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Paper No. 1576. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

SEISMIC AMPLIFICATION OF SURFACE LAYERS IN THE 1994 FAR-OFF SANRIKU EARTHQUAKE

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ABSTRACT

Nonlinear ground responses of the site of Hachinohe Institute of Technology are investigated by use of observed earthquake records and nonlinear response analysis. First, the surface layer of about 15*m* depth, which mainly consists of volcanic ashes and underlying diluvium sand layer, are modeled by soil profile data. The linear part of the initial model is modified by use of 60 low level earthquake records. Finally the nonlinear parameters are estimated by the records of the 1995 Off-Iwate Prefecture earthquake, which includes the highest acceleration value over 600*gal* on the surface. The estimated nonlinear ground model shows good agreement with the observed response under the strain level of 10^{-3}. Using the model, amplitude-saturated records of the site during the 1994 Far-Off Sanriku earthquake are appropriately restored. The estimated nonlinear soil model is also effective in the eastern area of the vicinity of Hachinohe, where the same type of surface layer is widely observed.

KEYWORDS

the 1994 Far-Off Sanriku earthquake; the 1995 Off-Iwate Prefecture earthquake; Hachinohe; dense strong-motion array observation, nonlinear ground motion; seismic amplification; surface layer

INTRODUCTION

The 1994 Far-Off Sanriku earthquake (M 7.5 in JMA scale) occurred on December 28, 1994, about 30*km* south from the epicenter of the 1968 Off-Tokachi earthquake. The JMA seismic intensity scale was VI in Hacninohe city. During this earthquake two persons died by the collapse of a building and heavy damages were caused in and around Hachinohe. The 1995 Off-Iwate Prefecture earthquake (M 6.9), the largest aftershock of the Far-Off Sanriku earthquake, occurred on January 7,1995 and many damages were caused in Hachinohe again.

The Far-Off Sanriku earthquake and the largest aftershock were very similar in the acceleration level and the duration of earthquake (Takita *et al.*, 1995). However these earthquakes differed with the distribution of the damaged area in Hachinohe. The central area and the western area were damaged during the mainshock and the eastern area was damaged during the largest aftershock. It is clarified that the difference of the damaged area in Hachinohe is representative from the difference of predominant period of subsurface layers (Moro,

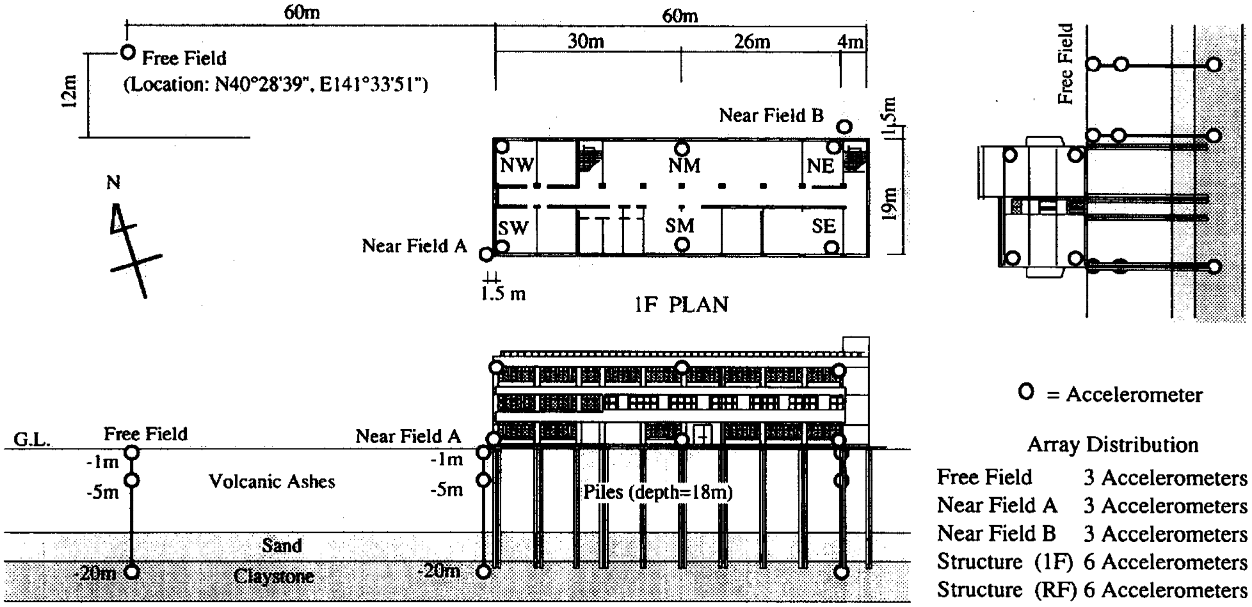


Fig.1 Dense strong-motion array observation system of Hachinohe Institute of Technology

1995; Ohara *et al.*, 1995; Okawa *et al.*, 1995). Furthermore, the strong nonlinearity of subsurface layers during the Far-Off Sanriku earthquake is clarified from the study on the subsurface layers at JMA Hachinohe station (Kato *et al.*, 1995). Then it will be important to evaluate the nonlinearity of the subsurface layers during the strong earthquake motion and to clarify the ground response characteristics of the subsurface layers.

Hachinohe Institute of Technology is at the southeast area of Hachinohe where is included in the area damaged during the largest aftershock. The dens strong-motion array observation system was started on April 1987 and the authors have been studied on the three dimensional motions of the soil-structure system during earthquakes (Takita *et al.*, 1988). About 850 earthquakes were recorded by the array system from 1987. It will be considered that the amount of the records is sufficient for the statistic study on the earthquake motion. The records of the 1994 Far-Off Sanriku earthquake were amplitude saturated in some channels. In the ground surface the acceleration level was exceeded the amplifier range (300*gal*). At the top of the building the level was exceeded the limit of the accelerometers (1000*gal*). After the mainshock the amplifier range of all accelerometers was up to 1000*gal*, then the largest aftershock was recorded without saturation at all points of the ground.

The purpose of this study is to clarify the seismic amplification of the surface layers at the site of Hachinohe Institute of Technology and obtain the information that will be used to the study on the ground response properties of the damaged area in Hachinohe. The procedure of this study is summarized as follows. First, the surface layers are modeled by soil profile data. The linear part of the initial model is modified by use of 60 low level earthquake records. Finally the nonlinear parameters are estimated by the records of the largest aftershock.

OUTLINE OF THE EARTHQUAKE RECORDS

Fig.1 is an illustration of the array system. The array system has 21 accelerometers and records 63 components. The accelerometers are set on the building of department of architecture and in the ground around the building. The building is a pile supported reinforced concrete structure with three stories. The accelerometers in the ground are separated to three points: Free Field point, Near Field A point and Near Field B point. In each point accelerometers are set in the depth 1*m*, 5*m* and 20*m* from the ground surface. Fig.2 shows the soil profile logged at Near Field A point. The soil layers of the ground are separated to surface layer, volcanic

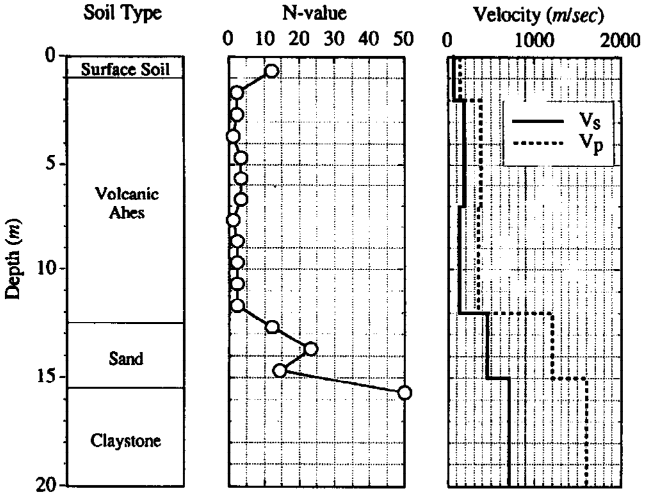


Fig.2 Soil profile at Near Field A point

Table 1 Frequency distribution of input acceleration level at Free Field G.L.-20*m*. The largest acceleration value is about 627*gal* that was recorded during the largest aftershock of the 1994 Far-Off Sanriku Earthquake.

Input Acce.Level (gal)	Record Frequency at Free Field Point			
	G.L.-20m		G.L.-1m	
	EW	NS	EW	NS
0.0 ~ 0.8	0	0	0	0
0.8 ~ 2.5	114	119	0	0
2.5 ~ 8.0	33	29	78	75
8.0 ~ 25.0	7	4	68	70
25.0 ~ 80.0	0	3	6	6
80.0 ~ 250.0	2	3	2	3
250.0 ~ 400.0	0	0	1	2
400.0 ~	0	0	1	0

ashes, sand and claystone. It is considerable, from soil boring log data, that the layers are plain. The base rock of this site is in the depth about 15.5*m* from the surface. The surface layers of the site are very soft and the Vs values of them are about 70*m*/*sec* ~ 460*m*/*sec* (see Fig.2 and Fig.4). The Vs value of the base rock is about 700*m*/*sec*.

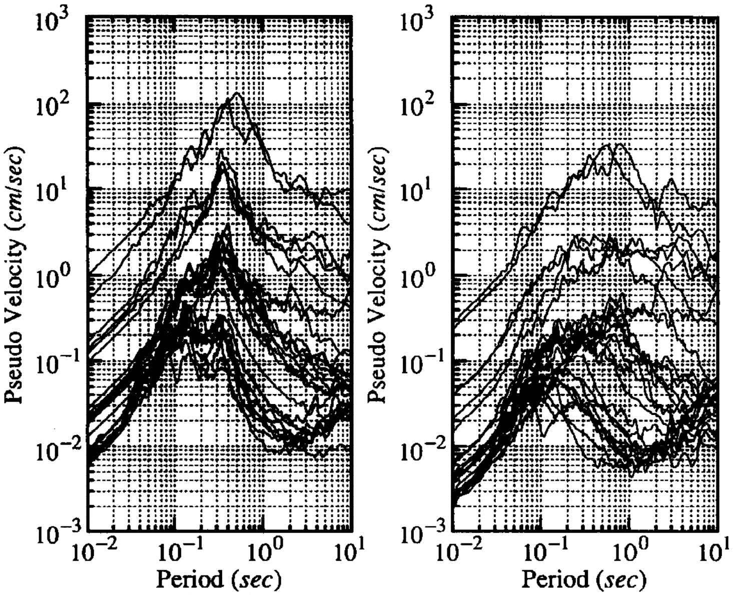
The 156 earthquake records were used in the study. They were selected by the input acceleration level that is greater than 1.0*gal* at the Free Field G.L.-20*m* point. Table 1 shows the frequency distribution of the acceleration level of the selected records. The largest acceleration value is about 630*gal* that was recorded during the 1995 Off-Iwate Prefecture earthquake (the largest aftershock of the 1994 Far-Off Sanriku earthquake). The record of the 1994 Far-Off Sanriku earthquake was amplitude saturated at the level of 300*gal*. It was found that the record of the mainshock includes some distortions affected by the trouble of circuit of the recorder too.

ESTIMATION OF THE LINEAR SOIL MODEL

At first we sorted the selected 156 records by their energy level. The energy level of an earthquake was estimated, for convenience, by the value of the harmonic mean of power spectra of EW and NS components recorded at Free Field G.L.-20*m*. The power spectra were calculated in the range from 0.0*Hz* to 30.0*Hz*.

Fig.3 shows 26 pseudo velocity response spectra. They were selected from the spectra of 156 records. The energy level of the earthquake corresponds with the first 10 spectra, the second 10 spectra and the last 6 spectra are the lowest level, moderate level and the highest level, respectively. From Fig.3 (a), it is clear that the predominant period shifts from about 0.3*sec* to 0.5*sec* when the energy level becomes greater. This indicates the nonlinearity of the surface layers of the site. The shift of the predominant period is shown in Fig.3 (b), too. This indicates that the nonlinearity of the base rock would be occurred during strong earthquakes.

Fig.4 shows Vs value and unit weight in each soil layer. These parameters were applied to the linear analysis. In the analysis, the soil layers were modeled by spring-mass model with 40 nodes. The layers were divided every 50*cm* thickness to keep the accuracy of the analysis. The viscous damping was defined as constant $2h\omega_1$ to evaluate the independence from frequency of the soil response. Here ω_1 is the first natural circular frequency of the ground. Damping constant h was defined as 2%. The response analysis was executed by Wilson's θ method. The unit weight of the soil was experimentally decided. The Vs values obtained by P-S logging were modified by the following procedures. At first the natural frequencies were evaluated from the transfer function and coherence that are calculated from 60 earthquake records with lower energy level. Next Vs values were



(a) Free Field G.L.-1m (b) Free Field G.L.-20m

Fig.3 The examples of pseudo velocity response spectra: the 10 spectra of the earthquakes with low energy level, 10 spectra of the earthquakes with moderate energy level and the 6 spectra of the earthquakes with the largest energy level. The largest two spectra are calculated by the mainshock and the largest aftershock of the 1994 Far-Off Sanriku earthquake.

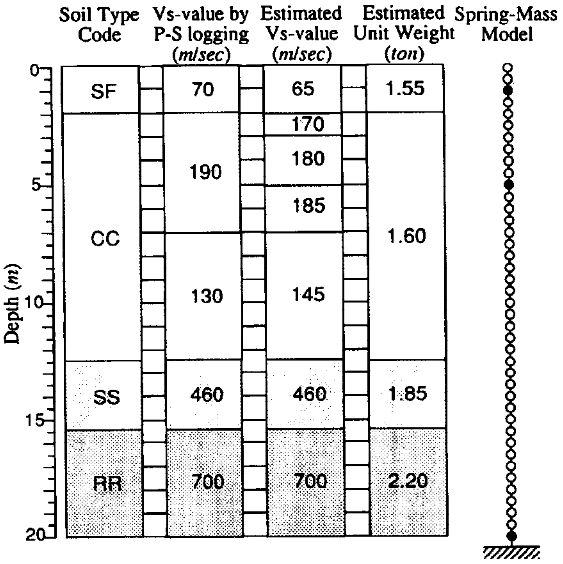


Fig.4 Estimated soil parameters for linear analysis and the spring-mass model: code SF, CC, SS and RR correspond with surface layer, volcanic ashes, sand and claystone, respectively. Filled circle of the model indicates the location of the accelerometer.

modified as the natural frequencies of the model agree with the natural frequencies evaluated from the observed records. In the parameter determination the accuracy of the model was increased by evaluating the correlerations among the points G.L.-1*m*, G.L.-5*m* and G.L.-20*m*.

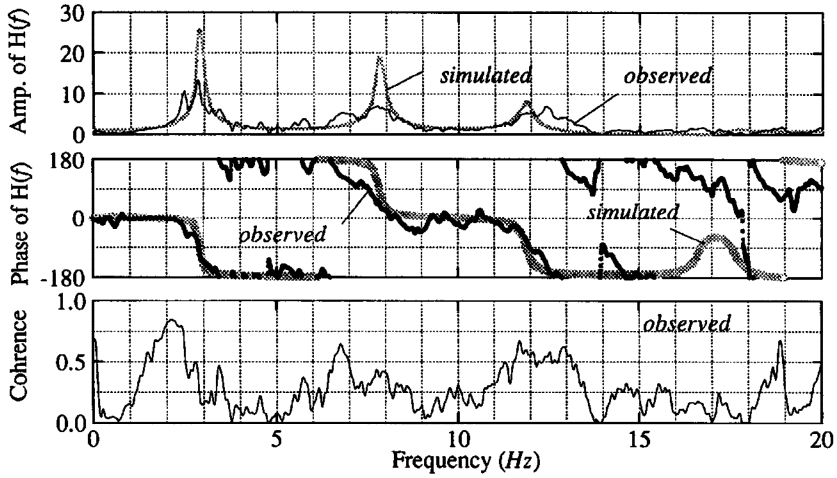
Fig.5 is the comparison of the transfer function calculated from 60 earthquake records with the transfer function simulated by the linear model. The lowest three natural frequencies of the ground, that are evaluated by the transfer functions of the observed records, are f_1=2.9*Hz*, f_2=7.7*Hz* and f_3=12.0*Hz*. The simulated transfer functions show agreement with the observed transfer functions in the frequency range lower than the third natural frequency f_3. The simulated results show agreement qualitatively with the observed results in phase aspect. Then it will be considered that the linear spring-mass model in Fig.4 is reasonable.

ESTIMATION OF THE NONLINEAR SOIL MODEL

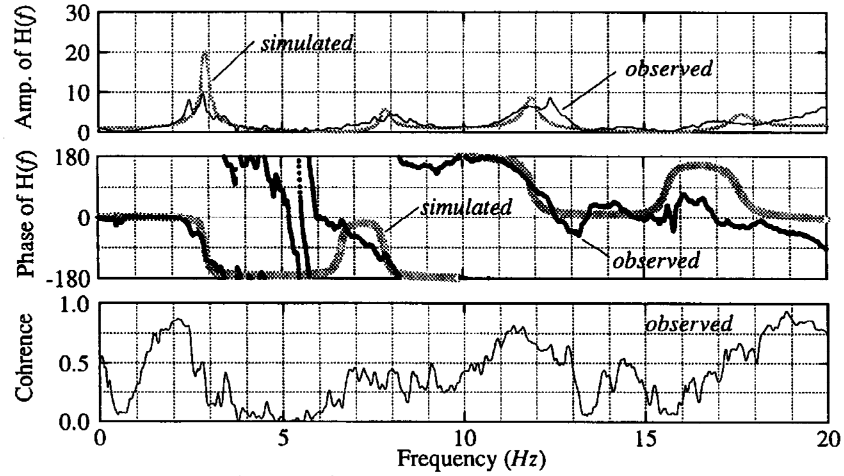
The nonlinear model of the ground was created from the linear model. The hysteretic property of soil was modeled by Ramberg'-Osgood type model (Ohsaki et al., 1978; Karkee et al, 1992). The response analysis was executed by Wilson's θ method. Fig.6 presents the G-γ curves used in the nonlinear analysis. Table 2 shows the parameters that define the hysteretic model used in the nonlinear analysis. These parameters were determined as the results of the nonlinear simulation agree with the observed earthquake motion of the largest aftershock. The parameter determination procedure was executed studying on the maximum strain level in each soil layer, the relationship between the reduction of rigidity and the shifting of the natural frequencies, the relationship between the value of equivalent damping constant and the peak of the transfer function, *etc.*

In Fig.7 thin solid line represents the observed record of the largest aftershock and gray line represents the simulated result by the nonlinear soil response analysis. This figure shows that the simulated results show good agreement with the observed records. The amplitude of the simulated response at G.L.-1*m* is smaller about 10% than the observed record. Fig.8 shows the transfer function of the observed record and the transfer function simulated by the nonlinear model. From Fig.8 it is clear that the frequency response in higher frequency range becomes smaller than the observed record. This will be considered that the diminution of the peak amplitude of the simulated wave was affected by the diminution of the amplitude in higher frequency components. Fig.9 shows the distribution of maximum values simulated by the nonlinear model. The results show the strong nonlinearity that the soil strain become greater than 10^{-3}. Fig.10 shows the simulated hysteretic curves at G.L.-20*m* and G.L.-12.5*m*.

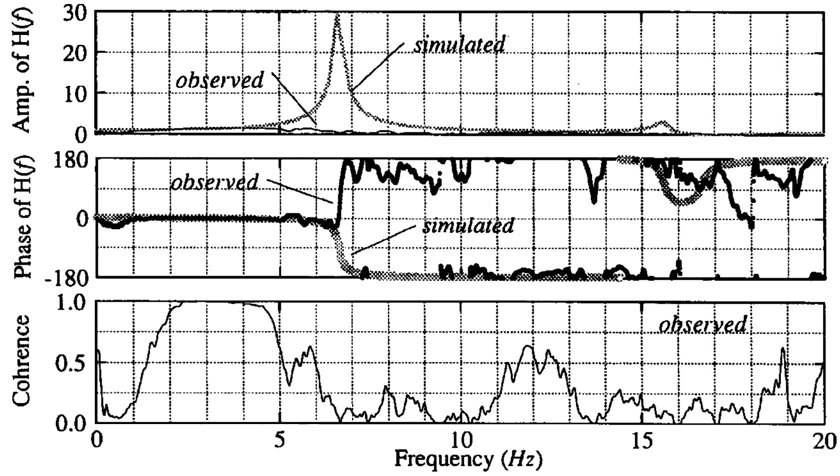
In the restoration of the amplitude saturated records of the 1994 Far-Off Sanriku earthquake, the parameters determined by the analysis of the largest aftershock were used. The results were presented in Fig.11~Fig.14. In Fig.11 thin solid line represents the observed record and the gray line represents restored records by the nonlinear simulation. In Fig.11 (a), the amplitude saturated part is found at about 33.75*sec*, which seems as a peak but it is saturate at 300*gal*. Furthermore the distorted part by the trouble of the recorder is found at right-hand part of the saturated part. From the simulated result shown in the figure, it is clear that the saturated part and distorted part are restored very well by the simulation. The maximum acceleration value of the restored record is 492*gal* at G.L.-1*m*. It will be considered that the maximum value of the restored record is smaller than the actual earthquake motion, because the nonlinear simulation on the largest aftershock gives smaller response than the actual records. Fig.12 shows that the simulated result agrees with the observed record in frequency domain. Fig.13 shows the distribution of the maximum values of the mainshock restored by the simulation. In this figure the strong nonlinearity of surface layer is found. Fig.14 shows the hysteretic curves of the restored mainshock.



(a) Free Field G.L.-1*m* *vs.* Free Field G.L. -20*m*



(b) Free Field G.L.-5*m* *vs.* Free Field G.L. -20*m*



(c) Free Field G.L.-1*m* *vs.* Free Field G.L. -5*m*

Fig. 5 Transfer functions and coherences that were calculated from 60 earthquakes with low input level and simulated transfer functions by linear soil model. The lowest three natural frequencies of the ground are evaluated as f_1=2.9*Hz*, f_2=7.7*Hz* and f_3=12.0*Hz*.

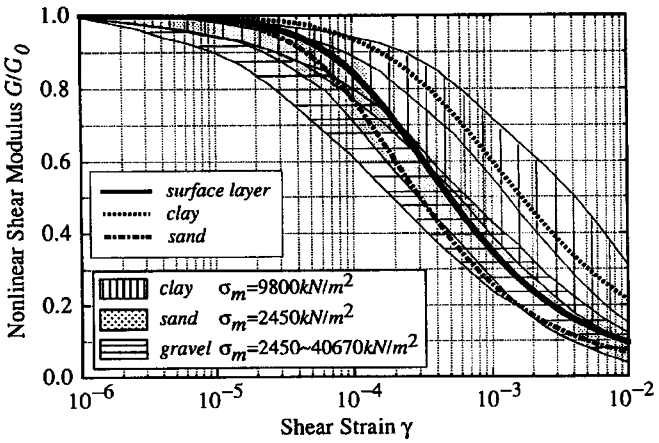


Fig.6 G-γ curves applied to the nonlinear analysis: the regions named clay, sand and gravel are experimentally determined (The Architectural Institute of Japan, 1993).

Table 2 Estimated nonlinear parameters that are applyied to he hysteretic model defined as

$$\gamma = \frac{\tau}{G_0}\left\{1+\alpha\left|\frac{\tau}{S_u}\right|^{\beta}\right\}$$

code	α	β	G_0 / S_u
SF	5.0	1.3	450
CC	2.5	1.1	200
SS	5.0	1.4	800
RR	15.0	1.9	1500

RESULTS

In this study the nonlinear soil model of the site of Hachinohe Institute of Technology was evaluated. In the study 156 earthquake records were used, that were observed by the dense strong-motion array observation system. The linear soil model was decided by 60 earthquake records with lower input-level. The nonlinear model was decided by the analysis of the largest aftershock of the 1994 Far-Off Sanriku earthquake.

The results of this study will be concluded as follows. (1) A linear soil model of the site that represents the lowest three natural frequencies of the ground was estimated. (2) The estimated nonlinear soil model shows good agreement with the nonlinear response during the largest aftershock not only in the amplification property but also phase property. (3) The amplitude saturated records of the 1994 Far-Off Sanriku earthquake were restored by the nonlinear response analysis. (4) It is clarified that the strain level of the subsurface layers greater than 10^{-3} during strong earthquake motion. The results of this study will be useful information to clarify the damage distribution in the eastern area of Hachinohe city and to clarify the difference of the damage distribution in Hachinohe city. At last, the authors wish to thank Dr. J. Tobita of Tohoku University for his helpful advice.

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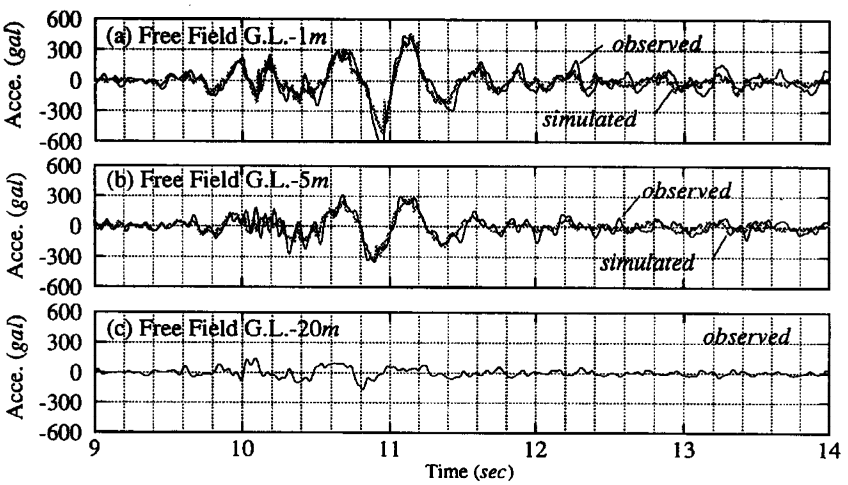
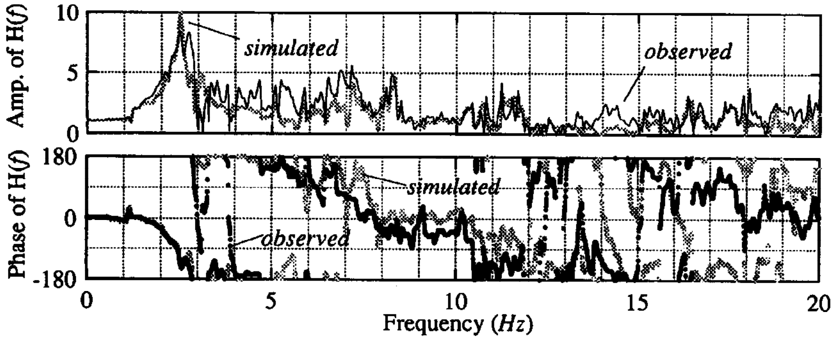
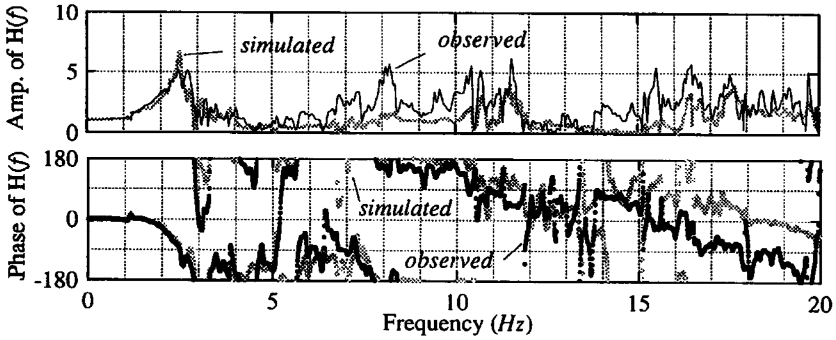


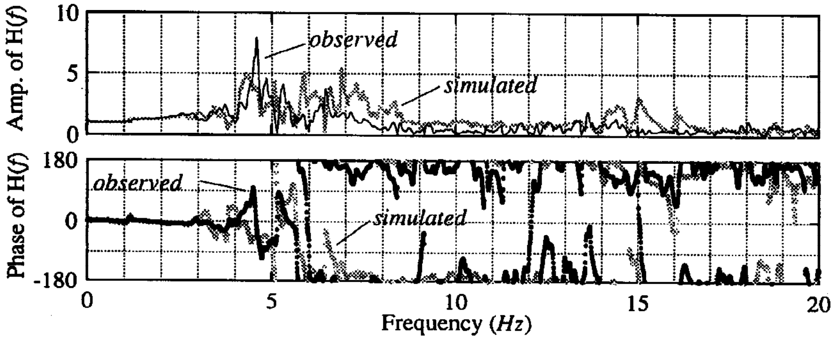
Fig.7 Observed acceleration waves of the largest aftershock (1995 Off-Iwate Pref. earthquake) and the simulated acceleration waves by the nonlinear soil model.



(a) Free Field G.L.-1*m* *vs.* Free Field G.L. -20*m*



(b) Free Field G.L.-5*m* *vs.* Free Field G.L. -20*m*



(c) Free Field G.L.-1*m* *vs.* Free Field G.L. -5*m*

Fig.8 Transfer functions of the largest aftershock (1995 Off-Iwate Pref. Earthquake) and the simulated transfer functions by the nonlinear soil model

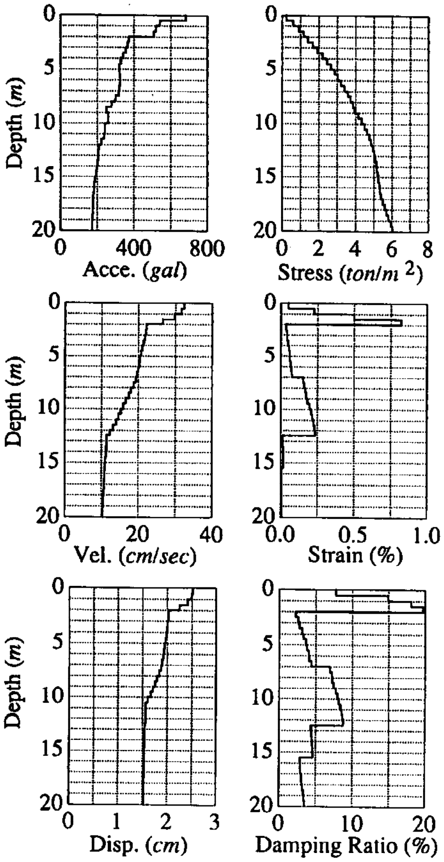
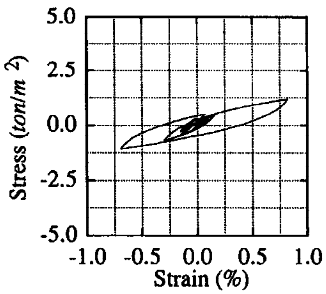
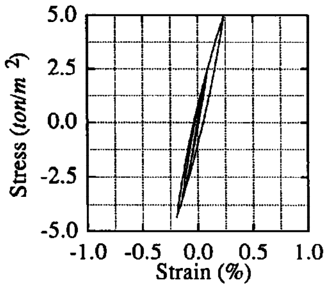


Fig.9 Maximum values of the largest aftershock simulated by the nonlinear soil model.



(a) Free Field G.L. -2*m*



(b) Free Field G.L.-12.5*m*

Fig.10 Hysteretic curves of the largest aftershock simulated by the nonlinear soil model

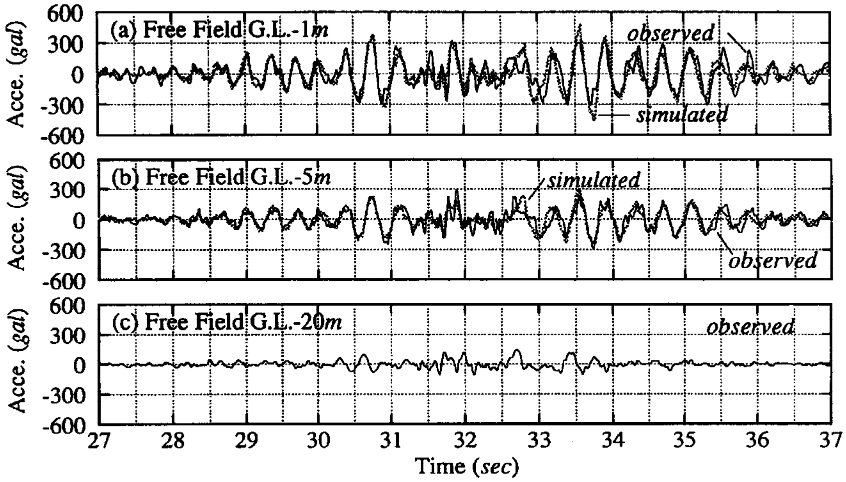


Fig.11 Amplitude saturated acceleration records of the 1994 Far-Off Sanriku earthquake and the restored acceleration waves by the nonlinear soil model

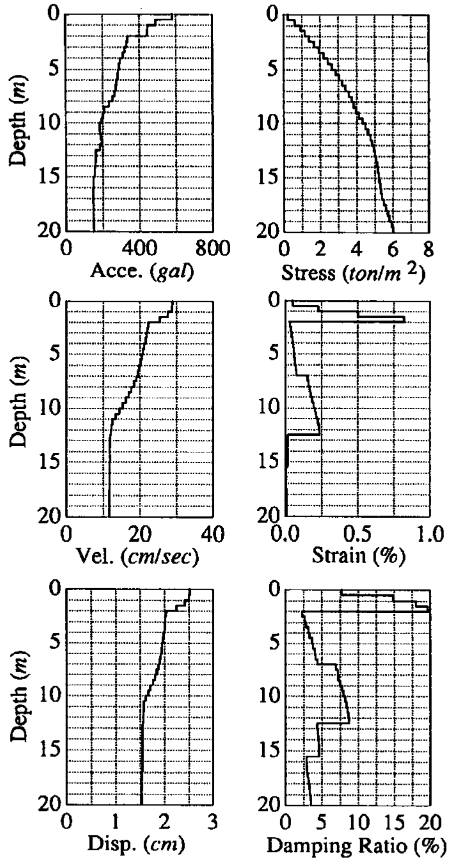
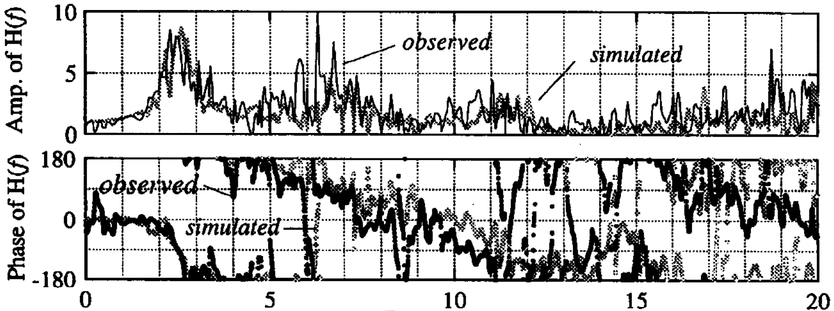
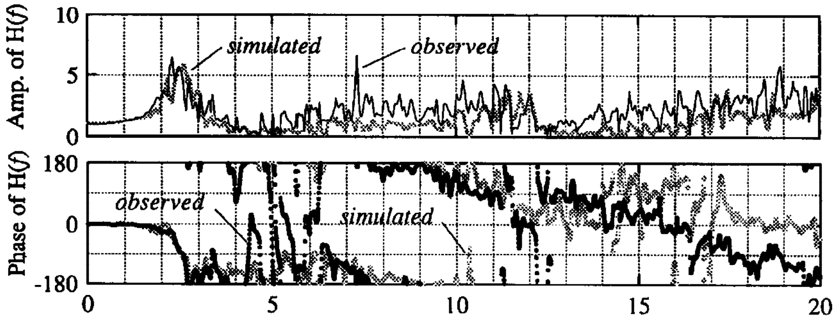


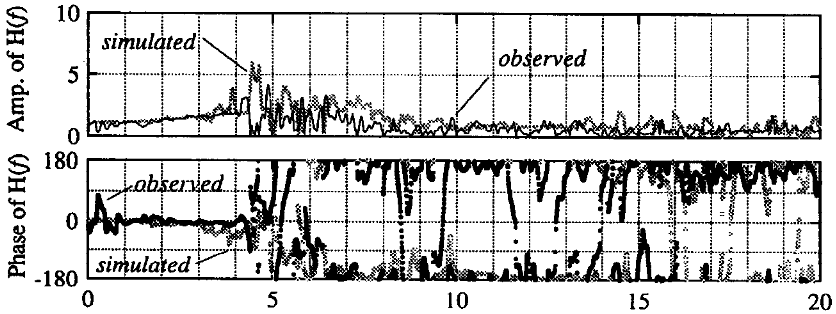
Fig.13 Maximum values of the 1994 Far-Off Sanriku earthquake simulated by the nonlinear soil model



(a) Free Field G.L.-1*m* *vs.* Free Field G.L. -20*m*

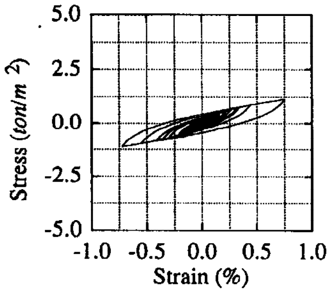


(b) Free Field G.L.-5*m* *vs.* Free Field G.L. -20*m*

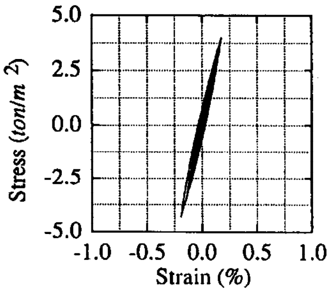


(c) Free Field G.L.-1*m* *vs.* Free Field G.L. -5*m*

Fig.12 Transfer functions of the 1994 Far-Off Sanriku earthquake and the simulated transfer functions by the nonlinear soil model



(a) Free Field G.L. -2*m*



(b) Free Field G.L.-12.5*m*

Fig.14 Hysteretic curves of the 1994 Far-Off Sanriku earthquake simulated by the nonlinear soil model