NONLINEAR RESPONSE OF FIRM GROUND IDENTIFIED FROM VERTICAL ARRAY RECORDS AND ITS SIMULATION USING MULTIPLE MECHANISM MODEL

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ABSTRACT :

In the design procedure of port structures including quay walls in Japan, the residual deformation of structures subject to strong ground motions is often evaluated by finite element analysis. For this analysis, the material parameters should be, in principle, determined based on in-situ geotechnical investigations and laboratory tests. The application of laboratory tests for a firm ground with a shear wave velocity over 300 m/s, however, is quite debatable because, due to a possible disturbance during sampling from the firm ground, the shear strength of the soil, for example, might be significantly underestimated. So far we have no reliable way to determine the model parameters for the firm ground in such analysis, although the results of such analysis are often dependent on how we model the firm ground. During the 2007 Off Mid Niigata Prefecture, Japan, earthquake (M_J6.8), very important data was obtained at a vertical array site KSH in the near-source region operated by the Tokyo Electric Power Company, Inc. (TEPCO). The layers spanned by the vertical array mostly consist of a firm ground with shear wave velocity larger than 300m/s. In this article, the authors try to simulate the response of the vertical array site using a computer program FLIP, which is a finite element code equipped with the multiple mechanism model. The simulation results suggest that use of a typical value of shear resistance angle may lead to underestimation of the shear strength of a firm ground subject to a very strong ground motion.

KEYWORDS: Soil nonlinearity, Firm ground, Vertical array, Multiple mechanism, The 2007 Off Mid Niigata Prefecture earthquake

1. INTRODUCTION

In the design procedure of port structures including quay walls in Japan, it is now a common practice to evaluate the residual deformation of structures subject to strong ground motions using finite element analysis (e.g., PIANC, 2001). For this analysis, the material parameters should be, in principle, determined based on in-situ geotechnical investigations and laboratory tests. The application of laboratory tests for a firm ground with a shear wave velocity over 300 m/s, however, is quite debatable because, due to a possible disturbance during sampling from the firm ground, the shear strength of the soil, for example, might be significantly underestimated. So far we have no reliable way to determine the model parameters for the firm ground in such analysis. Unfortunately, the result of the finite element analysis is often dependent on how we model the firm ground. If we model the firm ground with linear elements, then the residual displacement of a quay wall tends to be smaller. On the other hand, if we allow nonlinear behavior for the firm ground, then we obtain larger residual displacement. Obviously a more reliable basis is needed on which we can determine the model parameters for the firm ground.

During the 2007 Off Mid Niigata Prefecture, Japan, earthquake (M_J6.8), very important data was obtained at a vertical array site KSH in the near-source region, operated by the Tokyo Electric Power Company, Inc. (TEPCO). The layers spanned by the vertical array mostly consist of a firm ground with a shear wave velocity over 300 m/s. The peak ground velocity at the surface was larger than 100 cm/s. The data gave us a rare opportunity to examine how we should model the behavior of a firm ground with shear wave velocity over 300 m/s subject to a very strong ground motion exceeding 100 cm/s. In this article, the authors try to simulate the response of the vertical array site using a computer program FLIP (Iai *et al.*, 1992), which is a finite element code equipped with the multiple mechanism model (Towhata and Ishihara, 1985) and often used in the design practice for the port structures in Japan. The applicability of the code to other vertical array sites has been investigated in the conventional research (e.g., Iai *et al.*, 1995). Based on the results, the authors discuss how we should model a firm ground subject to a very strong ground motion in the finite element analysis.

2. OUTLINE OF VERTICAL ARRAY SITE

The location of the vertical array site KSH is shown in the left panel of Fig.1, together with the location of the epicenter of the 2007 Off Mid Niigata Prefecture, Japan, earthquake (M_J6.8). The site was very close to the earthquake and a very strong ground motion exceeding 100 cm/s was observed at the surface of the site as shown later. The subsurface structure of the site is shown in the right panel of Fig.1. The layers spanned by the vertical array are Holocene dune sand, Banjin formation (sand), Yasuda formation (mudstone) and Nishiyama formation (mudstone). According to the PS-logging, the shear wave velocity is over 300m/s for all of the layers (Fig.1), although the shear wave velocity at the top 25 m was estimated to be less than 300 m/s based on the aftershock data (e.g., Sekiguchi and Nakai, 2007). The seismometers are installed at four depths, namely, GL-2.5m (SG1), GL-50.8m (SG2), GL-99.4m (SG3) and GL-250m (SG4).

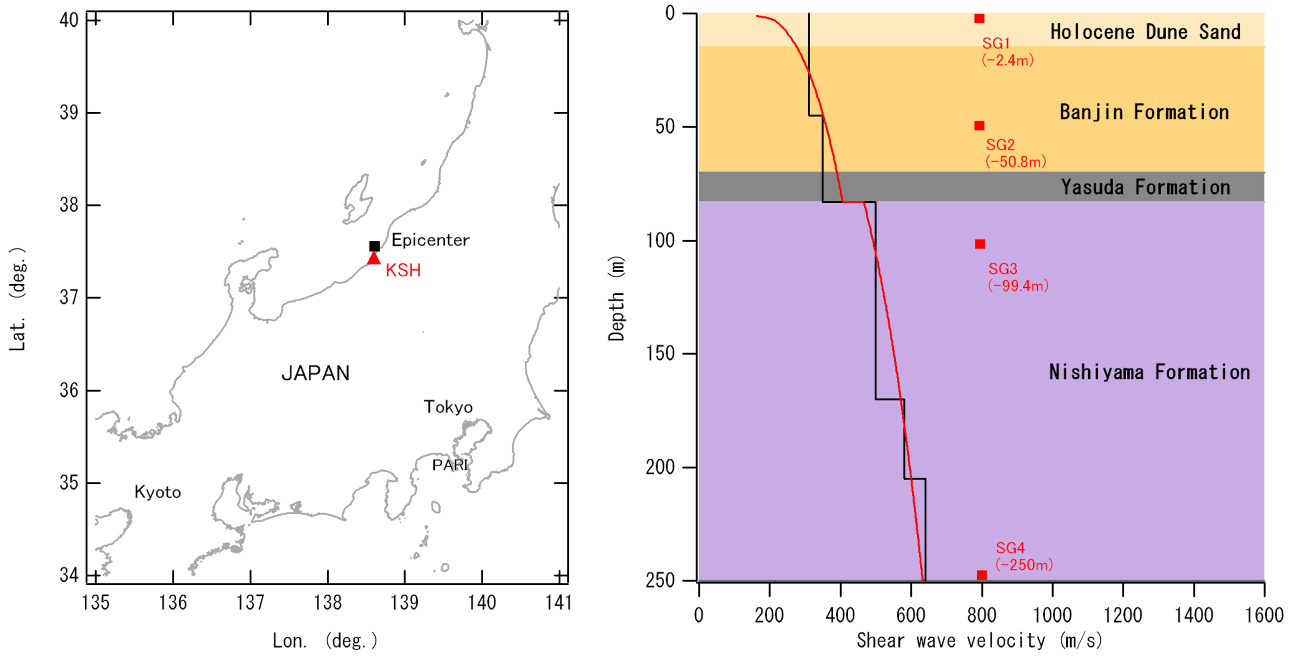

Figure 1 Location (left) and the subsurface structure (right) of the vertical array site. In the right panel, the black line shows the S-wave velocity from the PS-logging and the red line shows the confining-pressure dependent S-wave velocity assumed in the analysis.

3. OUTLINE OF ANALYSIS

One-dimensional response analysis was conducted for the vertical array site using the computer program FLIP (Iai *et al.*, 1992). The program is a finite element code equipped with the multiple mechanism model (Towhata and Ishihara, 1985). Although the program can consider excess pore water pressure, it is neglected in the present analysis because no significant evidence for liquefaction was reported at the site. The model parameters used for the analysis is shown in Table 1. It was assumed that the initial shear modulus G_{m0} is proportional to the square root of the confining pressure as

$$G_{m0}= G_{ma}(\sigma_{m0}' / \sigma_{ma}')^{0.5}, \tag{3.1}$$

in which σ_{ma}' is the reference confining pressure and G_{ma} is the initial shear modulus at the reference confining pressure. G_{ma} was determined so that the resultant shear wave velocities at small strain become consistent with the PS-logging data (see the red line in Fig.1). It was also considered in the determination of G_{ma} that the shear wave velocity at the top 25-30 m might be less than 300 m/s at small strain. In the analysis, in addition to the hysteresis damping, we considered the Rayleigh damping with a coefficient β of 0.002 (which roughly corresponds to h=0.003). The value of the coefficient will be discussed later. The shear resistance angle ϕ_f is used to determine the shear strength of the soil as

$$\tau_{m0}=(-\sigma_{m0}')\sin\phi_f \quad (3.2)$$

It should be noted that, in this analysis, ϕ_f should be regarded simply as a parameter indicating the shear strength of the soil, instead of a physical internal friction angle, because the value is applied not only for sand but also for mudstone.

Table 1 Model parameters for the analysis

Layer No.	Layer Name	H (m)	ρ (t/m^3)	σ_{ma} (kPa)	G_{ma} (kPa)	h_{max}	ϕ_f (deg)
1	Holocene dune sand	15.0	1.8	98	130000	0.3	36
2	Banjin formation	55.0	1.8	98	130000	0.3	36 or 84
3	Yasuda formation	13.0	1.8	98	130000	0.3	36 or 84
4	Nishiyama formation	167.0	2.0	98	190000	0.3	36 or 84

4. SIMULATION FOR SMALL EVENT

First, the response of the site for a small event was simulated to investigate the validity of the parameters G_{ma} and β. The observed accelerations at SG4 (2005/6/20 13:03; M_J=5.0; PGA=11Gal for EW component and 20 Gal for NS component) was used as input motions. The recorded and simulated Fourier spectral ratios are compared in Fig.2 (All of the Fourier spectra in this article are the vector sum of two horizontal components and Parzen-windowed with a band width of 0.05Hz). The recorded spectra correspond to five events (2005/6/20 13:03, 2005/8/21 11:29, 2006/12/26 5:17, 2007/1/8 18:59, 2007/3/25 18:11). Because the observed peak frequencies up to 4th order are reproduced correctly in the simulation, the assumed G_{ma} (Table 1) was appropriate. On the other hand the peak value of the spectral ratio for the fundamental mode is overestimated significantly. The use of a larger value of β does not improve the results (Fig.3). The reason for the discrepancy can be explained as follows. If all of the seismic waves are travelling vertically, the negative interference between the upcomming and downgoing waves produces a spectral hole for the records at depths and a high peak appears in the surface to depths spectral ratios. If the records are contaminated with obliquely

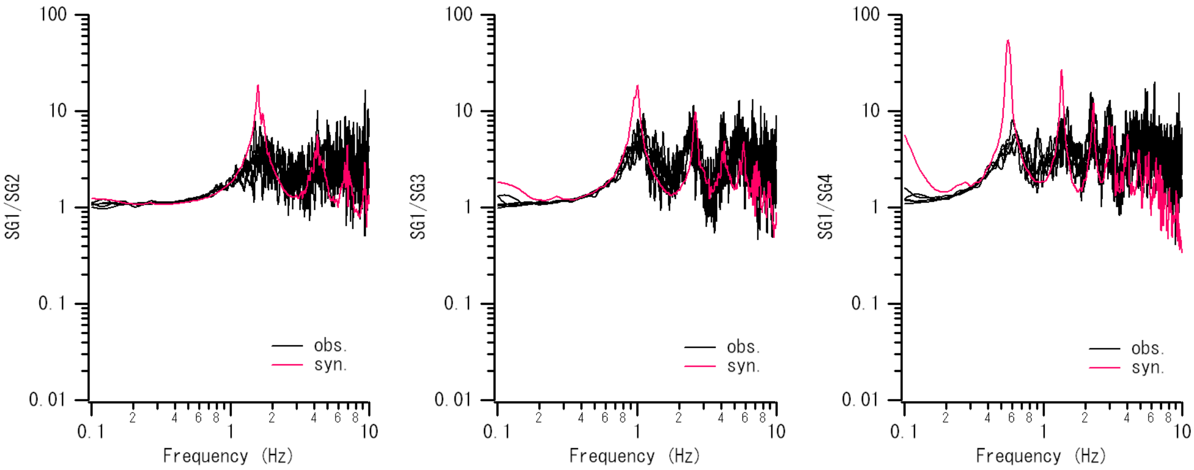

Figure 2 The recorded (black) and simulated (red) Fourier spectral ratios for small events. The simulated spectral ratios were obtained with β =0.002.

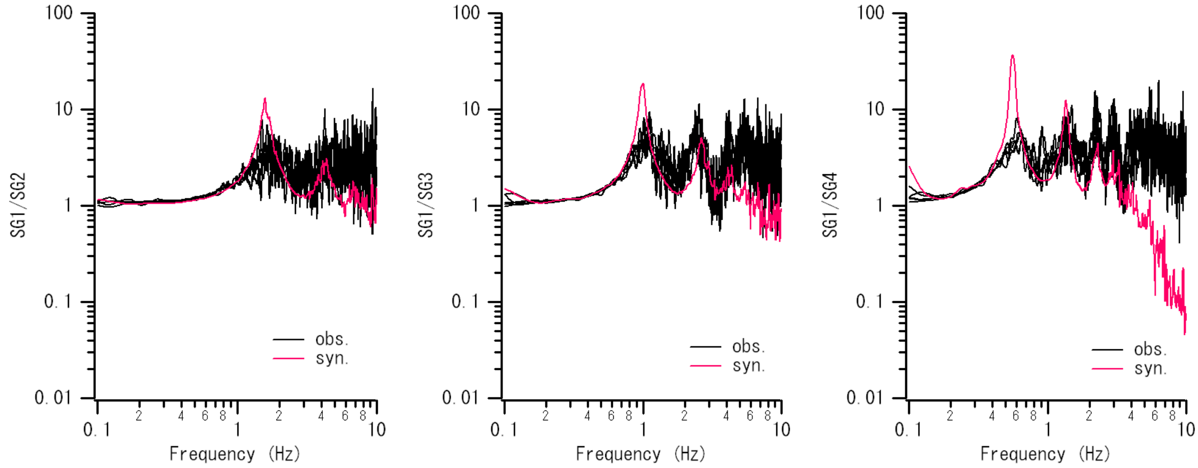

Figure 3 The recorded (black) and simulated (red) Fourier spectral ratios for small events. The simulated spectral ratios were obtained with β =0.01.

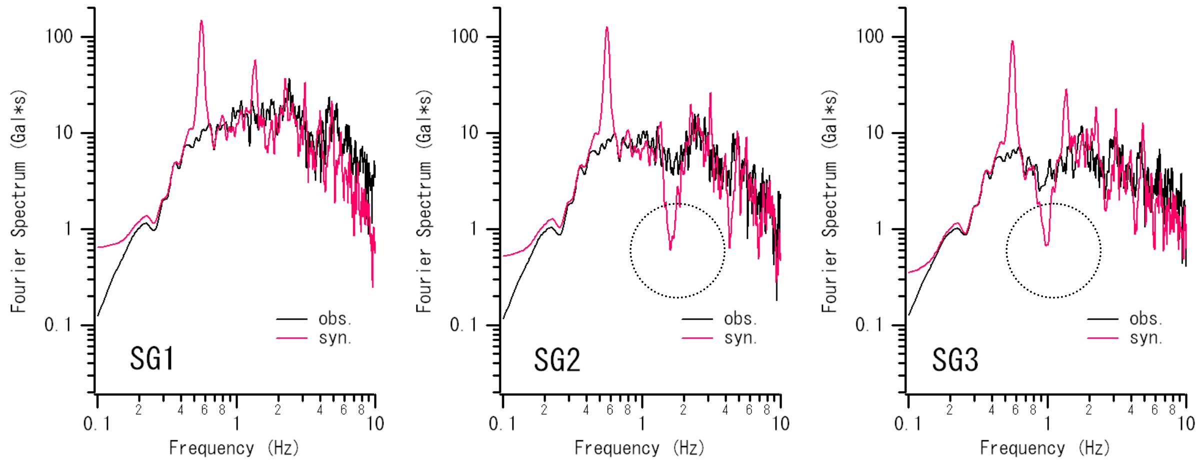

Figure 4 The recorded (black) and simulated (red) Fourier spectra for a small event (2005/6/20 13:03). The simulated spectra were obtained with β =0.002.

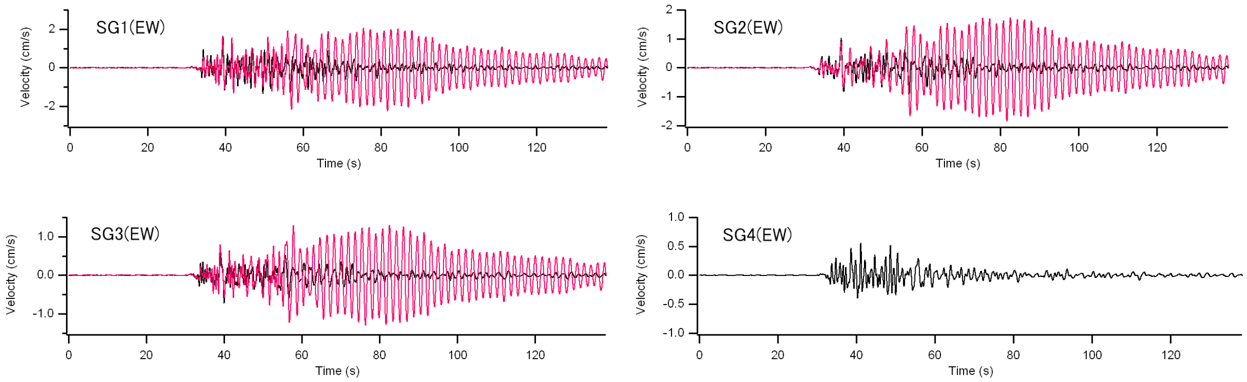

Figure 5 The recorded (black) and simulated (red) velocity waveforms (0.2-2 Hz) for a small event (2005/6/20 13:03). The simulated waveforms were obtained with β =0.002.

travelling body waves or surface waves the peak value of the ratio is significantly reduced because the denominator is not close to zero anymore. This seems to be the case for the response of the vertical array site for a small event. We can see this phenomenon more clearly by comparing the observed and simulated Fourier spectra for a small event (Fig.4). Although the simulated spectra for SG2 and SG3 have a clear hole around 1.5 Hz and 1.0 Hz, respectively (indicated by dotted circles), only a slight hole can be found in the observed spectra. This indicates that the observed ground motions are contaminated with obliquely traveling body waves or surface waves. The same conclusion can be reached by comparing the observed and simulated velocity waveforms for a small event (Fig.5). Although the discrepancy is significant for the later phases, the simulation results are good for the portions with duration of approximately 20 s after the S wave arrival, for which vertically traveling waves might be predominant. Thus the authors conclude that the value of the coefficient β =0.002 is appropriate for the site and use the same value in the following analysis for the large event.

5. SIMULATION FOR LARGE EVENT

Next, the response of the site for the large event was simulated to investigate the validity of the shear resistance angles used in the analysis. The observed accelerations at SG4 (2007/7/16 10:13; M_J=6.8; PGA=728Gal for EW component and 430 Gal for NS component) was used as input motions. If we assume linear soil properties, significant discrepancy arises between the observed and simulated Fourier spectral ratios (Fig.6). Thus the response of the site was obviously nonlinear during the large event. Then we conduct two cases of nonlinear analysis. In one case, the shear strength of the soil is evaluated with a typical value of shear resistance angle of $\phi_f=36^\circ$ for all of the layers. In the other case, very large shear strength is assumed for the firm ground (Banjin formation, Yasuda formation and Nishiyama formation) corresponding to a shear resistance angle of $\phi_f=84^\circ$. The simulation results are compared with the observed ones in Figs.7-14 in terms of Fourier spectral ratios, Fourier spectra, velocity waveforms and acceleration waveforms. As shown in Fig.7, the peak value of the Fourier spectral ratio SG1/SG4 is underestimated if we use $\phi_f=36^\circ$ for the firm ground (dotted circles). On the other hand, if we use $\phi_f=84^\circ$ for the firm ground, the peak value can be reproduced quite reasonably (dotted circles in Fig.8). Similarly, if we use $\phi_f=36^\circ$ for the firm ground, Fourier spectra, velocity waveforms and acceleration waveforms are underestimated (Figs. 9,11 and 13). If we use $\phi_f=84^\circ$ for the firm ground, all of these spectra and waveforms can be reasonably reproduced (Figs. 10,12 and 14). Thus we can conclude that use of a typical value of $\phi_f=36^\circ$ in Eqn. 3.2 may lead to underestimation of the shear strength of the firm ground. From Figs. 11-14, it can be seen that ground motions for the large event have a shorter duration compared with the small event and seem less contaminated with surface waves. Thus they can be reproduced better than the small event ground motions with the present analytical model. Multiple nonlinear effects (Nozu, 2004) might have reduced the surface wave components included in the large event ground motions.

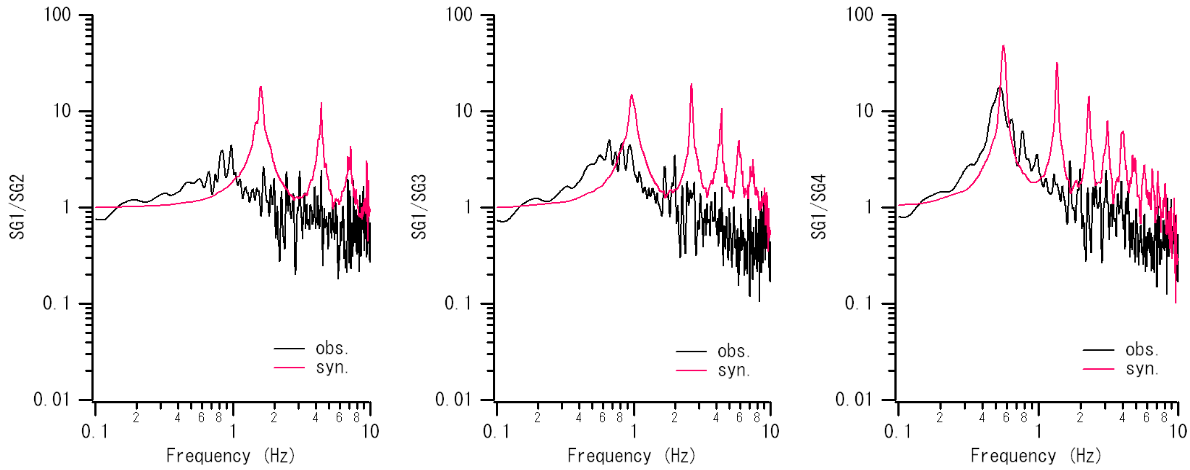

Figure 6 The recorded (black) and simulated (red) Fourier spectral ratios for the large event. The simulated spectral ratios were obtained assuming linear response of the site.

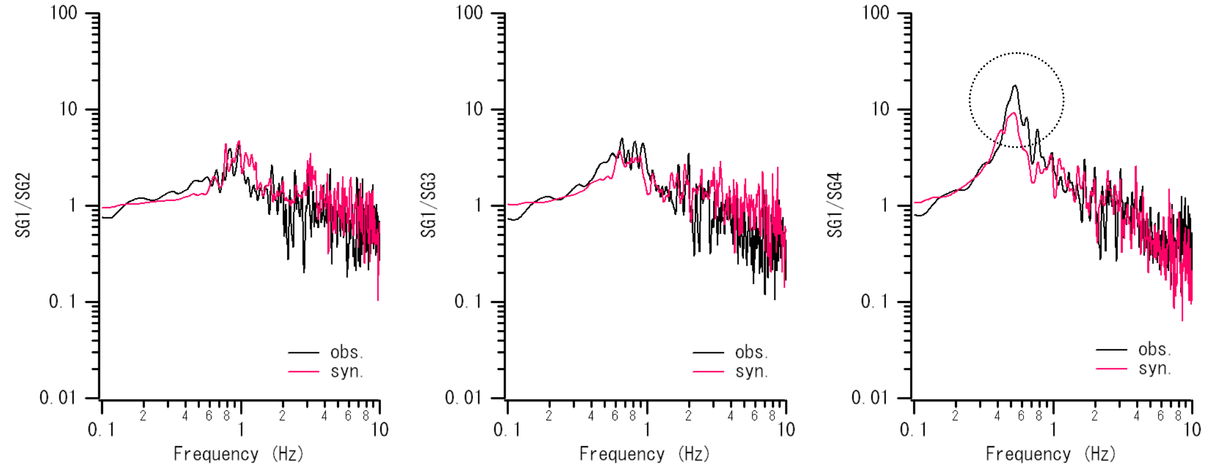

Figure 7 The recorded (black) and simulated (red) Fourier spectral ratios for the large event. The simulated spectral ratios were obtained with $\phi_f=36^\circ$ for the firm ground.

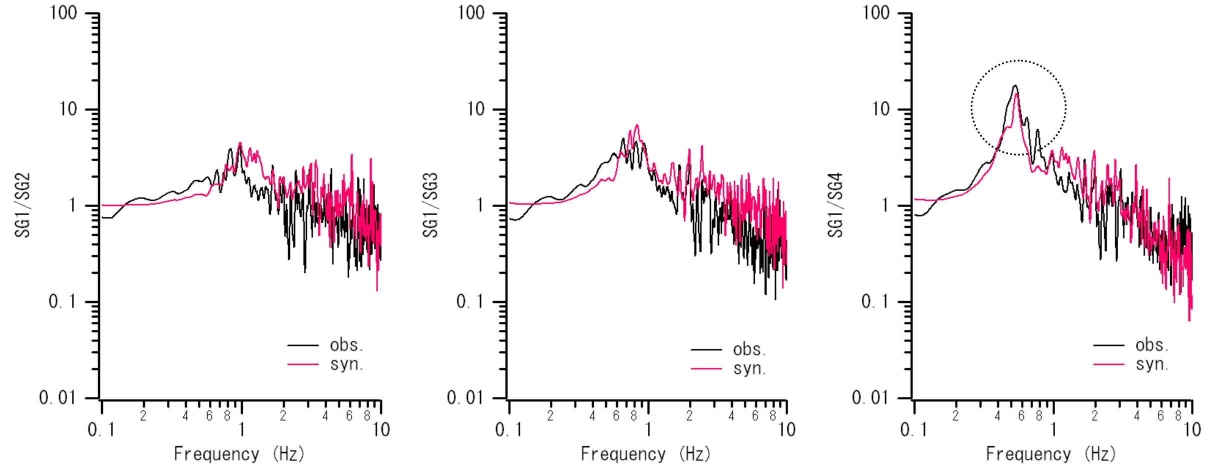

Figure 8 The recorded (black) and simulated (red) Fourier spectral ratios for the large event. The simulated spectral ratios were obtained with $\phi_f=84^\circ$ for the firm ground.

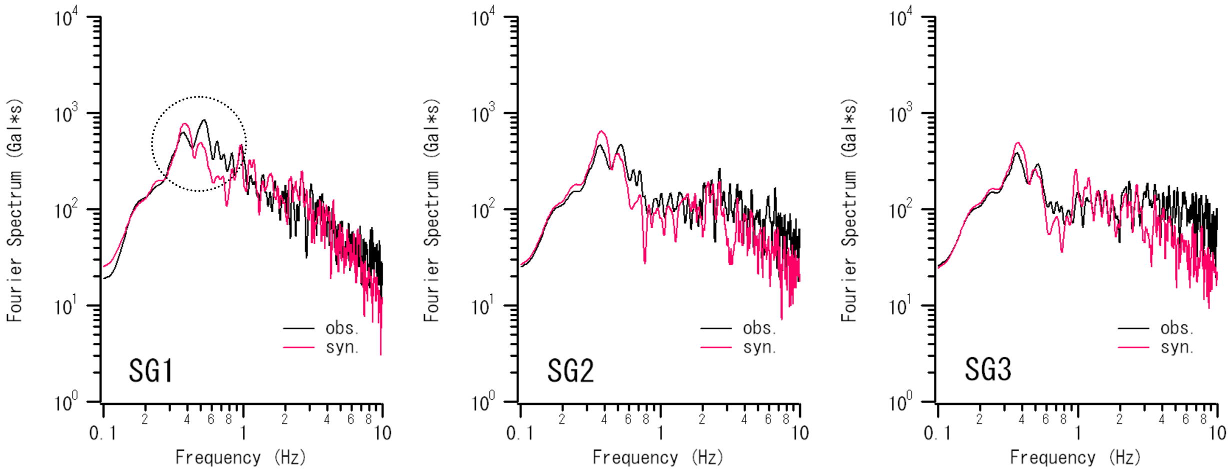

Figure 9 The recorded (black) and simulated (red) Fourier spectra for the large event. The simulated spectra were obtained with $\phi_f=36^\circ$ for the firm ground.

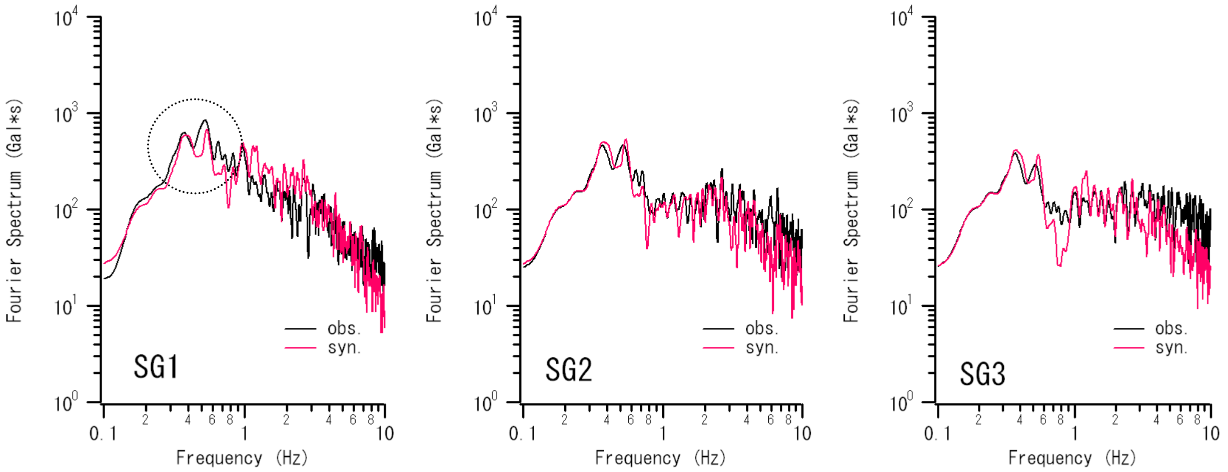

Figure 10 The recorded (black) and simulated (red) Fourier spectra for the large event. The simulated spectra were obtained with $\phi_f=84^\circ$ for the firm ground.

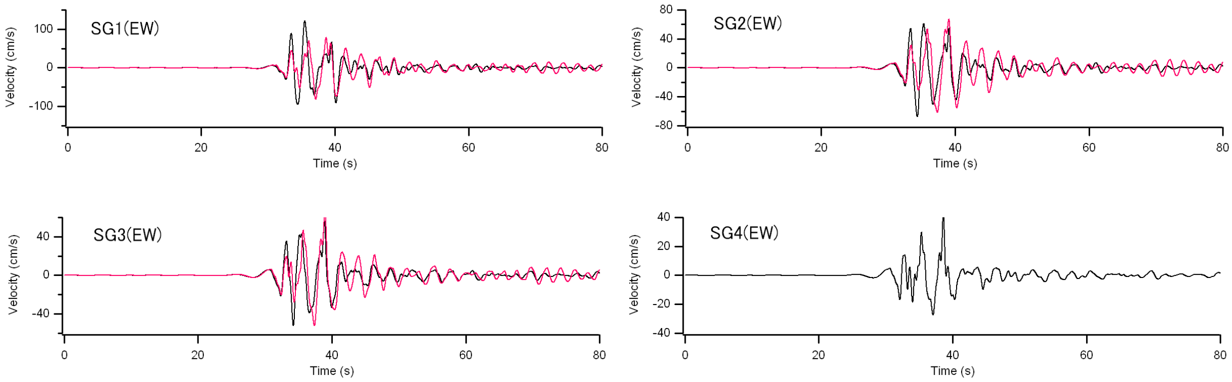

Figure 11 The recorded (black) and simulated (red) velocity waveforms (0.2-2 Hz) for the large event. The waveforms were obtained with $\phi_f=36^\circ$ for the firm ground.

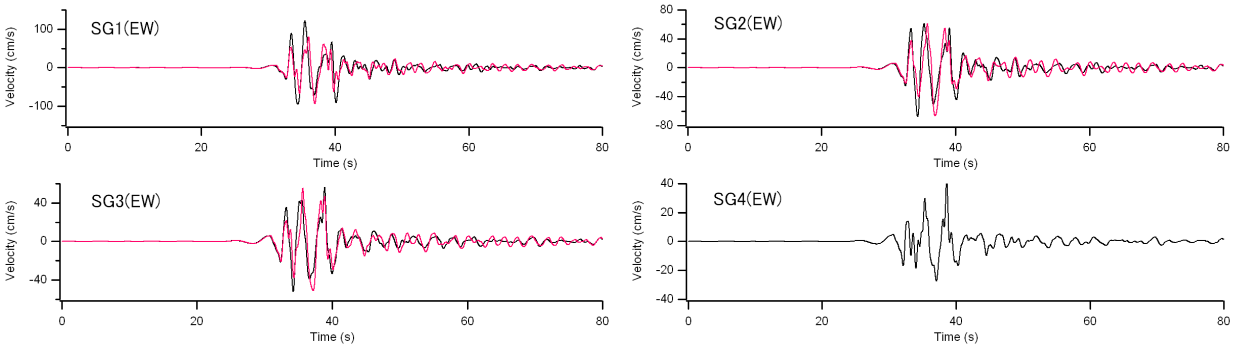

Figure 12 The recorded (black) and simulated (red) velocity waveforms (0.2-2 Hz) for the large event. The waveforms were obtained with $\phi_f=84^\circ$ for the firm ground.

6. CONCLUDING REMARKS

In this article, the authors tried to simulate the response of a vertical array site located in the near-source region of the 2007 Off Mid Niigata Prefecture, Japan, earthquake (M_J6.8) using a computer program FLIP. The layers spanned by the vertical array mostly consist of a firm ground with a shear wave velocity over 300 m/s. According to the simulation results, it was suggested that use of a typical value of shear resistance angle may

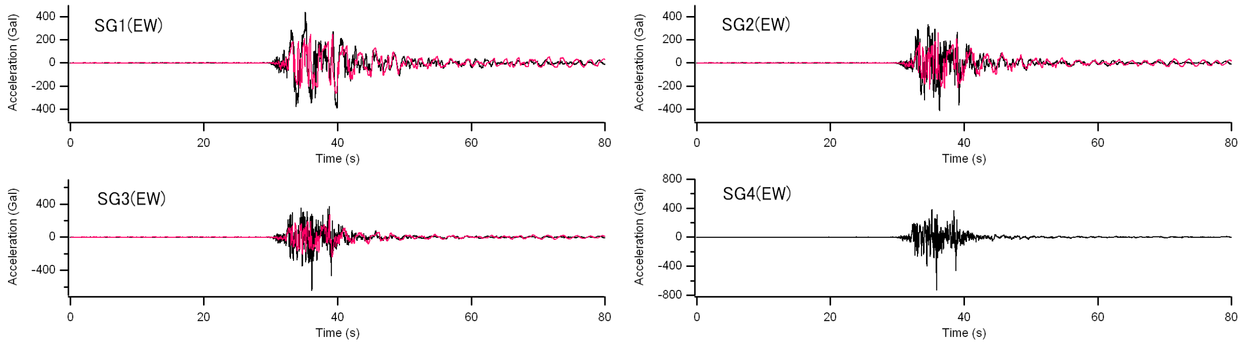

Figure 13 The recorded (black) and simulated (red) acceleration waveforms for the large event. The waveforms were obtained with ϕ_f=36° for the firm ground.

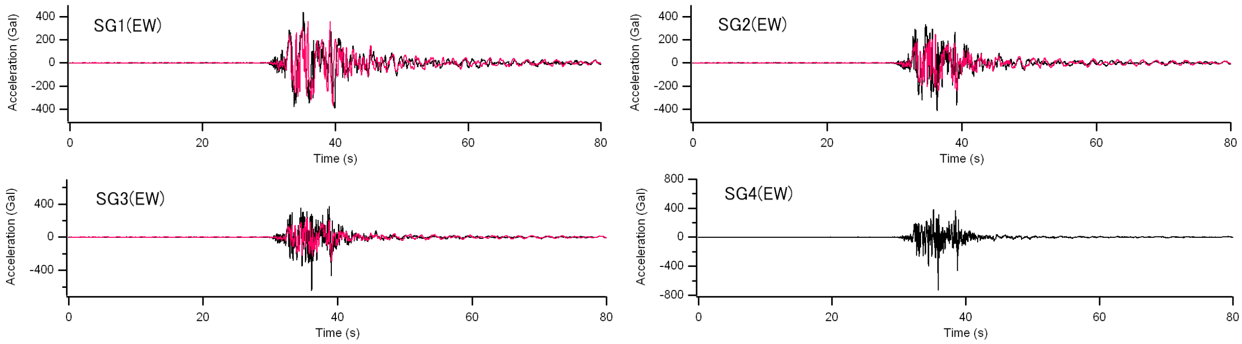

Figure 14 The recorded (black) and simulated (red) acceleration waveforms for the large event. The waveforms were obtained with ϕ_f=84° for the firm ground.

lead to underestimation of the shear strength of a firm ground and overestimation of the shear deformation of a firm ground subject to a very strong ground motion. The authors hope that the result would provide reasonable and useful constraints on the future analysis of quay wall deformation.

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