AN ARRAY DATABASE OF EARTHQUAKE GROUND MOTIONS RECORDED AT CHIBA EXPERIMENT STATION

Fumio Yamazaki[1], Shigeru Nagata[2], Tsuneo Katayama[3]
Lin Lu[4] and Turgay Türker[4]

SUMMARY

A three-dimensional seismometer array was installed in Chiba Experiment Station of Institute of Industrial Science, University of Tokyo in 1982. The array system is composed of 44 three-component accelerometers which are densely placed both on ground surface and in boreholes. A complementary system for the measurement of ground and buried pipe strains were also installed at the same site. The array system has been successfully in operation, and more than 160 earthquakes have been recorded. Considering a wide use of these seismograms, the Chiba Array Database has recently created including twenty-seven major events. The database organization, instrument corrections, and typical records are demonstrated in this paper.

INTRODUCTION

The array observation is one of the powerful tools to investigate various characteristics of earthquake ground motions. Depending on the aim of observation, there are several manners in the arrangement of seismometers. One of the typical types is a two-dimensional surface array represented by SMART-1 (Refs. 1, 2) in Taiwan which has three concentric circles with the radii of 200m, 1km and 2km. The records from this array have been utilized by a number of researchers (Refs. 3-6) to study the propagation and spatial variation of seismic waves. There are

---

1) Associate Professor, Institute of Industrial Science, University of Tokyo.
2) Research Associate, ditto.
3) Professor, ditto.
4) Graduate Student, ditto.

also a number of one-dimensional vertical arrays (e.g., Refs. 7-9) for the investigation of soil amplification and nonlinear response. The use of records from these arrays is mostly limited to the array owners, however.

A unique array system was installed in Chiba Experiment Station of Institute of Industrial Science, University of Tokyo in 1982 (Refs. 10-13). In this array, seismometers are placed very densely both on ground surface and in boreholes, thus constituting a three-dimensional network. Hence the records obtained from the array may be particularly useful for evaluating the spatial correlation of earthquake ground motions over a short separation distance and for examining the amplification theory. Note that there are some other three-dimensional dense arrays recently installed; e.g., one in Lotung, Taiwan (Ref. 14) to investigate soil-structure interaction, one in Tokyo Haneda airport (Ref. 15) to study soft soil behaviors during earthquakes, and four sites around the Suruga Bay-Izu region (Ref. 16) to investigate the effect of geological and topological conditions on earthquake ground motion.

The Chiba array has been successfully in operation and more than 160 events have been recorded. In order to utilize these records effectively, a database is created as described in the following sections. Although a lot of earthquake ground motions have been obtained by a number of array systems, no common database exists in Japan. In the United States, however, World Data Center A (WDC-A) for Solid Earth Geophysics, NOAA in Boulder Colorado collects, archives and disseminates strong motion records (Ref. 17) as well as other engineering data. Recently the Earthquake Engineering Committee of the Japan Society of Civil Engineers (JSCE) advocated the development of cooperative database system in Japan (Ref. 18). The Chiba array records will be included when such a system is created.

DENSE SEISMOMETER ARRAY IN CHIBA STATION

Site Condition

The Chiba Experiment Station is located about 30km east of Tokyo. The longitude of the station is 140°6'37"E and the

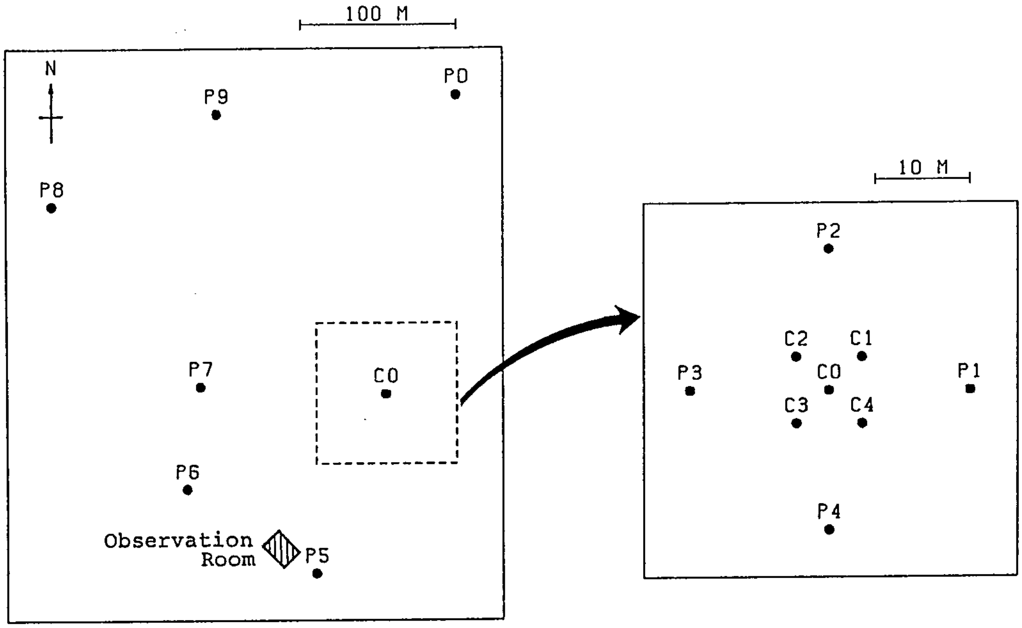


Figure 1 Layout of Boreholes

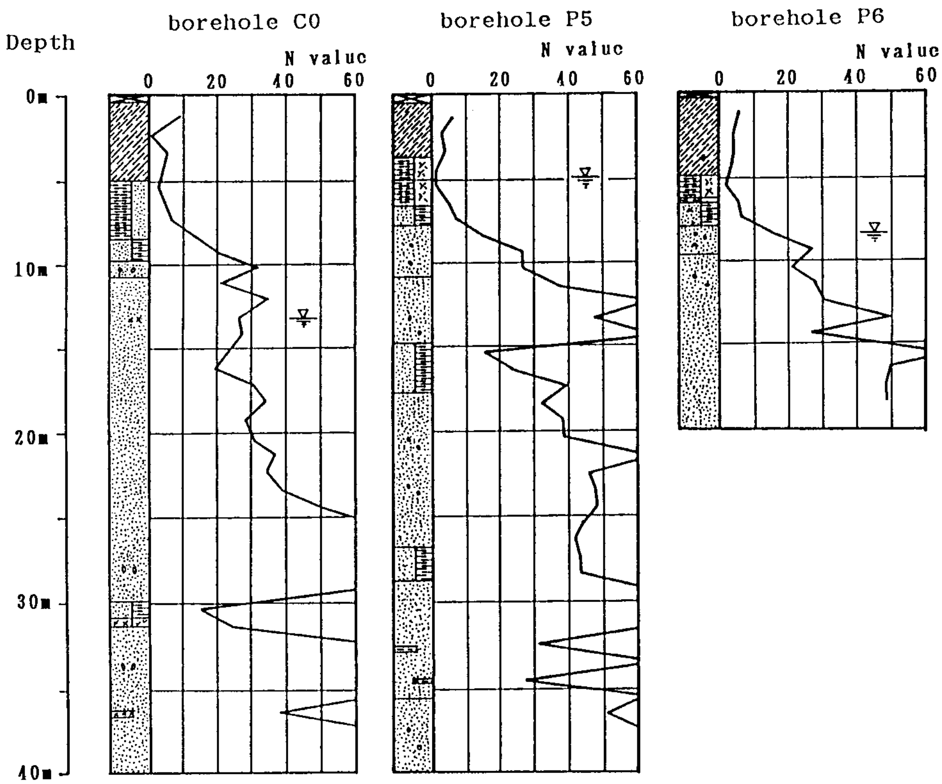


Figure 2 Typical Soil Profiles of Chiba Experiment Station

latitude 35° 37'17"N. Figure 1 shows the layout of boreholes where the standard penetration tests were carried out. The topographical and geological conditions of the site are generally simple with the ground surface being almost flat. Figure 2 shows the soil profiles at three boreholes (C0, P5 and P6) in the Chiba Station. The top 3-5m of the site is covered with the loam with the standard penetration N value being less than 10. The loam layer is underlain by a sandy clay layer with the thickness of 2-4m whose N values are also less than 10. A diluvium sand layer lies under the clay layer and its N values are greater than 20-30. This sand layer, whose stiffness increases with depth, is interspersed with clayey layers of relatively small N values. In spite of a slight difference in the depth of boundaries between different layers from one borehole to another, an overall agreement is good and indicates a relatively simple soil structure. The groundwater table was found to be lower than GL-5m.

Dense Array System

A dense array observation was started inside the Chiba Experiment Station in April, 1982. Near the ground surface (GL-1m), accelerometers are placed in the boreholes shown in Figure 1. At this time, the array system was composed of eleven boreholes (C0-C4 and P1-P6) with thirty-six accelerometers. Four boreholes (P7-P0) with eight accelerometers were added to the array in January, 1985. The number and location of borehole accelerometers are listed in Table 1.

There is a large triangular network P0-P8-P5 with each of three sides being approximately 300m. Around the borehole C0, eight accelerometers are densely arranged. Four of them (C1-C4) are only 5m from C0, and the other four (P1-P4) are 15m from C0. The large triangular network was laid to obtain the macroscopic propagation properties of seismic waves, while the very densely located array was established primarily to investigate the local soil strain characteristics during earthquakes.

The piezoelectric type acceleration transducers are used for the array observation. Table 2 summarizes the specifications of this type of accelerometers. The accelerometers have a practically flat sensitivity in the frequency range between 0.1Hz and

Table 1 Location of Borehole Accelerometers

Depth (m)	Borehole														
	C0	C1	C2	C3	C4	P1	P2	P3	P4	P5	P6	P7	P8	P9	P0
1	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
5	○	○	○	○	○										
10	○	○	○	○	○	○	○	○	○	○	○				
20	○					○	○	○	○	○	○	○	○	○	○
40	○									○					

Table 2 Specifications of Accelerometers

Type of Transducer	Piezo-electric Accelerometer
Sensing Directions	Two Horizontal and One Vertical
Full Scale Sensitivity	$1000 cm/s^2$
Sensitivity	$5 mV/cm/s^2$
Frequency Range	0.1 to 30 Hz
Output Impedance	10Ω
Operating Temperature	-20 to 40°C
Transverse Sensitivity	Max. 3 %
Linearity	Max. 0.1 % full scale
Water-proofness	$10 kg/cm^2$
Required Power	±6V D-C
Size of Casing	Φ65 x 335 mm
Weight	2.5kg

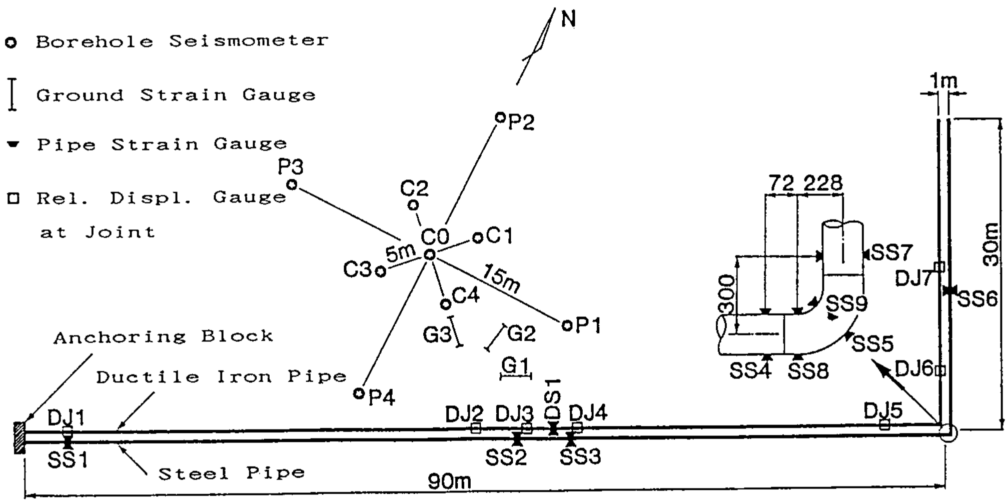


Figure 3 Layout of Complementary Observation System

30Hz. Three transducers (two horizontal and one vertical) and their amplifiers were installed in a cylindrical steel casing with an external diameter of 65mm and a length of 335mm. The accelerometers were installed in boreholes with diameters of 116mm where the maximum of five accelerometers were to be installed at different depths, and they were fixed at a predetermined depth by using cement mortar.

In December 1984, an additional system, which consists of simultaneous measurement of acceleration, velocity and displacement, was introduced on the first floor of the building where recording units are located. The velocity seismographs developed by Muramatsu (Ref. 19) and the low-magnification displacement seismographs of the Japan Meteorological Agency (JMA) are employed along with the piezoelectric accelerometer.

Complementary Measurement System

Except for the accelerometer array network, a complementary measurement system was also installed in December, 1982. This system consists of buried pipes of two different materials and three ground strain gauges as depicted in Figure 3.

A welded steel pipe and a ductile-cast-iron pipe of diameter 150mm are buried at GL-1.3m. Twenty-nine strain gauges were attached to these pipes to measure the strain in the steel pipe (denoted "SS#" in Figure 3), the strain in the ductile-cast-iron pipe (DS#) and the relative displacement over the joint in the ductile-cast-iron pipe (DJ#).

The relative displacements of ground are directly measured at GL-1.3m by means of three displacement transducers (G1-G3). The instrument consists of two 9mm-thick discs with diameter 80cm and a double tube connecting them at a distance of 3m. The transducer is placed in the external pipe and it measures the relative displacement between the discs. Note that all the measured relative displacements are converted to strains in the database described later.

Recording System

The signals from all the seismometers and strain gauges are recorded at every 0.005s by three units of the 64-channel digital recorder. The system is always kept in a full operational status. The signals are continuously fed into the storage which is capable of keeping the most recent 1.5s signals. The recording devices are activated when any one of the three components at P540 (GL-40m in P5 borehole) exceeds 1.0cm/s². The system continues in operation for 30s after the motion falls below this trigger threshold level. Each recorder has a digital magnetic tape with a recording capacity of 30 minutes. Timing information is internally generated, and in addition, the absolute time is corrected hourly by utilizing the signal from NHK radio station.

DEVELOPMENT OF CHIBA ARRAY DATABASE

Selection of Earthquakes

In the Chiba array, more than 160 earthquakes have been recorded since 1982 consisting of about 15,000 components of acceleration, strain, and velocity. Because the trigger is set in the relatively low level, most of the events are small ones. Thus we selected only major earthquakes when constructing the Chiba array database. Twenty-seven events whose peak ground acceleration at C001 (GL-1m of the borehole C0) is larger than 20cm/s² or whose maximum steel pipe strains (SS1-SS3) are larger than 5×10^{-6} are selected. Table 3 summarizes basic information on these events at the Chiba array. The epicenters of those events are plotted in Figure 4.

The largest event among the database is the Chibaken-Toho-Oki Earthquake (IEQK=8722) of December 17, 1987 with the peak ground acceleration over 300cm/s² at ground surface and the maximum buried pipe strain over 5×10^{-5}. All the other events are much smaller than this Chibaken-Toho-Oki event.

Development of Database

The procedure of the database construction is shown in Figure 5. The voltage signals from the seismometers and strain gauges are stored in digital magnetic tapes. Multiplying the conversion factor to these voltage values, the real values for

Table 3 Basic Information on Earthquake Records in Chiba Array Database

NO.	IEQK	Trigger Time at P540	Focal Depth (km)	JMA Magnitude	Azimuth (deg.)	Epicentral Distance (km)	Max. Acceleration at C001 (cm/s^2) EW	NS	UD	Max. pipe Strain ($x10^{-6}$)	T_D/T_R (s)
1	8205	82. 7.23 23:24:30	30	7.0	68.9	178	28.3	26.1	11.7	—	216/322
2	8307	83. 2.27 21:14:33	72	6.0	6.6	35	47.4	55.7	13.2	15.7	80/182
3	8401	84. 1. 1 18:04:47	388	7.3	234.4	373	25.5	24.2	12.7	6.9	141/223
4	8406	84. 3. 6 11:19:03	452	7.9	187.2	702	22.3	28.0	7.8	11.1	281/347
5	8414	84. 9.14 8:49:33	2	6.8	276.3	232	3.3	4.5	1.8	18.8	281/307
6	8416	84. 9.19 2:03:32	13	6.6	142.5	219	13.8	14.5	7.8	5.1	181/216
7	8420	84.12.17 23:49:59	78	4.9	240.1	5	22.1	24.1	40.8	6.7	37/ 63
8	8510	85. 6. 8 1:29:11	64	4.8	126.1	16	27.4	29.6	12.6	5.5	39/ 64
9	8519	85.10. 4 21:26:05	78	6.1	9.0	28	59.2	82.2	23.5	18.2	55/156
10	8525	85.11. 6 0:31:00	63	5.0	158.2	32	75.7	71.6	28.3	14.7	35/ 80
11	8601	86. 2.12 11:59:58	44	6.1	44.5	125	15.4	14.3	5.2	4.3	98/140
12	8602	86. 6.24 11:53:29	73	6.5	147.7	105	54.0	40.7	21.5	15.3	229/245
13	8611	86.11.22 9:42:14	15	6.0	204.3	131	5.2	6.0	2.7	19.5	185/199
14	8706	87. 2. 6 22:17:00	35	6.7	46.7	219	11.3	14.0	6.3	10.2	170/218
15	8717	87. 6.30 18:17:21	57	4.9	358.2	62	20.7	33.5	12.1	4.8	43/ 68
16	8722	87.12.17 11:08:27	58	6.7	128.1	45	213.6	327.1	124.8	55.6	39/282
17	8723	87.12.17 11:15:14	52	4.6	128.2	46	17.2	21.2	16.4	6.4	51/ 64
18	8725	87.12.17 14:07:18	58	4.4	126.5	42	23.8	13.8	9.3	3.9	28/ 44
19	8726	87.12.17 15:30:07	42	4.0	128.8	52	22.5	30.4	18.0	5.6	24/ 39
20	8802	88. 1. 5 10:09:17	42	4.2	128.3	37	40.6	40.8	10.1	7.8	17/ 39
21	8806	88. 1.16 20:42:20	48	5.2	133.3	38	54.9	97.8	19.8	15.9	37/ 81
22	8808	88. 1.18 19:37:24	32	4.1	243.6	17	19.0	26.2	9.6	4.4	19/ 34
23	8816	88. 3.18 5:34:45	96	6.0	276.3	42	48.4	59.8	15.2	18.3	59/138
24	8823	88. 8.12 14:15:08	69	5.3	200.8	62	46.4	35.2	12.0	11.6	44/ 70
25	8901	89. 2.19 21:27:21	55	5.6	337.6	48	55.7	49.1	25.4	12.8	54/118
26	8903	89. 3. 6 23:39:56	56	6.0	81.5	55	27.5	28.9	13.2	9.4	81/141
27	8904	89. 3.11 16:12:33	45	4.9	52.0	52	41.0	21.9	15.3	6.5	29/ 51

T_D : duration for database, Azimuth : clockwise from north
T_R : duration of original record

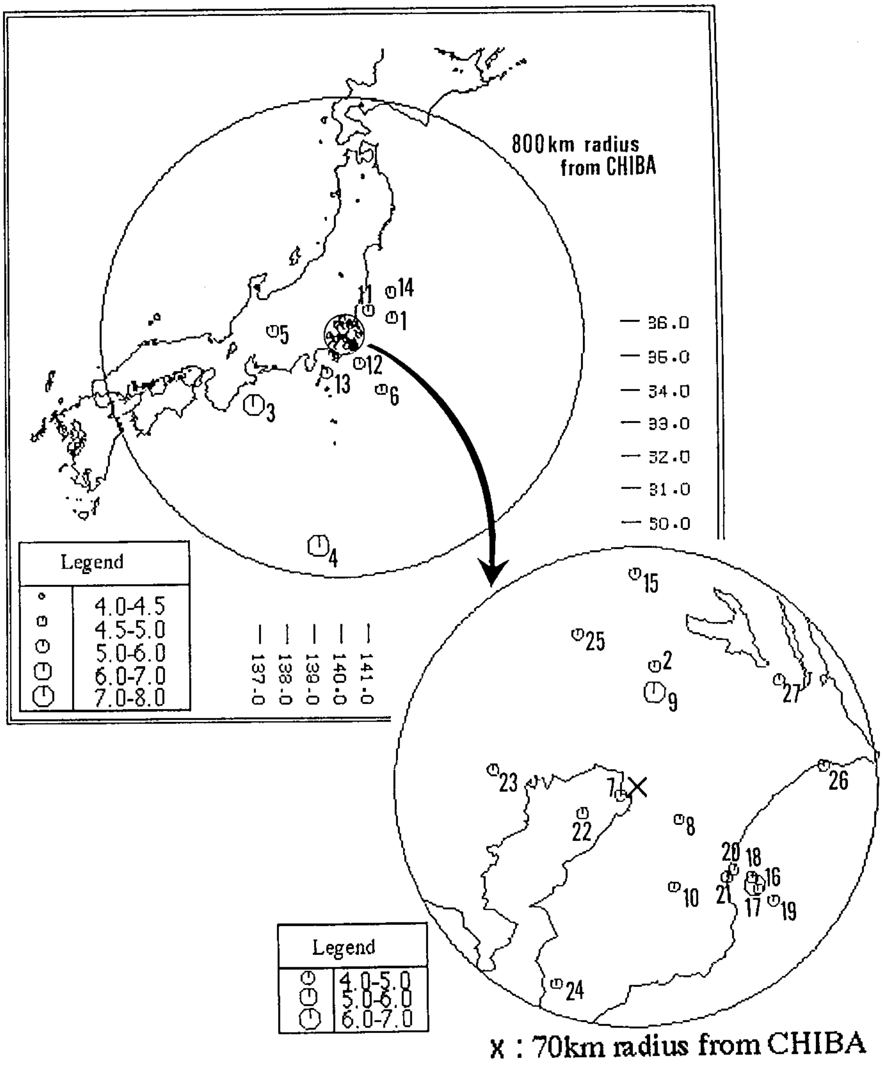


Figure 4 Epicenters of Events in Chiba Array Database

the acceleration, velocity and strain are obtained. The baseline correction is also carried out in this stage to have zero-mean for acceleration and velocity records. For strain records, zero-mean is assumed only for the initial delay time (=1.5s) since they sometimes exhibit a shift of baseline due to the friction of joints. A slight time lag of input signals among three recorders was found to occur and it may have a different value for a different event. Thus the time lag correction is performed by comparing the same signals recorded in the three tape units.

After judging whether this event is large enough for the criterion described previously, the duration of each event for the database is determined. The recording time is sometimes too long to store a whole record in the database. Thus the duration is truncated at the time when the cumulative power of horizontal acceleration records at C001 exceeds 99% of that for the total recording time. In this stage, the initial zero part of time series within the delay time is also reduced to be about 0.5s after checking the arrival of the P-wave at P540.

After these operations, the strain and velocity records are stored in the database. However, further corrections are applied to the acceleration records. Considering the sensitivity of the accelerometer, a high-cut filter is employed. Following a cosine curve, the Fourier amplitude of the records are reduced to zero between 27-33Hz.

From the early stage of the array installation, the orientation error of the buried accelerometers was detected (Ref. 10). When constructing the database, a detailed study for the three-dimensional correction of orientation error was further conducted using the recorded ground motions. The rotation angles for the correction of orientation error were determined by the maximum cross correlation method. A separate paper on this topic is now in preparation. After all these corrections, the acceleration database was completed.

Organization of Database

These two databases, one for acceleration and one for strain and velocity, are stored in magnetic tapes by the EBCDIC code in the VBS format. Each database consists of 27 sequential

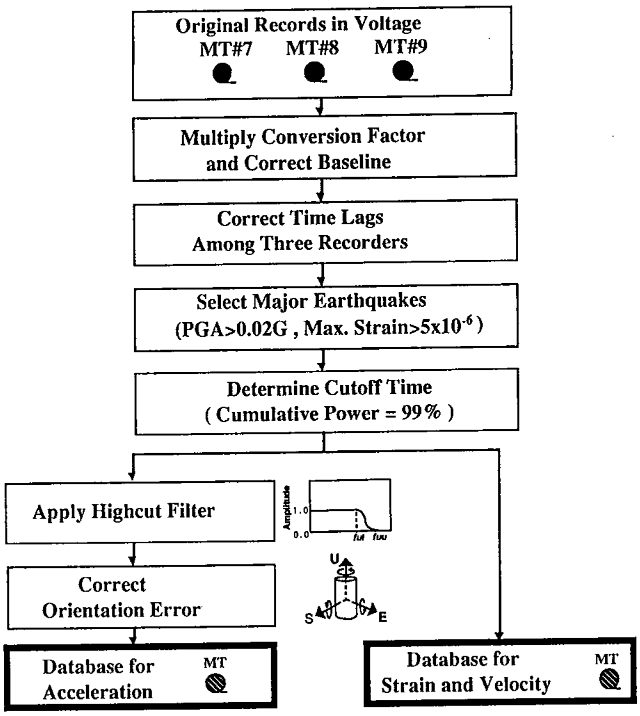


Figure 5 Procedure for Construction of Chiba Array Database

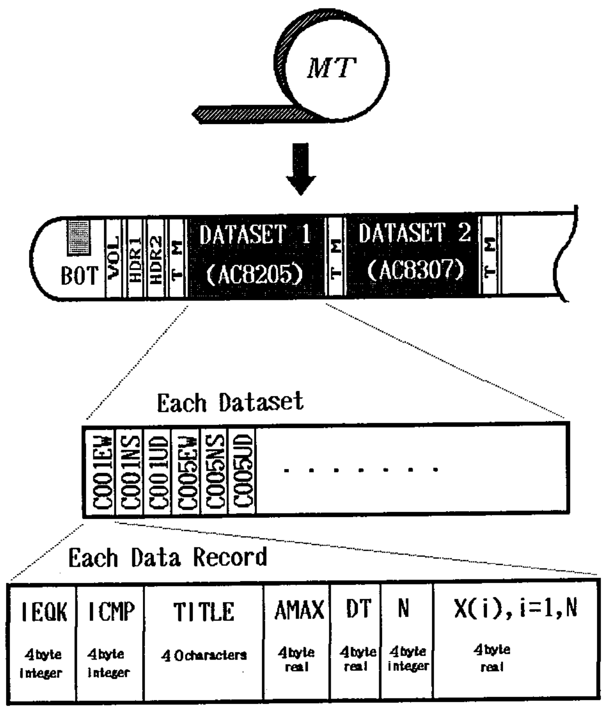


Figure 6 Organization of Chiba Array Database

(PS) datasets corresponding to the 27 events as shown in Figure 6. Each dataset includes 135 records for the acceleration database and 37 records for the strain and velocity database.

Each record is composed of heading data and time history data. The heading data includes the event code (IEQK), the component code (ICMP), the title of the record, the maximum value of the record, the time interval, and the number of time steps. The event and component codes are utilized when selecting necessary records from the database. Thus their combination is unique for each record. The time history data are followed after the heading data.

SOIL AMPLIFICATION DURING THE CHIBAKEN-TOHO-OKI EARTHQUAKE

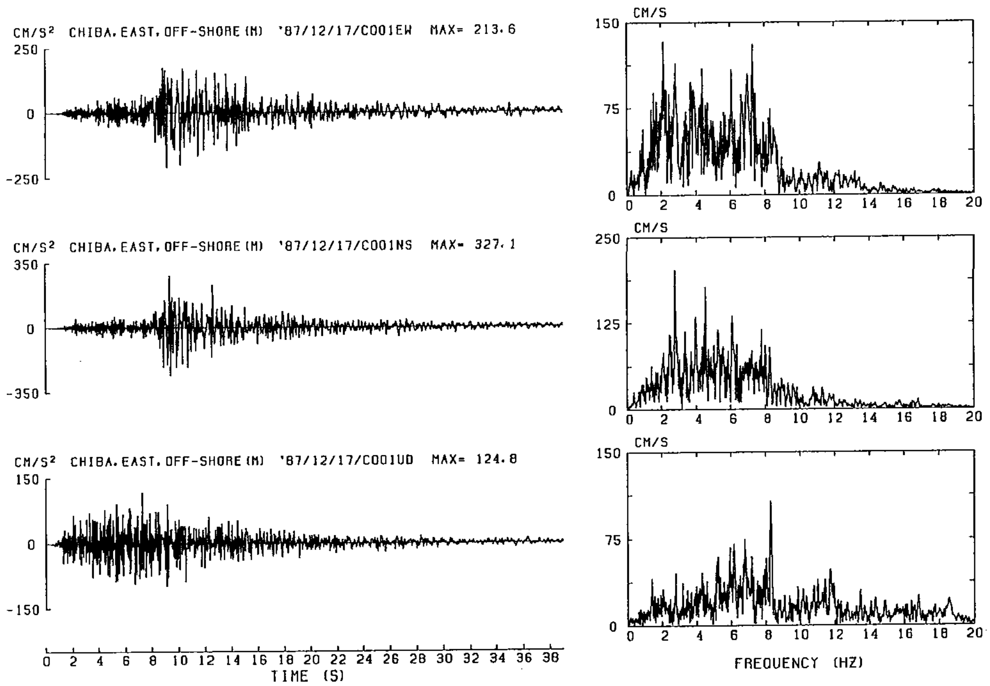
The Chibaken-Toho-Oki earthquake, which occurred off the east coast (Toho-Oki) of Chiba Prefecture (=Chibaken) on December 17, 1987, is selected for the demonstration of soil amplification at the Chiba array site. The peak ground accelerations at C001 are 213.6cm/s^2 in the EW-direction, 327.1cm/s^2 in the NS-direction, and 124.8cm/s^2 in the UD-direction, respectively. Figure 7 shows the acceleration time histories and their Fourier spectra at C001 and C040 (GL-40m in C0 borehole).

First, the incident angle of the ground motion is confirmed to be almost vertical by the tripartite method. Then the soil amplification from the recorded motions is compared with those by one-dimensional earthquake response analyses. Two analysis methods, the equivalent linear technique (the program SHAKE in Ref. 20) and the step-by-step nonlinear analysis, are employed.

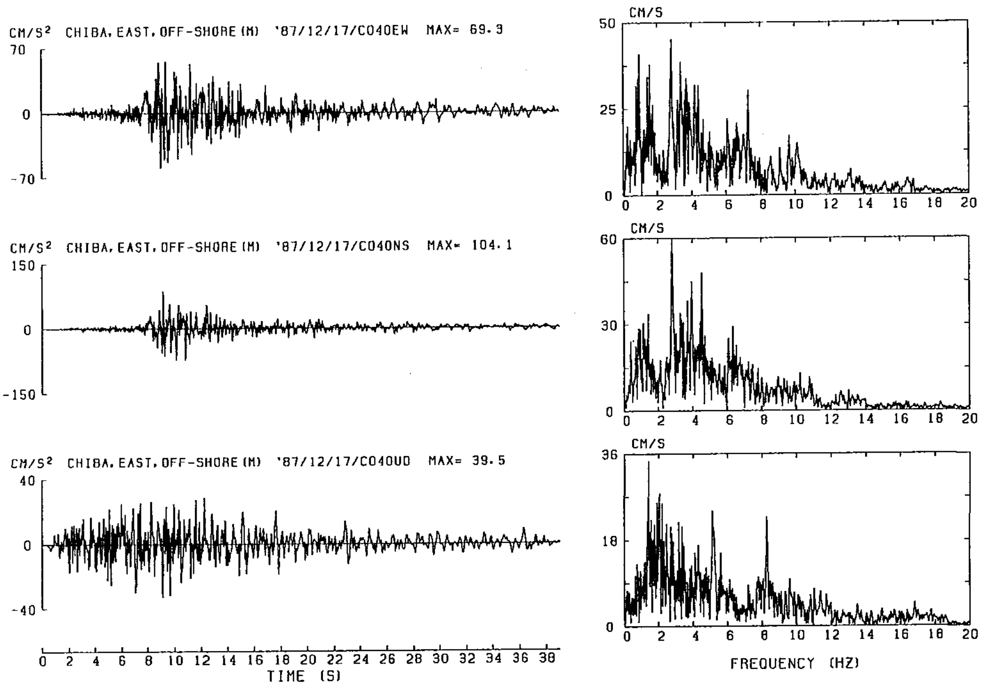
The layered soil model is constructed as shown in Table 4 based on the geological exploration in which the elastic wave velocities were measured by the downhole shooting method. In this table, the unit weight and nonlinear soil parameters are assumed because no test data are available.

In order to represent the nonlinear relationship between the shear strain and the shear stress, the Ramberg-Osgood (RO) model is employed with the skeleton curve as follows:

$$\tau = \frac{G_0 \gamma}{1 + \alpha \mid \tau \mid^{\beta}} \qquad (1)$$



(a) C001



(b) C040

Figure 7 Recorded Accelerations and Their Fourier Spectra (IEQK=8722)

Table 4 Soil Modeling of Chiba Array Site

Layer No.	Soil Type	Depth G.L.(m)	Sub-Layer	Location of Accelero-meters	V_s (m/s)	V_p (m/s)	Unit Weight* γ_t (t/m^3)	Initial Damping Ratio* (h_0)	Maximum Damping Ratio* (h_{max})	Reference Strain* (γ_r)
1	Loam	0.0 -5.0		GL-1 GL-5	140	320	1.15	0.02	0.25	$3x10^{-3}$
2	Sandy Clay	-10.0		GL-10	320	550	1.50	0.02	0.25	$3x10^{-3}$
3	Fine Sand	-15.0			320	550	1.95	0.02	0.25	$5x10^{-4}$
4		-24.0		GL-20	320	1670	1.95	0.02	0.25	$8x10^{-4}$
5		-40.0		GL-40	420	1670	2.00	0.02	0.25	$8x10^{-4}$

* assumed

where τ is the shear stress, γ is the shear strain, G_0 is the initial shear modules, and α and β are the parameters of the RO model. These two parameters are determined as (Ref. 21)

$$\alpha = \left[\frac{2}{\gamma_r G_0} \right]^{\beta} \quad ; \qquad \beta = \frac{2\pi\ h_{max}}{2-\pi\ h_{max}} \tag{2}$$

where γ_r is the shear strain when the shear modulus G reduces to 1/2 of its initial value G_0, and h_{max} is the damping ratio when the shear strain goes infinity. From Eq. 1, G/G_0 is written by

$$G/G_0 = \frac{1}{1 + \alpha \mid \tau \mid^{\beta}} \tag{3}$$

The relationship between G/G_0 and γ can be constructed numerically based on Eqs. 1 and 3.

Introducing the Masing rule, the damping ratio h is evaluated by the area of the hysteresis loop. The initial linear damping ratio h_0 is added in this study in order to avoid infinitesimal value of h. Thus the damping ratio for this RO model is described as

$$h = h_{max}\ (1 - G/G_0) + h_0 \tag{4}$$

In the nonlinear response analysis, this h_0 is considered as the Rayleigh damping for the first two modes of the linear system. Figure 8 plots the nonlinear soil properties used in the analyses.

The response analyses are carried for the NS-component of the Chibaken-Toho-Oki earthquake. The 0-36s of the recorded motion at C040 is employed as an input motion. The conditions of the equivalent linear analysis are determined as follows: the time interval Δt=0.005s; the number of data points for the Fast Fourier Transform (FFT) N=8192; the cutoff frequency f_{max}=20Hz; the effective shear strain factor 0.7, the allowable error for convergence =5%. In the nonlinear analysis, the Newmark's β method is employed as the method of time integration.

The maximum response values obtained by these two analyses are shown in Figure 9. The peak ground accelerations by the analyses are in a good agreement with the recorded ones. The maximum shear strains are smaller than 0.1%, thus the response results by the equivalent linear and nonlinear methods are very close. Note that in this figure, G/G_0 and the damping ratio for the RO model indicates those corresponding to the maximum shear

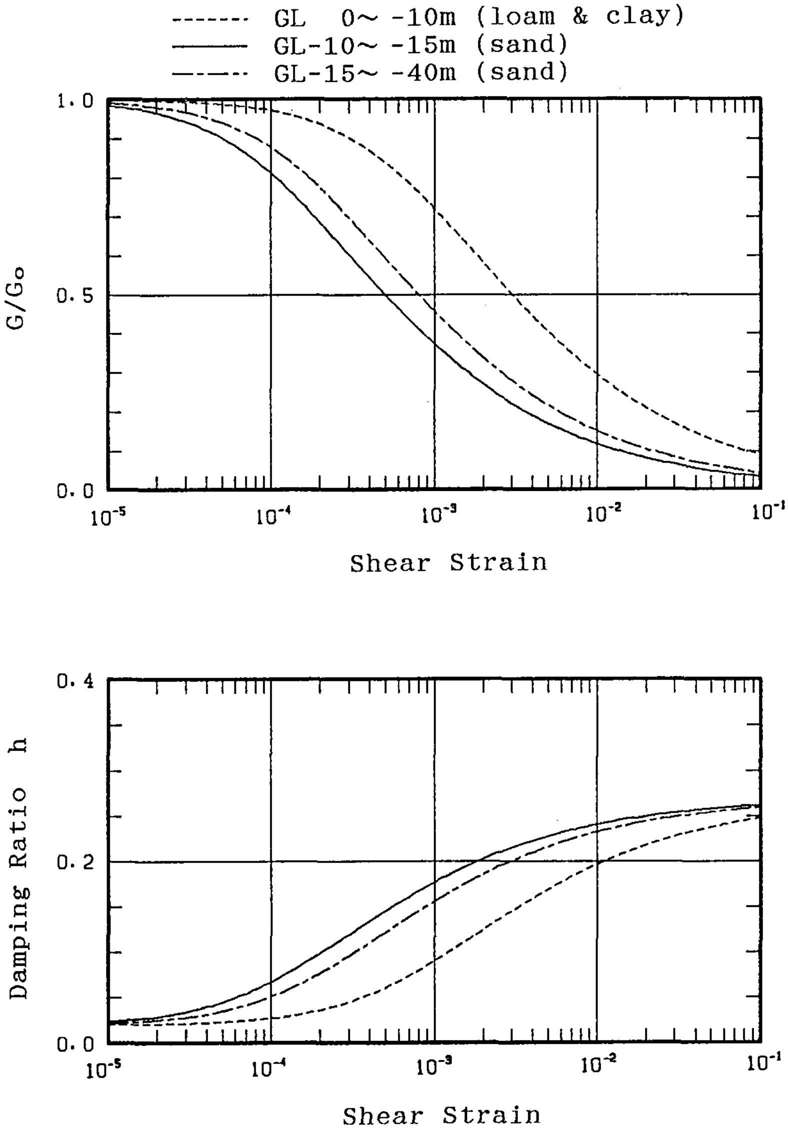


Figure 8 Assumed Strain-Dependent Soil Properties

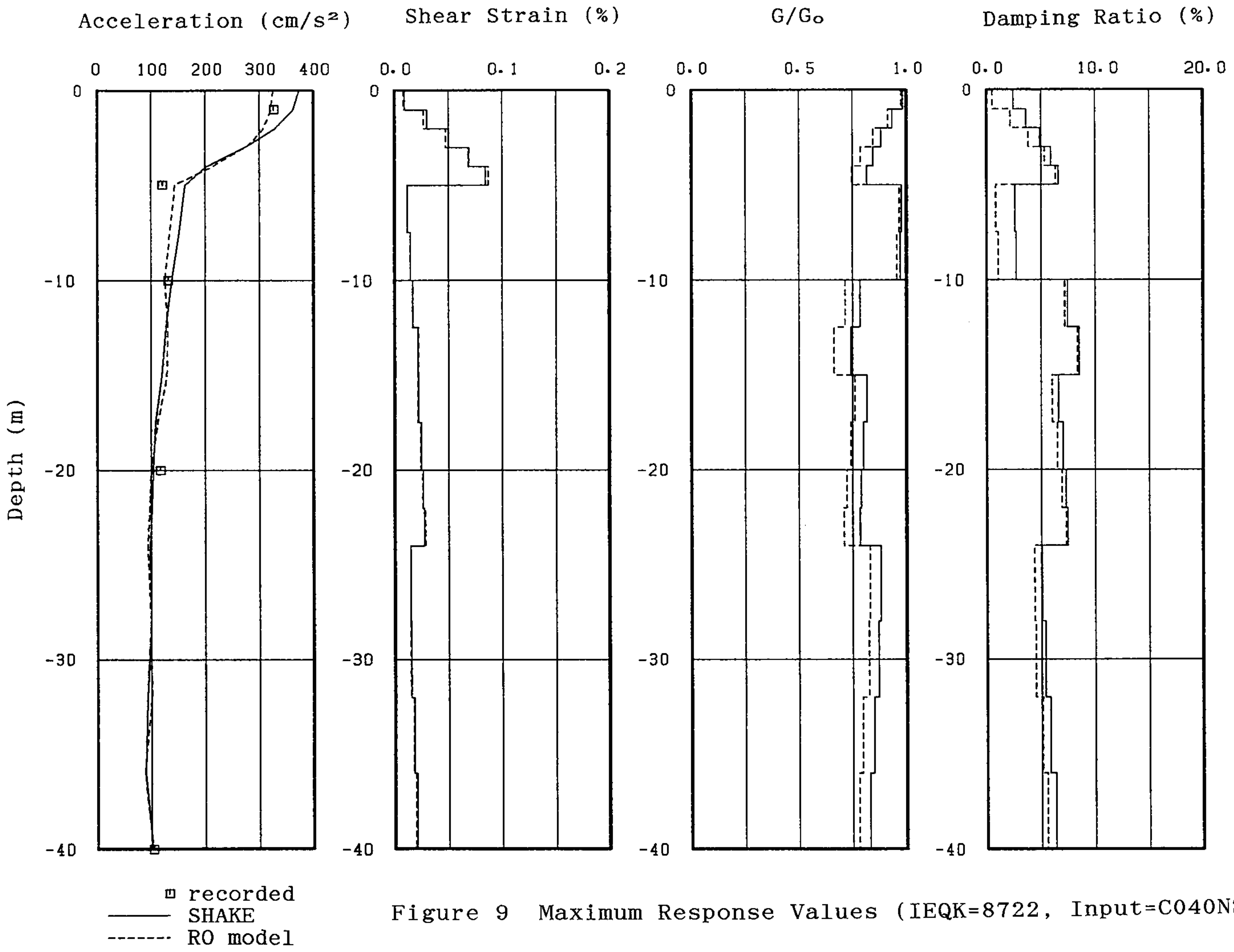


Figure 9 Maximum Response Values (IEQK=8722, Input=C040NS)

strain. The acceleration time histories by the analyses are compared with the recorded ones in Figure 10. The agreement between them are also found to be good.

More detailed comparison is made between the recorded and computed ground motions in terms of the transfer function:

$$H_{xy}(f) = S_{xy}(f)/S_{xx}(f) \qquad (5)$$

and the coherence function:

$$coh^2(f) = \frac{|S_{xy}(f)|^2}{S_{xx}(f)S_{yy}(f)} \qquad (6)$$

where S_{xx} and S_{yy} are the power spectra and S_{xy} is the cross spectrum. The Parzen window is employed in calculating these spectra with the band width =0.4Hz. Note that in the case of analysis by SHAKE, the transfer function is evaluated analytically. However, in order to get the similar smoothing effect as for the recorded motions and for the nonlinear analysis results, the transfer function for SHAKE is also calculated from the time histories.

Figure 11 shows the absolute values of the transfer functions (C001/C005, C001/C010, C001/C020, C001/C040) for the recorded motions and the results of two analysis methods. Although the transfer functions for the recorded motions have smaller amplitude at the first natural frequency, their overall agreement is fairly good.

The corresponding coherence functions are depicted in Figure 12. Three reasons are considered for the reduction of coherence in this situation.

(1) effect of smoothing at the natural frequencies

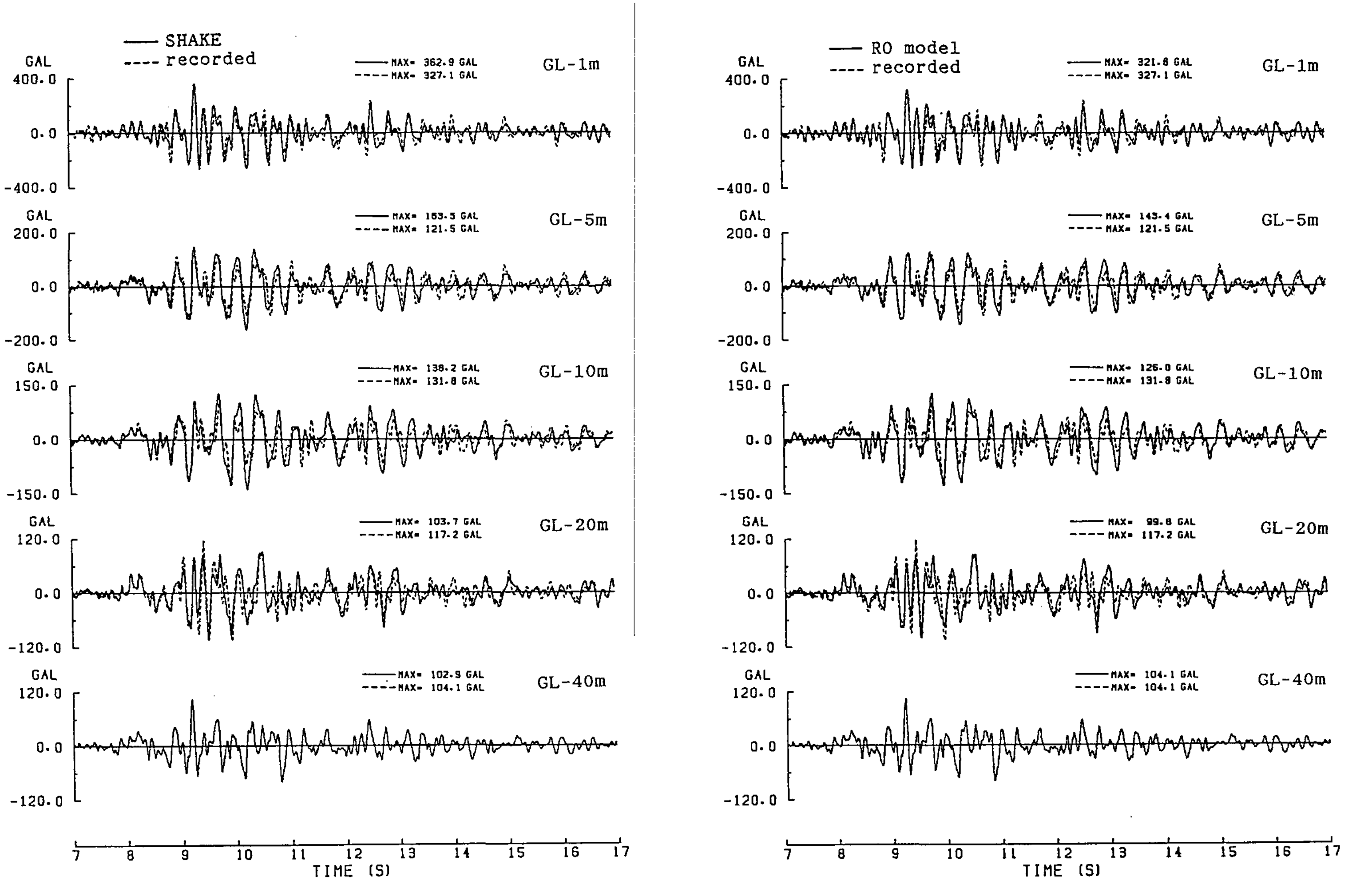
(2) effect of nonlinearity of the system

(3) effect of random incident angles of the input motion

Only the reason (1) is considered for the equivalent linear analysis (SHAKE), (1) and (2) are involved for the nonlinear analysis (RO model), and all the three reasons may be included for the recorded motions. The difference of three lines in the figure may be explained by these reasons.

CONCLUDING REMARKS

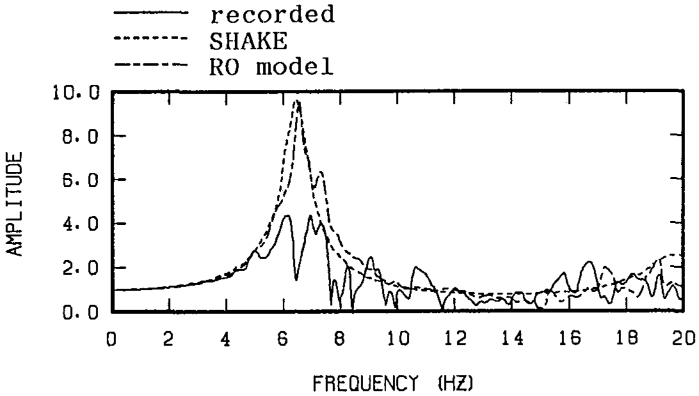
A strong motion database is developed for a dense seismometer array in Chiba Experiment Station. The system was in-



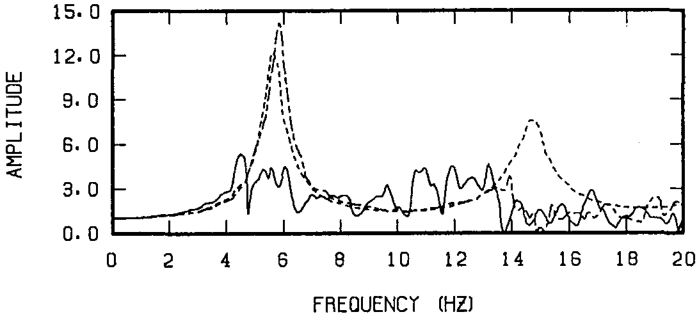
(a) Equivalent Linear Analysis

(b) Nonlinear Analysis

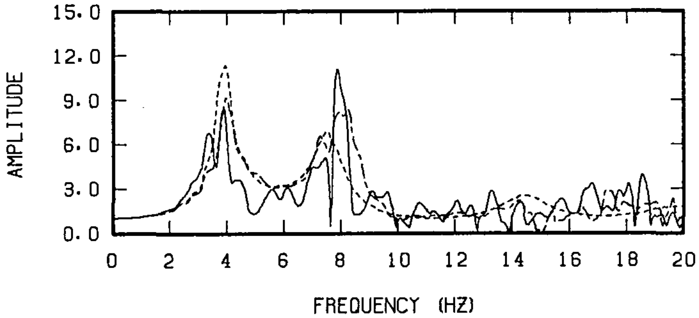
Figure 10 Recorded and Computed Ground Motions (IEQK=8722, NS-comp.)



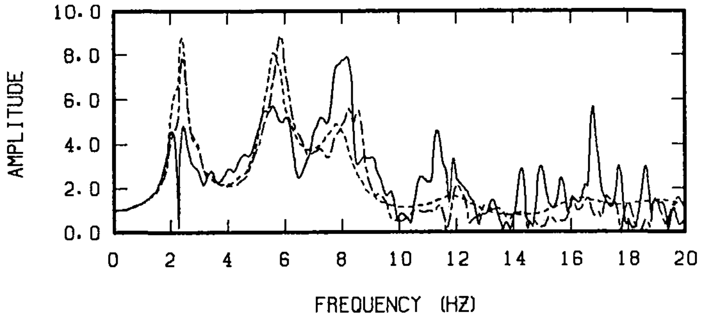
(a) C001/C005



(b) C001/C010

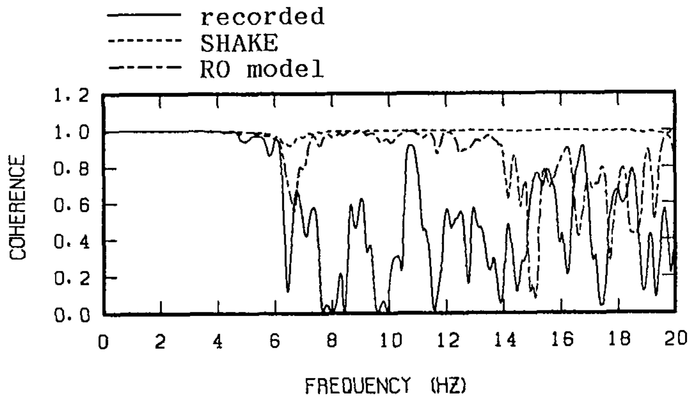


(c) C001/C020

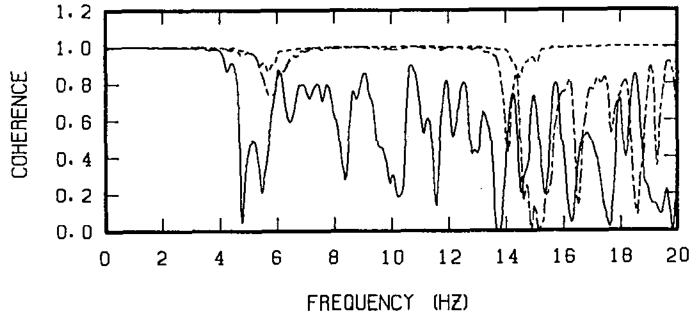


(d) C001/C040

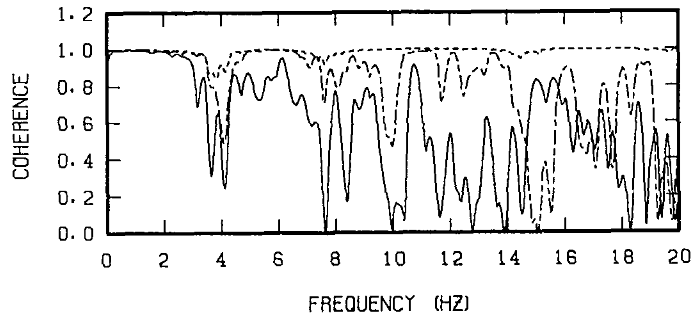
Figure 11 Recorded and Computed Transfer Functions (IEQK=8722, NS-comp.)



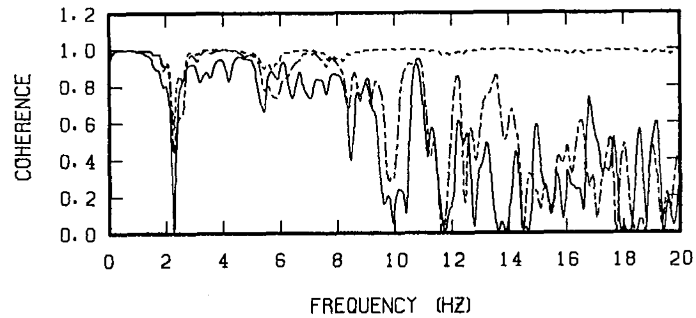
(a) C001/C005



(b) C001/C010



(c) C001/C020



(d) C001/C040

Figure 12 Recorded and Computed Coherence Functions (IEQK=8722, NS-comp.)

stalled in 1982 and it consists of a three-dimensional arrangement of borehole accelerometers and a complementary observation system for pipe and ground strains. The array system has been operating successfully and more than 160 events have been recorded. In order to use these valuable data effectively, the database including 27 major events has recently created.

Because of the dense arrangement of seismometers, the recorded motions may be especially useful when evaluating the spatial correlation characteristics of seismic waves as well as examining soil amplification. The Chiba Array database is available from the authors by request.

ACKNOWLEDGMENT

The authors express their appreciation to the Ministry of Education, Science and Culture of Japanese Government, Fujita Corporation and Kubota LTD. for financial supports to the array installation. Special thanks are extended to Mr. Nobuhiko Sato of Tokyo Sokushin Co. LTD., formerly a research associate of Institute of Industrial Science, University of Tokyo, for his continuing efforts to development and operation of the Chiba array system.

REFERENCES

1. B. A. Bolt, Y. B. Tsai, K. Yeh, and M. K. Hsu, "Earthquake Strong Motions Recorded by a Large Near-Source Array of Digital Seismographs," Earthquake Engineering and Structural Dynamics, Vol. 10, pp. 561-573, 1982.

2. C. H. Loh, J. Penzien, and Y. B. Tsai, "Engineering Analysis of SMART 1 Array Accelerograms," Earthquake Engineering and Structural Dynamics, Vol. 10, pp. 575-591, 1982.

3. T. Harada and T. Oda, "Probabilistic Modeling of Spatial Variation of Seismic Ground Deformation," Proc. of the 4th International Conference on Structural Safety and Reliability, Vol. II, pp. 277-286, 1985.

4. R. Harichandran and E. H. Vanmarcke, "Stochastic Variation of Earthquake Ground Motion in Space and Time," Journal of Engineering Mechanics, ASCE, Vol. 112, No. 2, 1986.

5. N. Abrahamson, "Spatial Interpolation of Array Ground Motions for Engineering Analysis," Proc. of the 9th World Conference on Earthquake Engineering, Vol. II, pp. 227-232, 1988.

6. T. Ishii, T. Sato and T. Satoh, "A Study on Seismic Wave Propagation in Lotung, Taiwan," Transaction of the 10th International Conference on Structural Mechanics in Reactor Technology, Vol. K1, pp. 7-12, 1989.

7. S. Omote et al. "Observation of Earthquake Strong-Motion with Deep Boreholes -An Introductory Note for Iwaki and Tomioka Observation Station in Japan-," Proc. of the 8th World Conference on Earthquake Engineering, Vol. II, pp. 247-254, 1984.

8. Y. Kitagawa, I. Ohkawa and T. Kashima, "Dense Strong Motion Earthquake Seismometer Array at Site with Different Topographic and Geologic Conditions in Sendai," Proc. of the 9th World Conference on Earthquake Engineering, Vol. II, pp. 215-220, 1988.

9. T. Tazoh, M. Sato, K. Shimizu and A. Hatakeyama, "Nonlinear Seismic Response Analysis of Soil Deposit using Strong Seismic Records," Proc. of the 9th World Conference on Earthquake Engineering, Vol. II, pp. 507-512, 1988.

10. T. Katayama and N. Sato, "Ground Strain Measurement by a Very Densely Located Seismometer Array," Proc. of the 6th Japan Earthquake Engineering Symposium, pp. 241-248, 1982.

11. T. Katayama, J. Farjoodi and N. Sato, "Measurement of Seismic Ground Strain by a Dense Seismometer Array," Proc. of the 8th World Conference on Earthquake Engineering, Vol. II, pp. 207-214, 1984.

12. J. Farjoodi and T. Katayama, "Application of Dense Seismograph Array Data to Evaluate Engineering Properties of Strong Ground Motions," Proc. of the 7th Japan Earthquake Engineering Symposium, pp. 511-516, 1986.

13. N. Sato, T. Katayama, M. Nakamura, T. Iwamoto and N. Ohbo, "Observation of Seismic Ground Motion and Buried Pipe Strain in a Very Dense Seismometer Array," Proc. of the 9th World Conference on Earthquake Engineering, Vol. VII, pp. 29-34, 1988.

14. H. T. Tang et al. "A Large-Scale Soil-Structure Interaction Experiment: Design and Construction," Nuclear Engineering and Design, Vol. 111, No. 3, pp. 371-379, 1989.

15. S. Noda, E. Kurata and H. Tsuchida, "Observation of Earthquake Motions by Dense Instrument Arrays at Soft Ground," Proc. of the 9th World Conference on Earthquake Engineering, Vol. II, pp. 221-226, 1988.

16. T. Okubo, T. Arakawa and K. Kawashima, "Dense Instrument Array Program of the Public Works Research Institute and Preliminary Analysis of the Records," Proc. of the 8th World Conference on Earthquake Engineering, Vol. II, pp. 151-158, 1984.

17. J. F. Lander, C. A. Angel and J. L. Coffman, "Activities of the World Data Center in Earthquake Engineering," Proc. of the

8th World Conference on Earthquake Engineering, Vol. II, pp. 79-86, 1984.

18. Working Group for Strong Motion Arrays, "Research Report on Development of a Database for Strong Motion Array Records -Introduction of Array Observation Systems in Japan and Prospect for a Cooperative Database System-," Earthquake Engineering Committee, JSCE, May, 1989.

19. I. Muramatsu, "Development of Velocity Seismograph," Jishin, Vol. 30, pp. 317-338, 1977 (in Japanese).

20. P. B. Schnabel, J. Lysmer, and H. B. Seed, "SHAKE - A Computer Program for Earthquake Response Analysis of horizontally Layered Sites," EERC Report, 72-12, 1972.

21. F. Tatsuoka and S. Fukushima, "Stress-Strain Relation of Sand for Irregular Cyclic Excitation (1)," Seisan-Kenkyu, Vol. 30, No. 9, 1978 (in Japanese).