Dense Strong Motion Instrument Array in Sendai

by

Izuru Okawa[1], Toshihide Kashima[2] and Shin Koyama[2]

ABSTRACT

This paper describes an on-going earthquake observation project in Sendai, Japan. The observation system includes 11 observation sites and a control center. A number of records with intermediate amplitudes have been obtained to this date.

In this report, the earthquake observation system is introduced at first. The description includes the outline of the geological condition of the Sendai area, the objective area of the observation, the surface geology of the 11 observation sites from the investigation in sites, and the recorded data until the project started. During the period, the seismic activity of the area was not so high. Therefore, the amplitudes of acceleration records are not large enough to be called "strong motion". However, these data are essential for the purpose to examine the dynamic amplification property of the surface soils.

Key words: Instrument Array, Local Site Effect, Strong Earthquake Motion, Surface Geology

1. INTRODUCTION

It has often been said that the damage to structures during earthquake is more or less associated with the subsoil conditions on which they stood. It means that characteristics of earthquake ground motions at ground surface greatly reflect the dynamic properties of underlying soils. However, the dynamic property varies with surficial geology such as irregularity and inhomogeneity of soil deposits.

The Building Research Institute (BRI) started the earthquake observation program 40 years ago, when the development of the recording system and analysis programs was underway.

In 1983, BRI started to install instruments in Sendai City area to accumulate earthquake records focusing on the effect of surface geology on seismic motion with a long-term vision of re-establishing the methodology to specify design input motions for buildings[1]. Private companies (16 general contractors and a group of design firms) cooperatively merged this project from 1987. At the end of the fiscal year of 1989, the recording system was completed, consisting of 11 sites including outcrop rock, reclaimed land, soft soil ground around which considerable damage was found during the 1978 Miyagi-ken-oki earthquake[2].

This report introduces the earthquake recording system and results of analyses of the recorded motions. In addition, other observation projects operated by BRI are introduced.

2. ARRAY CONFIGURATION

The Sendai area is assigned as one of sites with the highest priority in Japan for the deployment of strong motion instrument arrays. The array system of our project consists of eleven sites as shown in Fig. 1, with spacing of 3 to 4 kilometers on the E-W line passing through the center of the city, and the N-S line passing through Nigatake and Oroshimachi. These areas, i.e., around Nigatake and Oroshimachi, also suffered severe structural damage during the 1978 Miyagi-ken-oki earthquake.

Four of the sites, SHIR, OKIN, TRMA and NAKA, are located where the thickness of alluvium is 60 to 80 meters. A fault, Rifu-Nagamachi tectonic line, is also the line of separation of the two zones. Most of the damage occurred on the eastern side during the 1978 Miyagi-ken-oki earthquake. Table 1 shows the installation depths of accelerometers, and the shear wave velocity of the layer in which the lowermost accelerometer is placed. Also shown in Table 1 is the soil classification, specified in the Building Standard Law of Japan, for each of the observation sites.

---

1) Head, International Institute of Seismology and Earthquake Engineering (IISEE), Building Research Institute (BRI), Ministry of Construction, Tsukuba Science City, 305-0802, Japan

2) Senior Research Engineer, ditto

3. OBSERVATION SYSTEM

Each site has three accelerometers arranged vertically. One on the surface, one at 20 to 30 m underground with a shear wave velocity of 300 to 400 m/s, and one on the base layer having a shear wave velocity of 700 to 800 m/s and underlying at depth of 50 to 80m in the area. A controlling and monitoring center is located at BRI in Tsukuba and is connected to a sub-controlling-center in Sendai via public telephone line. The sub-controlling-center is facilitated in the building of the Local Headquarters of Ministry of Construction for the Tohoku (northeastern) district of Japan in Sendai. The sub-controlling-center is further connected to all observation sites via exclusive telephone lines. Figure 2 shows a block diagram of the entire system.

The array observation system consists essentially of three accelerometers, an amplifier, an A-D converter, a pre-event memory, a digital magnetic tape recorder, and a clock. In order to obtain both a large dynamic range and a high resolution in recording, a digital system is used. Specifications of the array observation system are shown in Table 2.

4. OBSERVED EARTHQUAKES

Table 3 lists acceleration records are used in this report. The JMA (Japan Meteorological Agency) Seismic Intensities for those earthquakes were 3 or above at Sendai. The JMA magnitudes of earthquakes ranged from 4.1 to 8.1 and epicentral distances extended to 800 km. The maximum acceleration was 106 cm/s^2 on the ground surface at NAGA site.

5. CHARACTERISTICS OF EARTHQUAKE MOTIONS

In this chapter, the geological condition and configuration of accelerometers are outlined for each site. And then amplification effect of subsoil is discussed through the comparison of spectral ratios between observational results and analytical ones. Fourier spectral ratios in the E-W direction and theoretical transfer functions of SH-wave with damping ratios of 5 % and 10 % for each site is shown in Figs. 3 to 13. All Fourier spectra are smoothed using the Parzen window with a width of 0.2 Hz. Fourier spectral ratio is obtained from a spectrum of the record on the ground divided by one at the lowermost point.

(1) MIYA site (Miyagino)

This site is classified as lowland, close to the border between the hill. The Tertiary Pliocene layer is found at 26 meters below the surface. The degree of compaction of the Tertiary layer is lower at the upper layer, which changes to sand. The compaction for the lower layers is high. The sand-gravel layer, found at the upper part of the Tertiary, contains clay, and is firm.

Fourier spectral ratios in the E-W direction are shown in Fig. 3. The broken line and the dotted line indicate transfer functions of SH-wave with damping ratios of 5 % and 10 %, respectively. Large amplification can be observed in the frequency rage near 2.4 Hz on both of observed and theoretical results.

(2) NAKA site (Nakano)

This site lies on the basin of Nanakita-gawa River. The Tertiary layer is found approximately 58 meters below the surface. Thick alluvia layer lies above the layer. This site belongs to the soft soil category. The Tertiary pelite or tuff deposit is fairly firm but fragile against a light hammer blow. The upper layer is rather loose, but the lower is fairly firm.

Fourier spectral ratios of observed records and theoretical transfer function are drawn in Fig. 4. Shapes of both results are in full accord with each other and peak at a frequency of 1.3 Hz.

(3) TAMA site (Tamagawa)

This site is on the Tertiary rock formation except for the thin fill layer on the surface. The rock consists mainly of tuff and sand. The upper portion of the rock is loose, the lower is extremely firm. TAMA site can be the reference site to discuss amplification effect of surface geology at other sites.

Figure 5 shows spectral ratios and theoretical transfer functions. Peaks of spectral ratios appear at a frequency of 7.5 Hz. However, these are not so high as theoretical peaks.

(4) ORID site (Oridate)

This site consists mainly of relatively soft pelite or tuff. The lower part of the layer is andesite with upper part of andesite being weathered and fragile. The layer at more than 70 meters below the surface is fairy firm.

Through the comparison between observed

and theoretical results in Fig. 6, good agreement can be recognized

(5) TSUT site (Tsutsujigaoka)

Up to 5 meters below the surface is a loose layer consisting of diluvial sand-gravel, clay, and fill. The Tertiary deposits are below the layer. The upper part of the layer consists of a firm sandstone layer, and a mostly firm sand-gravel-like layer. The deeper we go, the firmer the soil becomes, but it is very fragile.

Figure 7 points out remarkable amplification at the higher frequency range of 5 to 7 Hz. The agreement between Fourier spectral ratios and transfer functions is also good.

(6) TRMA site (Tsurumaki)

This site is on the basin of Nanakita-gawa River. Due to the erosion of the riverbed, the Tertiary layer lies at the depth of valley-shaped soil structure. Consequently, the depth of the Tertiary layer extends as much as 80 meters. The layer is sandstone. The consolidation is low and the layer is fragile. The alluvial deposit contains surface layers, partly thin sand or clay layers. Most of the layers of the deposit are sand gravel, which are fairly firm.

The first predominant frequency of the transfer function is 1.26 Hz, but peaks of Fourier spectral ratios appear at the higher frequencies and are lower than the peaks of transfer functions, as shown if Fig. 8.

(7) OKIN site (Okino)

This site is on the basin of Natori-gawa River. The Tertiary layer is found at approximately 50 meters below the surface. It consists mainly of sandstone, relatively firm but fragile. The upper alluvial part has layers of clay and sand at the uppermost, the remaining part is mostly sand gravel. The sand gravel layer contains clay and is fairly firm.

Figure 9 indicates theoretical transfer function and Fourier spectral ratios of observed acceleration records. The spectral ratios generally accord with the theoretical results, although vary widely.

(8) SHIR site (Shiromaru)

This site, along with Okino site, is on the basin of Natori-gawa River. The Tertiary layer is found at approximately 50 meters below the surface. The upper part of the layer is getting weathered, and has a non-consolidated portion. On the other hand, the lower part is fairly firm and a sand- gravel layer is found as well. The alluvial layers consist mostly of sand-gravel layers, except for the surface layer of approximately a 3-meter thickness, which also contains clay fines, and is a fairly consolidated layer. The diameters of some of the gravels are large.

Spectral ratios and transfer functions in Fig. 10 show similar trend to results of OKIN site. The deviation of spectral ratios is relatively large.

(9) TRGA site (Tsurugaya)

A Tertiary layer is found below the surface fill. The layer contains sand and tuff sandstone. The consolidation is fairly high near the surface.

Figure 11 shows quite low agreement between Fourier spectral ratios and theoretical transfer functions. Physical parameters of soil layers must be reevaluated.

(10) NAGA site (Nagamachi)

This site is on the basin of Natori-gawa River, and also close to the Rifu-Nagamachi tectonic line. The Tertiary layer is found at the depth of approximately 57 meters below the surface. The layer consists mainly of sandstone. The consolidation of the upper part of the layer is low. The upper part of the alluvial deposit contains loose composite layers of clay, sand, and gravel, up to the depth of approximately 30 meters from the surface. The lower part of the deposit consists of sand gravel containing clay and is fairly firm.

Transfer functions of SH-wave, in Fig.12, have agreement with observed spectral ratios up to the second predominant period. In the higher frequency range, differences of both become lager.

(11) ARAH site (Arahama)

This site is between Nanakita-gawa and Natori-gawa Rivers. Although this site is classified as a hill, the Tertiary layer is found at a relatively shallow depth. The depth of the layer is approximately 35 meters below the surface, and consists of sandstone and pelite. The consolidation is relatively low. The upper alluvial deposit consists of layers of sand and silt, and makes a formation of a loose soil deposit. A sand gravel layer is found, with a thickness of 4 meters, at the interface above the Tertiary layer.

The first predominant period of transfer functions is 1.22 Hz as shown in Fig. 13. This is the softest ground condition in our observation sites. Although number of records is few, a degree of accordance is satisfactory.

6. OTHER PROJECTS OF BRI

BRI is carrying out earthquake motion observation projects not only in Sendai but also all over Japan. We are briefly introducing other project in this chapter.

(1) Nationwide Strong Motion Observation

BRI has installed strong-motion instruments in major cities throughout Japan. There are now 47 observation sites in operation using the digital strong-motion instrument. The objects of observation are mainly buildings, and the measuring point is usually placed both on the top and in the foundations of the building. Every observation site is connected to BRI via telephone line in order to mitigate maintenance work and to collect data immediately.

The observation network has obtained many noteworthy records. For example, in the 1993 Kushiro-oki (Off Kushiro) Earthquake, 711 gal was recorded as the peak acceleration on the ground surface at Kushiro Local Meteorological Observatory. Also, in the 1994 Sanriku-haruka-oki (Far off Sanriku) Earthquake, an enormous acceleration record was obtained in the building next to the severely damaged old Hachinohe municipal office building.

(2) Strong-Motion Instrument Network in the Metropolitan Area

The 1995 Hyogo-ken-nanbu Earthquake (Kobe Earthquake) awakened us again to the importance of disaster prevention measures for large-scale urban areas. It is important to predict the probability of a future earthquake and its impact, and make as many preparations as possible in anticipation of such an event. It is also very essential to grasp the damage situation immediately to put in effect the necessary countermeasures. BRI has established twenty new observation sites placed radially in the Tokyo metropolitan area. This project aims to investigate the characteristics of the seismic motion affecting the whole Kanto Plain through observation records. The system immediately collects information on the seismic intensity at the time of an earthquake occurrence.

(3) Strong-motion observation at Annex, BRI

The project to observe the complicated behavior of the building and the effect of the soil-structure interaction during earthquakes has been started with the construction of the Urban Disaster Mitigation Research Center (Annex) building in BRI recently. The amplification process by the ground surface layers and the three-dimensional behavior of the buildings are recorded using twenty-two accelerometers placed in and around the annex and main buildings.

7. CONCLUSIONS

The earthquake observation project with dense accelerometer array configuration is now under way. High quality records are being accumulated year by year. We are ready to make these data open to the public via the Internet, hoping the research of ground motion prediction becomes more active and the seismic design methodology for buildings is more upgraded in the future.

The earthquake records used in this study have been obtained in the Dense Strong Motion Earthquake Seismometer Array Observation Project which has been implemented as a cooperative research project between Building Research Institute (BRI), Ministry of Construction and the Association for Promotion of Building Research (KKSK). For the implementation of the project, the steering committee for Dense Strong Motion Earthquake Seismometer Array Observation, which consists of 18 organizations (i.e., BRI, 16 general contractors and a union of design office firms), is organized by KKSK.

REFERENCES

1) Kitagawa Y., et al., "Dense Array Observation and Analysis of Strong Ground Motions at Sites with Different Geological Conditions in Sendai", BRI Research Paper No.139, Building Research Institute, July 1994
2) Building Research Institute, "Report on the Damage by 1978 Off-Miyagi Prefecture Earthquake" (in Japanese), Research Report of BRI, No.86, pp.75-81, 1978.

Table 1 Location and geology of observation sites and depths of accelerometers

Site name	Abr.	Latitude	Longitude	Soil type*	f_1 (Hz)	Year	V_S (m/s)	Depth (m)		
Miyagino	MIYA	38°15'24"N	140°55'16"E	2	2.40	1984	**680**	1	22	54
Nakano	NAKA	38°15'14"N	141°00'26"E	3	1.28	1985	**720**	1	30	61
Tamagawa	TAMA	38°19'03"N	141°00'34"E	1	7.50	1986	**1400**	2	11	33
Oridate	ORID	38°15'26"N	140°48'39"E	1**	2.06	1987	**1050**	1	57	76
Tsutsujigaoka	TSUT	38°15'30"N	140°53'36"E	2	2.08	1988	**950**	1	36	59
Tsurumaki	TRMA	38°15'38"N	140°58'15"E	3	1.26	1988	**660**	1	25	79
Okino	OKIN	38°13'26"N	140°55'05"E	3	2.14	1988	**820**	1	17	62
Shiromaru	SHIR	38°11'29"N	140°54'53"E	2	2.70	1988	**830**	1	20	76
Tsurugaya	TRGA	38°17'16"N	140°54'53"E	2	1.78	1988	**1000**	2	37	62
Nagamachi	NAGA	38°13'45"N	140°53'01"E	2	1.44	1989	**700**	1	29	81
Arahama	ARAH	38°13'11"N	140°59'00"E	3	1.22	1989	**750**	1	31	76

f_1: Theoretical first predominant frequency, V_S: Shear wave velocity of lowermost layer.

* Soil types according to Japan Building Standard. 1: hard, 2:medium, 3: soft.

** 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.

Table 2 Specifications of the array observation system

Instrument	Specification	
Accelerometer	Type:	Tri-axial velocity-feedback type
	Frequency range:	0.05 to 30 Hz for 1G
Amplifier and AD Converter	Resolution:	16 bit
	Dynamic range:	96dB
	Sampling rate:	1/100 or 1/200 sec.
Pre-event Memory	Delay device:	IC memory
	Delay time:	5 sec.
Clock	Oscillator:	Quartz with accuracy of 10^{-7}, 10^{-8}
	Precision:	±0.01 sec.
	Calibration by:	NHK(JBC)
Digital Data Recorder	Medium:	Digital magnetic tape with 9 track, half-inch in width and 1600 BPI in recording density

Table 3 List of observed earthquakes

#	Date	Time	*M*	*h* (km)	*Δ* (km)	Max. Acc.	*I*
8608	1986/10/14	06:11	5.0	53	135	26.2 (NAKA)	3
8615	1986/12/01	5:15	6.0	51	108	29.6 (TAMA)	3
8701	1987/1/9	15:14	6.6	72	191	43.5 (NAKA)	4
8702	1987/1/14	20:04	7.0	119	505	11.1 (NAKA)	3
8704	1987/1/21	8:36	5.5	50	112	48.8 (NAKA)	3
8708	1987/2/06	21:24	6.4	30	178	47.4 (NAKA)	3
8709	1987/2/6	22:16	6.7	35	167	94.1 (NAKA)	4
8717	1987/3/10	12:24	5.6	29	166	15.7 (NAKA)	3
8719	1987/4/7	9:41	6.6	37	136	74.5 (NAKA)	4
8721	1987/4/17	4:23	6.1	45	151	45.3 (NAKA)	3
8724	1987/4/23	5:13	6.5	49	145	75.0 (NAKA)	3
8739	1987/9/4	13:55	5.8	42	185	25.4 (NAKA)	3
8740	1987/10/4	19:27	5.8	51	125	60.1 (NAKA)	3
8911	1989/4/28	0:27	4.9	53	98	29.0 (OKIN)	3
8915	1989/6/24	4:59	4.1	14	11	35.0 (TRMA)	3
8926	1989/11/02	3:26	7.1	0	256	22.8 (TRMA)	3
9217	1992/7/18	17:37	6.9	0	269	11.2 (TRMA)	3
9234	1992/12/18	1:21	5.9	34	160	41.0 (TRMA)	3
9305	1993/1/15	20:07	7.8	101	594	36.3 (TRMA)	3
9325	1993/11/11	9:06	5.5	36	154	18.5 (TRMA)	3
9327	1993/11/27	15:11	5.9	112	51	104.2 (NAKA)	4
9409	1994/8/14	18:06	6.0	42	136	45.3 (NAKA)	3
9410	1994/8/16	19:09	6.0	22	154	22.0 (ARAH)	3
9413	1994/10/4	22:24	8.1	23	806	59.7 (OKIN)	3
9414	1994/12/10	18:26	5.1	51	111	28.4 (NAKA)	3
9417	1994/12/28	21:20	7.5	0	343	35.3 (NAGA)	3
9502	1995/1/7	7:37	6.9	30	261	28.0 (OKIN)	3
9602	1996/2/17	0:23	6.5	6	178	106.4 (NAGA)	4
9604	1996/4/23	13:08	5.2	76	117	75.0 (OKIN)	3
9701	1997/2/20	5:22	5.3	88	99	46.7 (SHIR)	3

M: JMA (Japan Meteorological Agency) magnitude, *h*: focal depth, *Δ*: averaged epicentral distance, *I*: JMA seismic intensity at Sendai

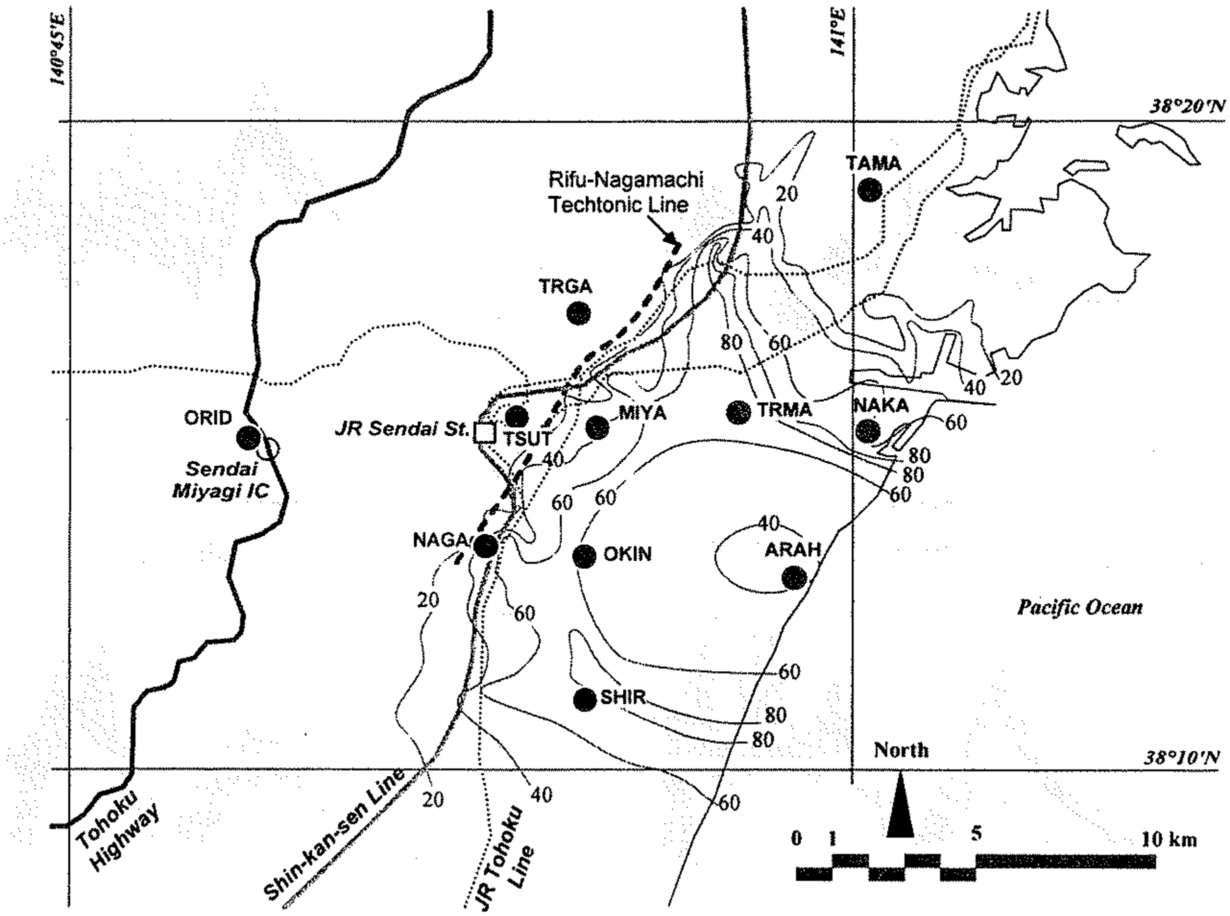

Fig. 1 Location of observation sites in Sendai. Contour lines indicate thickness of alluvium.

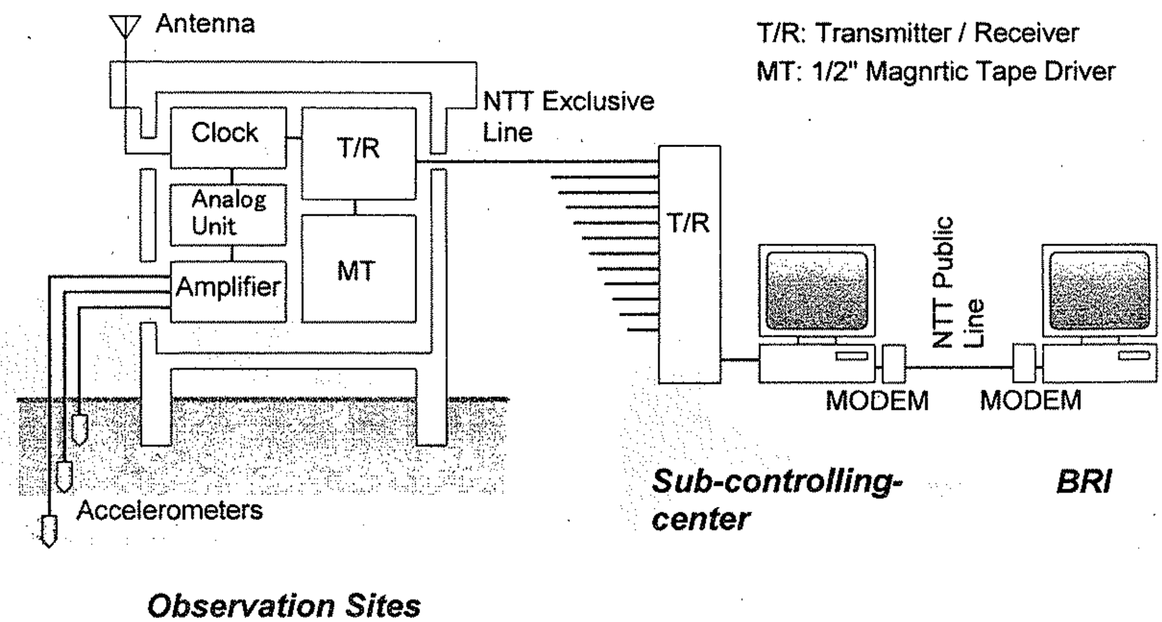

Fig. 2 Block diagram of observation system. Observation sites a the sub-controlling-center are located in Sendai.

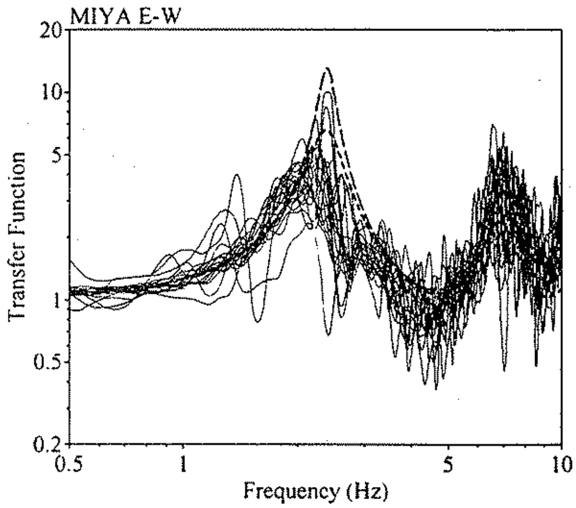

Fig. 3 Fourier spectral ratio at MIYA site

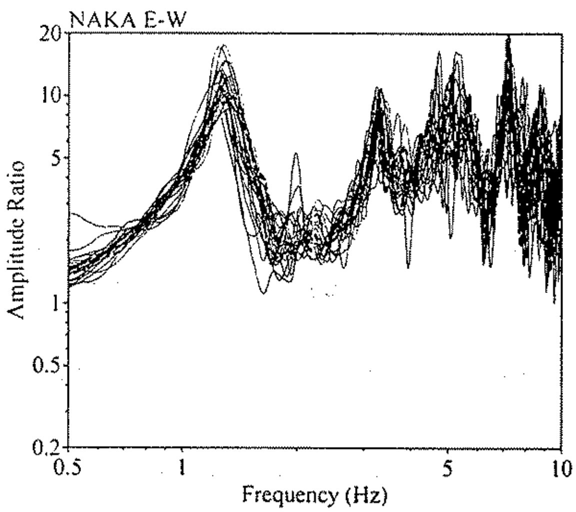

Fig. 4 Fourier spectral ratio at NAKA site

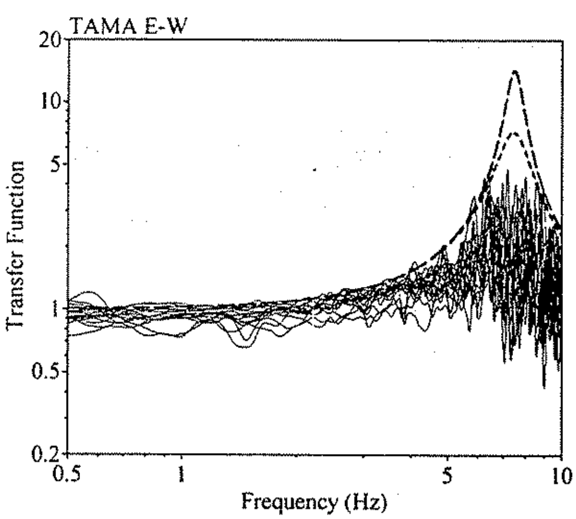

Fig. 5 Fourier spectral ratio at TAMA site

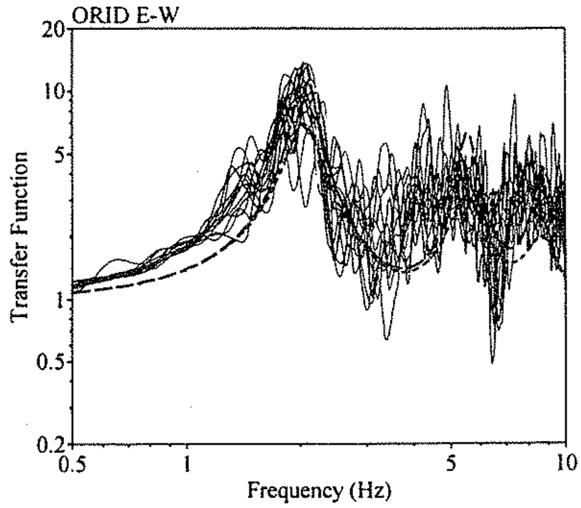

Fig. 6 Fourier spectral ratio at ORID site

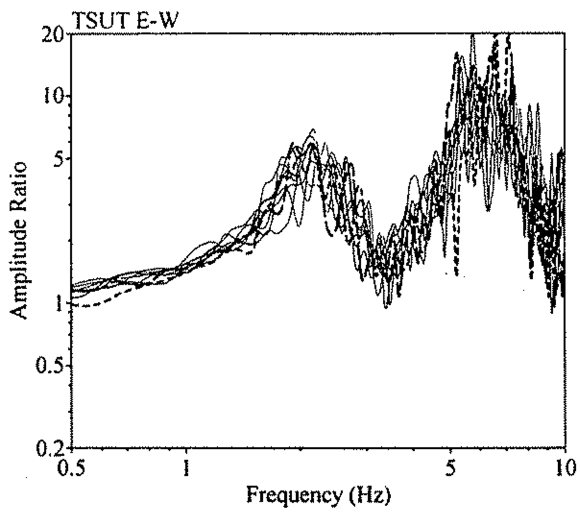

Fig. 7 Fourier spectral ratio at TSUT site

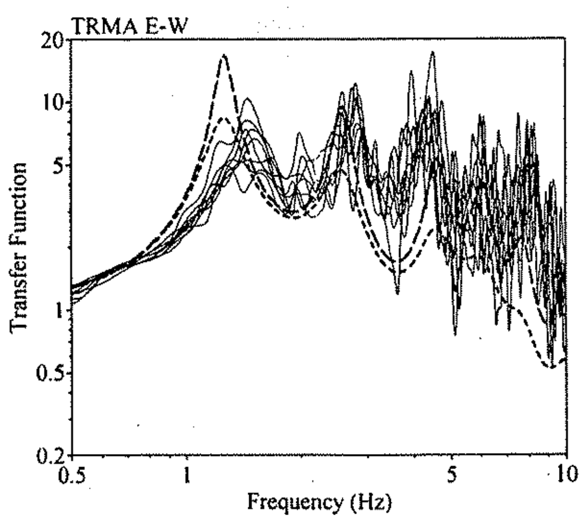

Fig. 8 Fourier spectral ratio at TRMA site

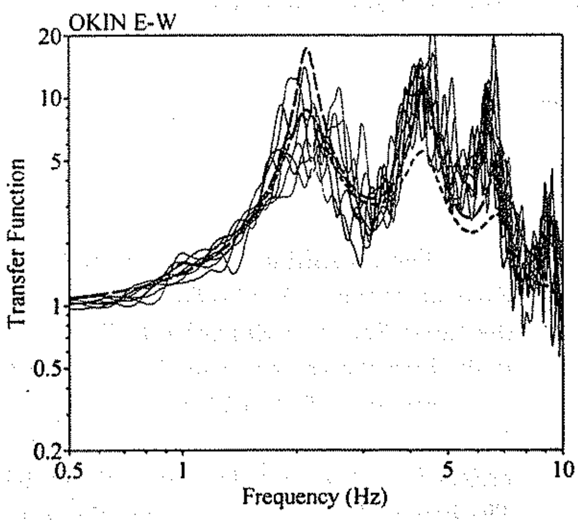

Fig. 9 Fourier spectral ratio at OKIN site

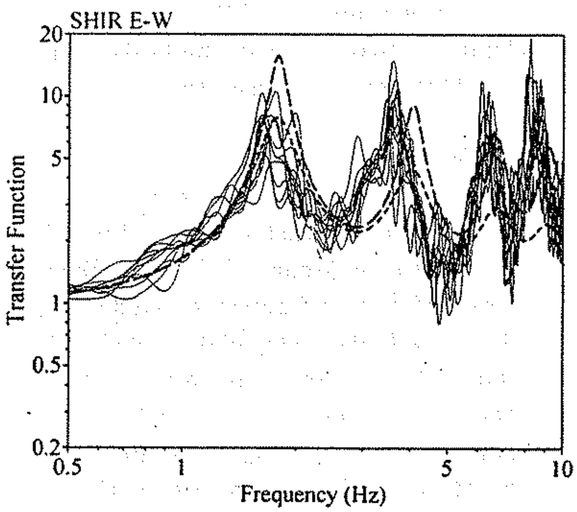

Fig. 10 Fourier spectral ratio at SHIR site

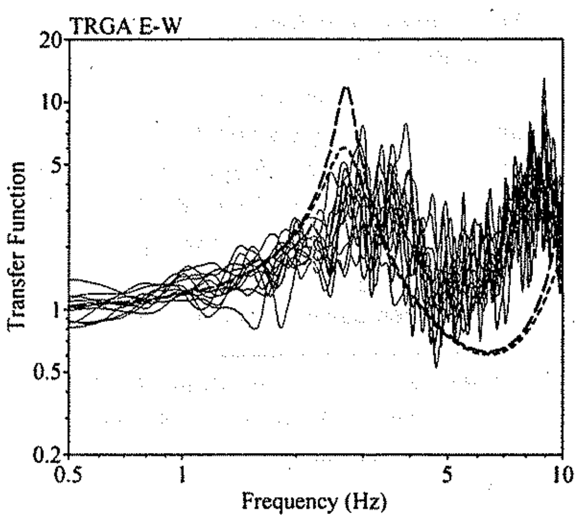

Fig. 11 Fourier spectral ratio at TRGA site

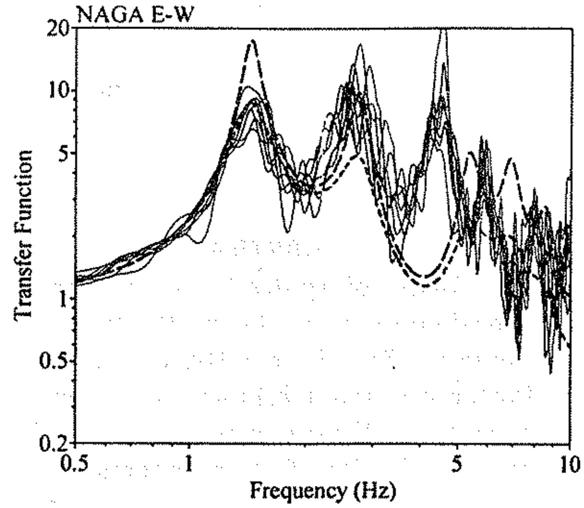

Fig. 12 Fourier spectral ratio at NAGA site

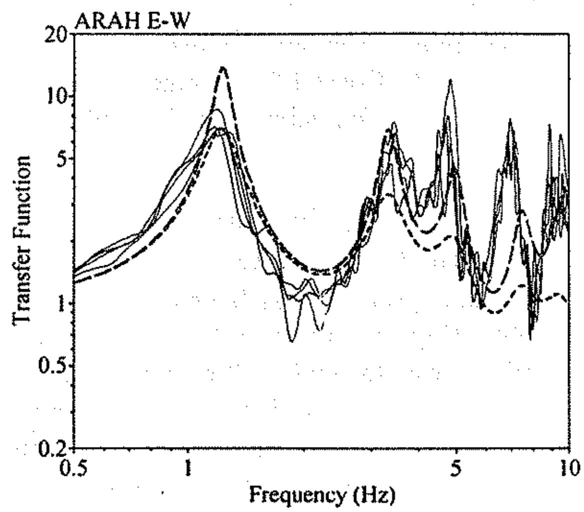

Fig. 13 Fourier spectral ratio at ARAH site