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Site effect characterization using records of dense strong motion earthquake seismometer array in Sendai

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ABSTRACT: The array observation in Sendai is providing data on the site effect. It may be said that the differences of the records among the sites are produced by the site effect, because each of the source mechanism and the propagating path has the same effect on the motion of every site, when the source is located sufficiently far. Using the array observation records, a characterization of the site effect is made in this paper in view of the possibility of the quantitative definition of the site effect.

1 INTRODUCTION

It is often said that the earthquake motion at the ground surface varies even within a small area, because the underground structure differs from place to place. The earthquake records obtained in Sendai show the variety of surface motions which reflect the dynamic characteristics of the underlying soil layers.

The objectives of this paper is to identify the reasons to cause the differential surface motions to estimate the earthquake motions for the dynamic design of buildings.

The dense seismometer array observation at various sites with different topographic and geologic conditions began in 1983, and observation stations were set up and the total system became operational finally in 1989.

Comparisons of computed parameters were combined with the soil condition at the site. We also kept the following items in mind.

1) the variation of the above parameters among the sites
2) the variation of the above parameters at each of the sites between earthquakes
3) Locations of the epicenters.

2 OBSERVATION SITES AND EARTHQUAKE DATA

2.1 Geology of the observation sites

The Sendai area has a wide variety of topography and geology, and there are many types and scales of structures. Our array observation system is deployed as shown in Fig.1. The Sendai area suffered severe damage from the 1978 Off-Miyagi Prefecture Earthquake (M=7.4). After the earthquake, various studies were conducted to examine the earthquake damage.(BRI 1978) The Rifu-Nagamachi tectonic line passes through the center of the map and divides the area into two parts. The area to the west of this tectonic line is characterized by hilly tertiary terrain and several levels the terraces. The surface deposit of this terrace is loam, which is underlain by hard clay, gravel, pelite, and shale. The hilly terrain is composed of very hard shale, but the surface is covered with loam in several places. The alluvial plain develops east of the tectonic line and consists mostly of sand, silt, and gravel. The depth of the tertiary base rock changes abruptly near the tectonic line. There are several areas in the plain which are covered by very soft peat or mud.

The layout of the array configuration is also shown in Fig.1.(Kitagawa et al. 1988) The contour lines for the thickness of alluvial layers are drawn in the map. It is seen that four of the sites, SHIR, OKIN, TRMA, NAKA, are located where the thickness of alluvium is 60 to 80 meters. In Table 1, the soil conditions, the installation depths of seismometers at 11 sites are shown. The soil classification, specified in the Building Standard Law of Japan, is also shown in the table for each of the observation sites. It can be seen that the TAMA is a hard rock site, NAKA, OKIN, TRMA,

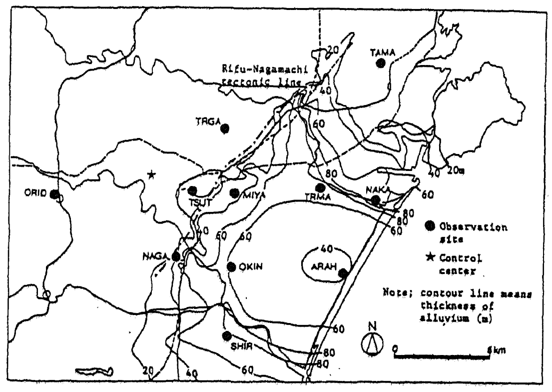

Fig.1 Location of the observation sites with contour of alluvium

Table 1 Geology of observation sites and depths of seismometers

Site name	Abr.	Soil	Cmplt.	Depth(m)		
Miyagino	MIYA	2	1984	1	22	54
Nakano	NAKA	3	1985	1	30	61
Tamagawa	TAMA	1	1986	2	11	33
Oridate	ORID	1*	1987	1	57	76
Tsutsujigaoka	TSUT	2	1988	1	36	59
Okino	OKIN	3	1988	1	17	62
Tsurumaki	TRMA	3	1988	1	25	79
Tsurugaya	TRGA	2	1988	2	37	62
Shiromaru	SHIR	2	1988	1	20	76
Nagamachi	NAGA	2	1989	1	29	81
Arahama	ARAH	3	1989	1	31	76

* Although the soil condition for ORID site was presumed hard soil, it was confirmed by the soil survey that the surface soils were so heavily weathered that the soil condition type might be assigned to be the second classification.

ARAH are soft soil sites. This classification was made using the geotechnical data prior to the installation of seismometers. At each of the sites three observation depths are determined, i.e., one on the surface, one at 20 to 30m depth with a shear wave velocity of 300-400 m/s, and one in the structural base layer with a shear wave velocity of 700-800 m/s and lying at a depth of 50 to 80m.

2.2 Strong motion data

A record of an amplitude as large as the one for 1978 Off-Miyagi Prefecture Earthquake was not obtained since the seismic activity around Sendai was not very high for these years. However, a large amount of data for the earthquakes of smaller magnitudes has been accumulated.(Kashima et al. 1990) Table 2 shows the 22 earthquakes used in this study. The epicenters are plotted on the map in Fig.2. It is seen that two events occurred

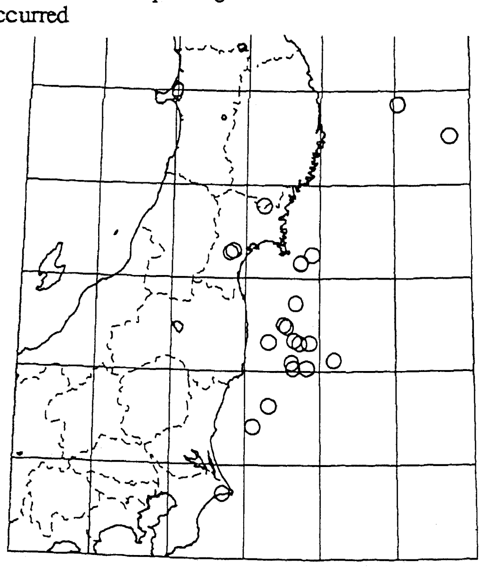

Fig.2 Location of earthquake epicenters

Table 2 Earthquakes used in this study

EQ No.	Date	Time	M	Depth (km)	Distance (km)	I_{JMA}*
8719	87/04/07	09:41	6.6	37	136	IV
8721	87/04/17	04:23	6.0	42	150	III
8724	87/04/23	05:13	6.5	49	145	III
8739	87/09/24	13:55	5.8	42	185	III
8740	87/10/04	19:27	5.8	51	125	III
8812	88/10/19	09:09	5.8	32	160	II
8902	89/02/04	19:57	5.4	61	110	II
8904	89/02/15	13:33	4.4	53	75	II
8907	89/03/06	23:40	6.0	56	285	II
8909	89/04/19	18:43	3.4	14	15	II
8911	89/04/28	00:27	4.9	52	98	III
8915	89/06/15	05:00	4.1	14	11	III
8925	89/10/29	14:27	6.5	0	280	II
8926	89/11/02	03:26	7.1	0	250	III
9006	90/04/23	04:24	4.2	87	107	I
9007	90/05/01	14:46	4.1	64	93	I
9015	90/07/28	13:00	5.2	3	170	II
9016	90/08/25	12:36	5.8	37	206	II
9101	91/01/16	23:49	4.7	48	86	I
9102	91/03/17	14:22	4.1	26	66	I
9103	91/04/03	03:22	3.6	53	73	-
9104	91/04/09	08:26	4.4	46	121	-

I_{JMA}* : Seismic Intensity in JMA scale felt at Sendai

beneath the Sendai area and most of the events occurred off the Pacific sea coast line.The records other that these listed are not used in the analysis, because the amplitude level was very low.

The largest number of records are available for three sites, MIYA, NAKA, TAMA, because these sites were completed at the first stage of the project.

The distribution of magnitude and epicentral distance is shown in Fig.2. As is often the case for the strong motion earthquake observations, the records with larger magnitudes and smaller distances cannot be frequently obtained.The top-listed MIYA site has data for 22 events. The ARAH site listed lowermost and lastly completed has data for the recent 8 events.Therefore, the *number of data has is not uniform for the sites*

The event with the largest magnitude, EQ8926 has an

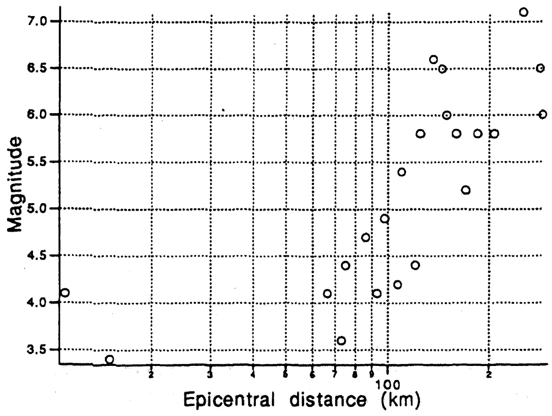

Fig.3 Distribution of magnitude and epicentral distance.

epicentral distance of 250km to Sendai. The magnitudes of the events are mostly too small especiall to evaluate the design ground motions for buildings. However, the data is efficiently used when the discussion is restricted within the effect of surface geology on the ground motions. The acceleration records were base-line corrected using the low cut filter (Okawa 1988) and integrated to obtain the velocity and displacement.

The average of two horizontal components is used for horizontal acceleration.

Fig.4(a) to 4(c) show the distribution of maximum acceleration amplitudes for horizontal motions at the ground surface vs the epicentral distances. The data of NAKA site, corresponding the soft soil condition, has larger amplitudes than other sites. The distribution for maximum velocity amplitudes are shown in Fig.5(a) to 5(c). The data for NAKA site has also the largest amplitudes among three sites. The records for TAMA site show the smallest amplitudes. In these figures, the symbols are changed for magnitude ranges.

3 AMPLIFICATION IN SURFACE SOIL

3.1 Maximum amplitudes

The vertical distribution of max. acc. amplitudes and max. vel. amplitudes are plotted for each of the sites in Fig.6 and Fig.7, respectively. As shown in the figures, a larger amplification is found near the ground surface. For most of the sites. the amplification between the deepest and the second deepest points is not very large. There is little difference in amplification between acceleration and velocity. It can also be said that the

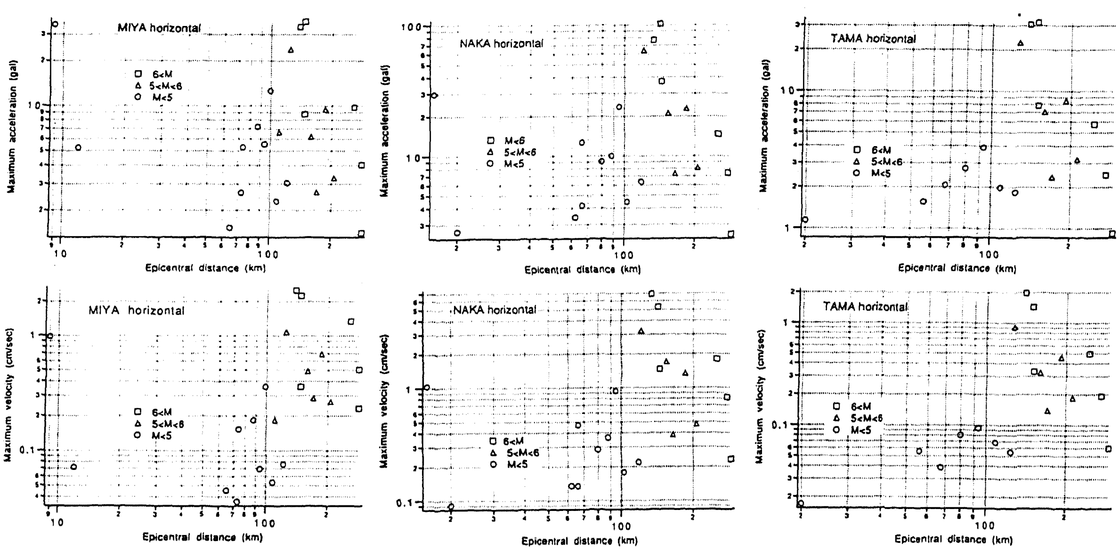

Fig.4 (upper) Maximum acceleration amplitudes vs epicentral distance (a) MIYA, (b)NAKA, (c) TAMA
Fig.5 (lower) Maximum velocity amplitudes vs epicentral distance (a) MIYA, (b)NAKA, (c) TAMA

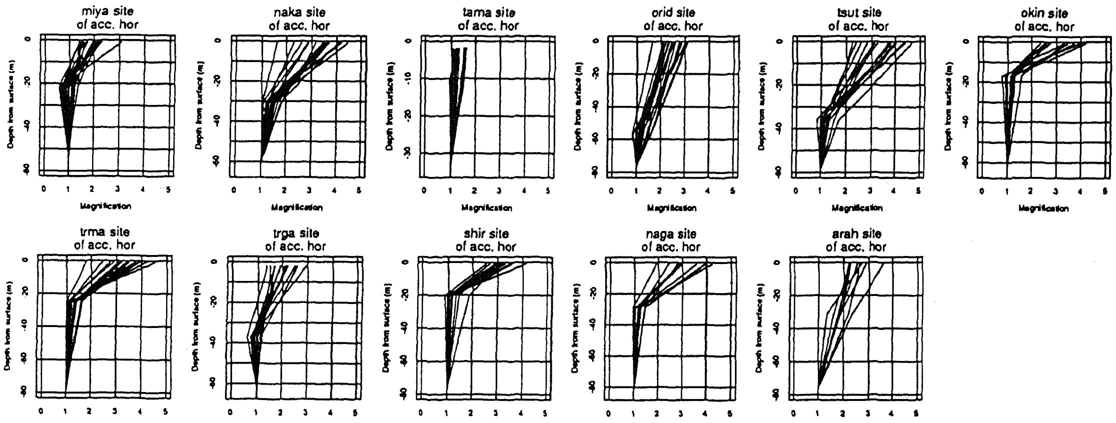

Fig.6 Vertical distribution of maximum acceleration amplitudes (normalized, horizontal component)

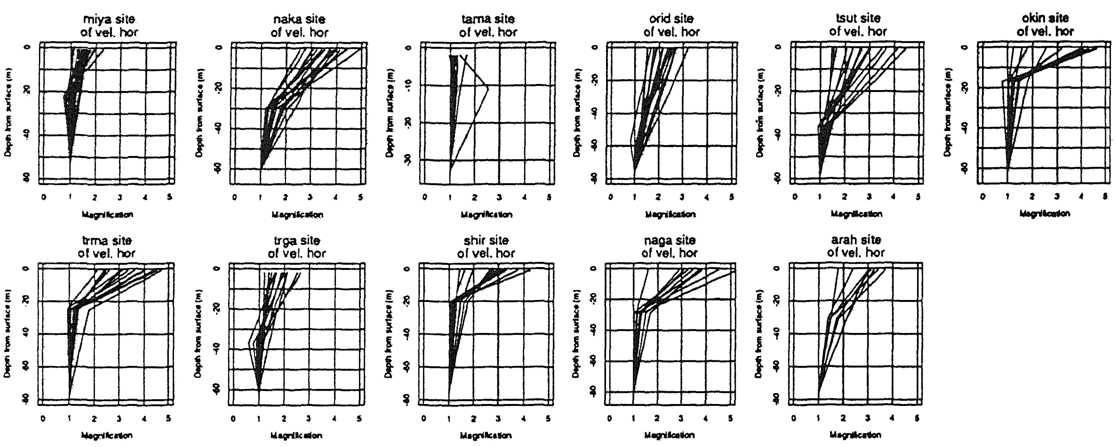

Fig.7 Vertical distribution of maximum velocity amplitudes (normalized, horizontal component)

variation between the events is large for a site. It is generally seen that the softer the soil condition, the larger the amplification becomes.

3.2 Spectral amplifications

The response spectra with 5 percent of critical damping for recorded motions of the 22 events, shown in Table 2, were calculated. Investigations on site amplifications in terms of the response spectral values were made using these computed values. The response spectral ratios of surface motion to the base motion were computed for each of the sites. The spectral ratios between the ground surface (the uppermost seismometer depth) and the deepest level are plotted for each of the sites in Fig.8. The predominant period for the MIYA site was approximately 0.5 to 0.6 seconds. For TAMA site, as shown in Fig.8, the spectral ratios are almost 1.0 for periods longer than 0.5 seconds, due to the stiff soil at the site. The predominant period of this site was 0.1 to 0.2 seconds. For most of the earthquakes, the spectral ratios for a site were consistently similar as shown in the figures. Although the location of earthquake source seems to influence the spectral ratios, a clear description can not be made, at this time, due to insufficient data.

3.3 Vertical motions

The vertical component of strong ground motion is often examined in its ratio to the horizontal component. Here, the vertical distribution of the ratio of the vertical amplitude to the horizontal amplitude are shown for MIYA, NAKA, and TAMA sites for acceleration amplitudes in Fig.9. For MIYA site, the ratio is between 0.4 to 0.7. For NAKA site, the ratio is from 0.3 to 0.5. For TAMA site, the ratio varies from 0.55 to 1.2. A definite difference in the ratio with the depth is not clearly seen. A tendency is rather found that the portion closer to the surface has smaller vert/hor ratios. It might be due to the change of the incidental angle in the process of wave propagation. The ratio distribution for velocity amplitudes has the similar tendency. Therefore, only the results for acceleration amplitudes are herein shown.

4 INTERRELATION OF SURFACE MOTIONS

The distances between the observation sites in Sendai are approximately 2 to 5 kilometers. Considering the seismic wave propagation underground, the incident wave at a depth of a site is assumed to be identical to the neighboring sites. The validity of this argument can be examined through the variation of the spectral ratios of the surface motions between two sites. The argument may not apply to records obtained at near-source region, because the epicentral distance becomes comparable with the distances between the sites and the incident waves to the base are different in that case.(Okawa 1990) The MIYA site was selected as a reference site for computing and comparing the amplitudes the spectral values at the ground surface.

4.1 Maximum amplitudes

The maximum amplitudes at the ground surface for 10 sites except for MIYA site were divided by the amplitude for MIYA site. Then the average values

Table 3 Average surface amplitude ratio

site	no. of data	Acc.(h)	Acc.(v)	Vel.(h)	Vel.(v)
MIYA	22	1.000	1.000	1.000	1.000
NAKA	21	2.191	1.250	2.421	1.056
TAMA	18	0.783	0.974	0.684	0.815
ORID	20	0.932	1.065	1.061	1.209
TSUT	16	1.366	0.962	1.274	0.949
OKIN	16	1.617	1.056	1.804	1.076
TRMA	16	1.897	1.378	2.248	1.334
TRGA	16	0.857	0.682	0.874	0.818
SHIR	16	1.530	1.363	1.512	1.128
NAGA	10	1.584	1.074	2.025	1.240
ARAH	8	2.101	1.276	2.363	1.278

h: horizontal, v: vertical, Surface amplitude at MIYA site is taken as reference point

were computed for all events. The results are listed in Table 3 for acceleration and velocity, for horizontal and vertical components with the values of standard deviations. From this table, NAKA, TRMA, NAGA, ARAH sites produce larger amplitudes. On the other hand, TAMA and TRGA sites take smaller value take smaller amplitudes on the average.

4.2 Surface spectral values

The comparison can also be made for the response spectra of surface motions between two sites. The spectral ratio between NAKA and MIYA, is shown in Fig.10. The distance between NAKA and MIYA is about 7 kilometers. Although a large scatter in the ratio is seen, the average interrelation for two sites can be found. This ratio might give a site effect which is evaluated comparatively by minimizing the source and the path effects. Fig.11 shows the spectral ratios between TAMA and MIYA sites. The distance between these two sites is about 8 kilometers. It can be said that the interrelation of response spectral values between two sites is similar.

5 CONCLUSIONS

The relations of the ground motion parameters among the sites and among the earthquakes were mainly discussed using the records of the array observation in this paper.

The pattern of the scatter of ground motions during earthquakes can be examined using the surface records at sites, i.e., to check whether the surface acceleration at site A is noticeably greater than that for site B, and vice versa. This issue is left for further investigations that should include items such as the influence of the source property, and location of the epicenter or the source region-dependency. In addition, for the ground motion predication in seismic zonation, the properties with which earthquake ground motion are modeled should be selected considering those properties with which the seismic performance of superstructures are modeled.

Concerning the amplification properties at each of the sites, the base layer is, in most cases, considerably difficult to determine. We do not have sufficient data on underground geological conditions. Even if we could determine the base layer, it is not enough to evaluate the site effect only through one-dimensional considerations. The earthquake record of the array-type observation is useful to compensate for information which the conventional observation system could not have captured. Our observation system deployed in Sendai is providing data on relative susceptibility to earthquakes at the site of the area.

The main results from the above analyses are as follows.

1) Maximum amplitudes preserve the relations among sites for different earthquakes.
2) For most of the earthquakes, the spectral amplifications for a site are consistently similar. However, there are some site having larger scatters in the ratios.
3) Although the location of earthquake source seems to influence on the spectral ratios, the ratio vert/hor, definite properties could not found.
4) Each site has a specific feature in the relation to another site. The ratios take similar values within this study using a limited number of data.
5) Further investigation is necessary because of the insufficient data for large magnitude and short distance.
6) Comparative analysis between sites using the surface motion data is useful to identify the relative susceptibility to earthquake effect. It is also important to correlate with the surrounding condition such as topography and geology.

6 ACKNOWLEDGMENT

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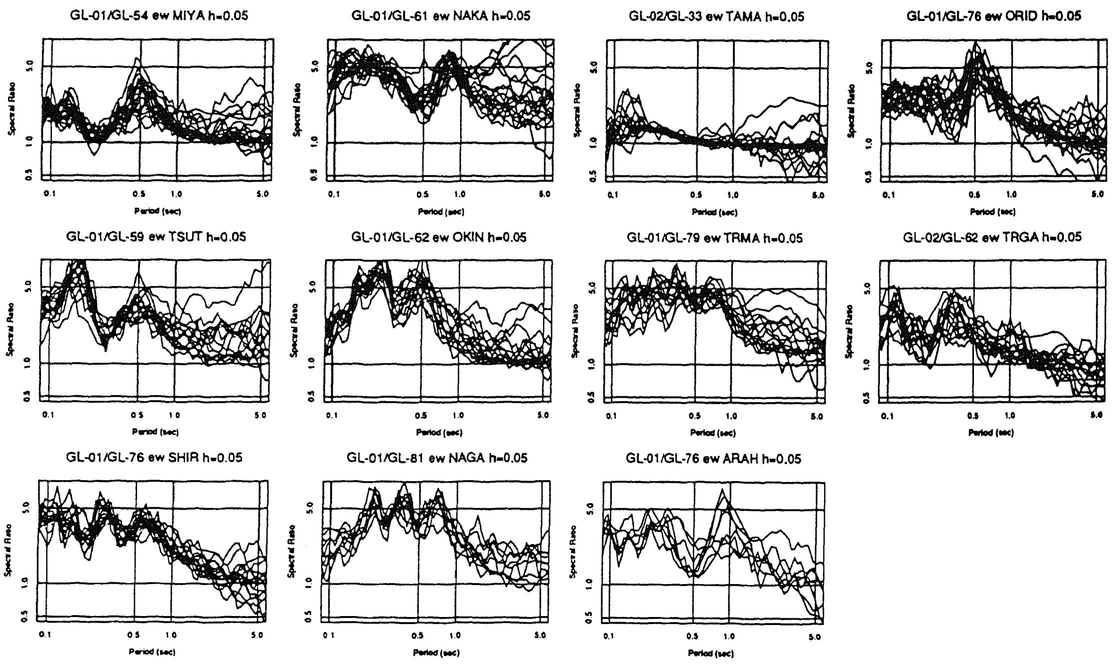

Fig.8 The spectral ratio between surface and base

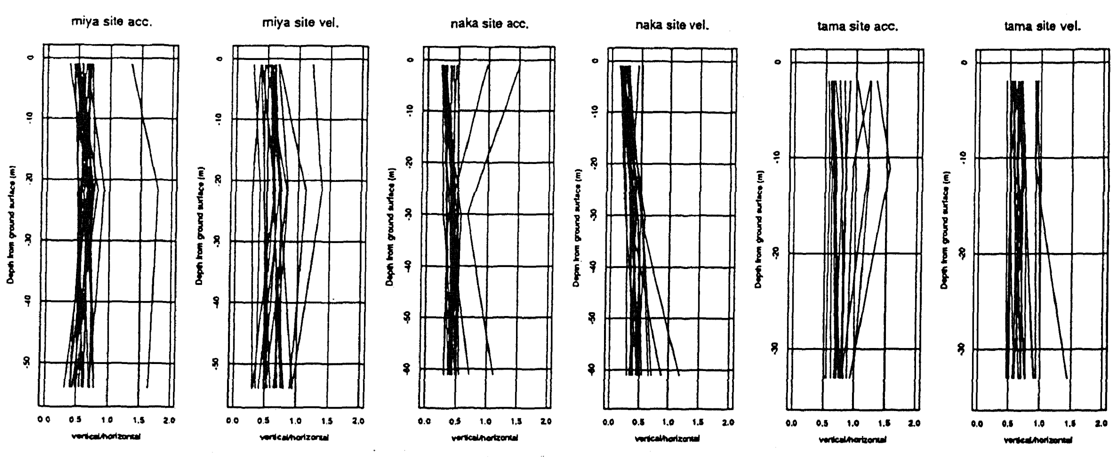

Fig.9 Vertical distribution of the ratio of max. acceleration between vertical and horizontal components

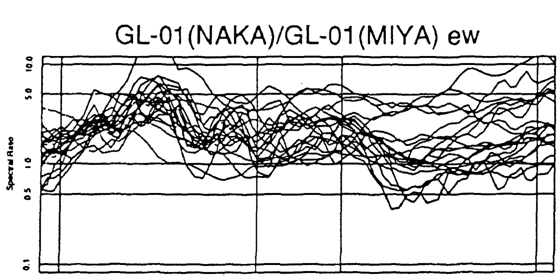

Fig.10 The ratio of the surface motion between NAKA and MIYA site for horizontal component

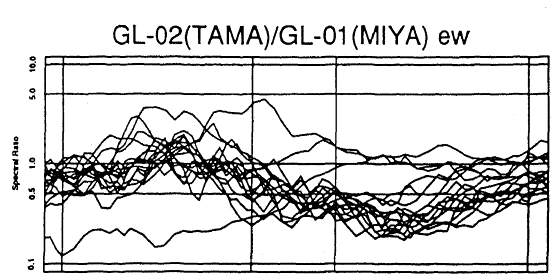

Fig.11 The ratio of the surface motion between TAMA and MIYA site for horizontal component