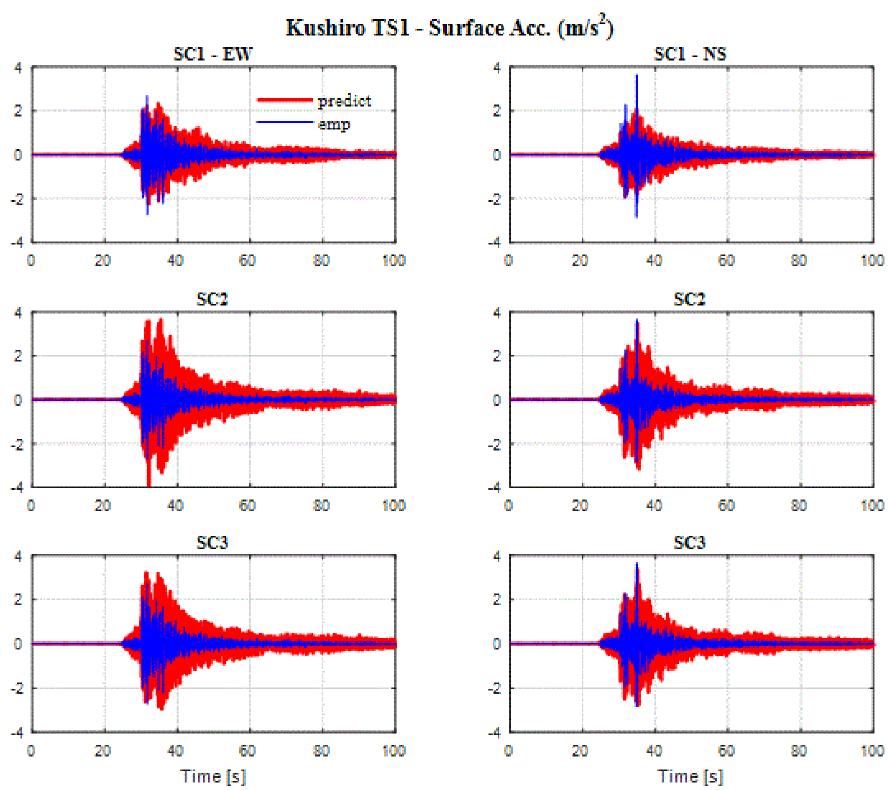

Fig. 13 – Surface accelerations for Kushiro TS1 event (blue: records; red: nonlinear predictions)

Acceleration time histories are in better agreement with observations for the SC1 model (especially for NS component), if we look at PGA GOF scores and waveforms, but however, the soil response seems to be overestimated, whatever the motion (strong or weak). Moreover, the energy and frequency content of the signals are not well captured by any of the soil models, except for low frequencies (low GOF scores for CAV and higher ones for B1 band).

4. Conclusions

In this paper, we have compared the results obtained with the CyberQuake software [1] to field observations for the shallow Sendai and deep Kushiro sites, selecting some weak and strong ground motions, with various frequency contents. For each site, parameters of the elastoplastic constitutive model [2] have been calibrated from degradation curves provided by PRENOLIN.

For the shallow site, various 1D computing assumptions have been compared: the equivalent linear approach (in frequency domain) and the FEM transient dynamic approach with nonlinear (elastoplastic) behavior, for which either an effective or total-stress approach was considered. The nonlinear effective-stress approach seems to give better results for all the selected input motions (waveform, amplitude and frequency content). The total-stress (either equivalent linear or nonlinear) assumptions overestimate the soil response in case of strong motion, and underestimate resulting strains, due to stiffer materials.

For the deep site, the soil response is globally overestimated and frequency content is not well captured. Globally, strong differences have been observed even for weak input motions and for all the benchmark participants. This has raised questions about the 1D assumption and the vertical incidence of input motions. Further investigations and another iteration would have been needed for this site, in order to improve the soil models: during the PRENOLIN benchmark duration, only two computation iterations were performed on Kushiro instead of three for Sendai.

This study also demonstrates the importance of using a methodology for agreement quantification with respect to observations, which enables to assess and compare several parameters representative of the ground motion (amplitude, frequency and energy content, significant duration, …) and hence helps selecting the most appropriate parameters with respect to the foreseen engineering analyses (e.g. structural fragility assessment).

5. Acknowledgments

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6. References

References must be cited in the text in square brackets [1, 2], numbered according to the order in which they appear in the text, and listed at the end of the manuscript in a section called References, in the following format:

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