AN EVALUATION OF SURFACE SOIL AMPLIFICATION PROPERTIES FROM THE ANALYSIS OF RECORDED MOTIONS

Izuru OKAWA[1], Toshihide KASHIMA[2], Shin KOYAMA[3] And Yoshikazu KITAGAWA[4]

SUMMARY

The Building Research Institute (BRI) started to install instruments in Sendai city area in 1983 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 ground motions for the design of buildings. Private sectors (16 general contractors and a group of design firms) cooperatively joined this program from 1987. At the end of the fiscal year 1989, the recording system was completed, consisting of as many as 11 recording sites including outcrop rock site, reclaimed land, soft soil ground around which considerable damage was found during the 1978 Miyagi-ken-oki earthquake. This paper summarizes the earthquake recording and research activity associated with the program during the period that followed.

INTRODUCTION

It has often been said that the damage to structures during earthquakes is more or less associated with the subsoil conditions on which they stand. It means that we should bear it in mind the characteristics of earthquake ground motions at ground surface greatly reflect the dynamic properties of underlying soils. However, the dynamic property varies with surface geology such as irregularity and inhomogeneity of soil medium. Sendai area was severely damaged by 1978 Miyagi-ken-oki earthquake [BRI, 1978], which prompted the revision of the Japanese seismic design code to the current version. During the earthquake the damage was concentrated at the area with poor soil conditions or with geotechnical problem such as the artificially developed slope or fill ground. Recognizing the importance of recorded strong motions in the current seismic design practice, BRI started to install seismometers in Sendai principal area with dense array configurations to obtain data for investigating the correlation between the building damage and the soil conditions. The earthquake records with relatively small amplitudes have been mostly obtained to date, due to the low seismic activity for the period. As mentioned above, one of the purposes of the earthquake recording on the ground is to quantitatively differentiate ground motions with various soil conditions. The relative amplitude/spectral ratio among sites was investigated using specific reference site. [Okawa et al., 1990, Okawa et al., 1992] In this paper, we summarise the research activities conducted to date within this project in concluding the co-operative research works, although the earthquake recording is to be continued by BRI and partly taken over by Tohoku university.

RECORDING SYSTEM AND SITE CONDITIONS

The Sendai area is assigned as one of sites with the highest priority in deploying the strong motion instrument arrays. The array recording system of this project consists of eleven sites as shown in Figure 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

[1] *Building Research Institute,Ministry of Construction, Tsukuba, Japan*
[2] *Building Research Institute, ministry of Construction, Tsukuba, Japan*
[3] *Building Research Institute, ministry of Construction, Tsukuba, Japan*
[4] *Hiroshima University, Higashi-Hiroshima, Hiroshima, Japan*

and Oroshimachi. These areas also suffered severer structural damage during the 1978 Miyagi-ken-oki earthquake.

Four of the recording sites, SHIR, OKIN, TRMA and NAKA, are located where the thickness of surface alluvium is 60 to 80 meters. The Sendai district is generally classified into three areas, shown in Figure 1; (1) the hilly tertiary terrain, (2) the terrace area, and (3) the alluvial plain. The oblique NE-SW line passing near the center of the map is called the Rifu-Nagamachi tectonic line, a seismic fault. Hilly tertiary terrain and several levels of the terraces characterize the area to the west of this tectonic line. 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 locations. The alluvial plain develops east of this tectonic line and consists mostly of sand, silt, and gravel. The depth of the Tertiary base rock varies abruptly near the tectonic line. There are several areas in the plains that are covered by very soft peat or mud. The descriptions of geological conditions are summarized in reference [Kitagawa et al., 1994]. As indicated in Table 1, Two sites, TAMA, ORID had been estimated as hard soil or rock. However, ORID shows weathering in the surface. On the other hand, although TRGA had been estimated as class 2 soil, the surface soil survey result shows the site has stiffer feature than prior estimation. The sites other than ORID and TRGA shows slightly different features estimated before installation of seismometers. From soil survey, NAKA and TRMA sites showed considerably soft soil condition. Most of the damage occurred on the eastern side during the 1978 Miyagi-ken-oki earthquake.

The contour lines of thickness of surface alluvial soil are also shown in Figure 1. 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 recording sites. 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. The details of seismometers and recording systems are explained in several reports published in the past.

The soil classification is explained as follows. The firm, hard soil or Tertiary rock is class 1. The extremely soft soil goes into class 1, in which some geotechnical consideration such as pile foundations or soil improvement is necessary, when larger construction is planned. The intermediate soil is class 2. In Table 1, Column ‘Soil’ indicates the soil class. The soil class indicated in Table 1 is determined from the preliminary geotechnical survey such as SPT and PS logging.

RECORDED EARTHQUAKE MOTION AND PREVIOUS STUDIES

Many earthquakes were triggered by this system during this period. Table 1 shows the list of earthquakes for which the JMA intensity at Sendai was greater than 3. There are totally 35 major earthquakes. The scatters of magnitude, focal depth and epicentral distance are shown in Figure 2. The epicentral distance scatters from 11km to 800 kilometers. It might be mentioned that the larger the magnitude, the longer the epicentral distance becomes. In the previous studies, the consistency and variation of amplification properties with earthquakes are mainly examined. [Okawa, et al., 1990, Kashima, et al., 1990] In addition, The relationship of amplitudes with recording sites is examined. [Okawa, et al., 1992, 1995] and the earthquakes are separated into 3 groups to examine the effect of source location on seismic motion. [Okawa, et al., 1995]

The results of these previous studies are briefly summarized in the following sections. The studies previously conducted include; (1) Soil amplification depends on soil classification and predominant period of the surface soil. (2) Effect of soil nonlinearity to the amplification was not conducted due to the lack of strong motion data (3) Frequency-dependency of damping factors of soil (4) wave propagation property invoked by the deep ground structure. (5) Liquefaction potential and soil amplification

The amplification ratios computed with the recorded motion for one-site shows similar values for different earthquakes. However, the consistency seems to somewhat lost in case of the closer events for closer events. The average amplitude ratio for surface horizontal motion varies from 0.5 to 1.5 and has smaller variation on seismic source location. The ratio for surface vertical motion varies from 0.7 to 1.3 and has larger variation on seismic source location. The average of amplitudes of two horizontal components is used for assessment of horizontal acceleration, velocity and spectral values. Considering the difference in the location of sources, the ratios to the average is largest for NAKA site, and TRMA site. It is commonly seen that the variation of horizontal amplitudes among sites is larger than vertical amplitudes. The TAMA and TRGA site show the lowest values. As is described previously, these two sites TAMA and TRGA have firm soil condition compared with others. The ratios examined above were also compared for different source regions. The variation due to source region is not so large. The relations of ratios among sites are mostly maintained independent upon the source locations. For vertical amplitudes, it can be said that the ratio varies less than that for horizontal amplitudes. However, The variation due to source region increased. It means that the vertical motion takes larger influences of source location than horizontal motion. For vertical amplitude, the TRMA and SHIR sites take larger values and site TAMA and TRGA sites take smaller values. The surface motion includes the effect of soil amplification. Therefore, it is easily understood that the variation of amplitudes for deeper soil levels decreases.

Table 1: Location and geology of recording sites and depths of seismometers

Site name	Abr.	Lat.	Lon.	Soil	Cmplt.	Depth (m)		
Miyagino	MIYA	38.15'24"N	140.55'16"E	2	1984	1	22	54
Nakano	NAKA	38.15'14"N	141.00'26"E	3	1985	1	30	61
Tamagawa	TAMA	38.19'03"N	141.00'34"E	1	1986	2	11	33
Oridate	ORID	38.15'26"N	140.48'39"E	1	1987	1	57	76
Tsutsujigaoka	TSUT	38.15'30"N	140.53'36"E	2	1988	1	36	59
Okino	OKIN	38.13'26"N	140.55'05"E	3	1988	1	17	62
Tsurumaki	TRMA	38.15'38"N	140.58'15"E	3	1988	1	25	79
Tsurugaya	TRGA	38.17'16"N	140.54'53"E	2	1988	2	37	62
Shiromaru	SHIR	38.11'29"N	140.54'53"E	2	1988	1	20	76
Nagamachi	NAGA	38.13'45"N	140.53'01"E	2	1989	1	29	81
Arahama	ARAH	38.13'11"N	140.59'00"E	3	1989	1	31	76

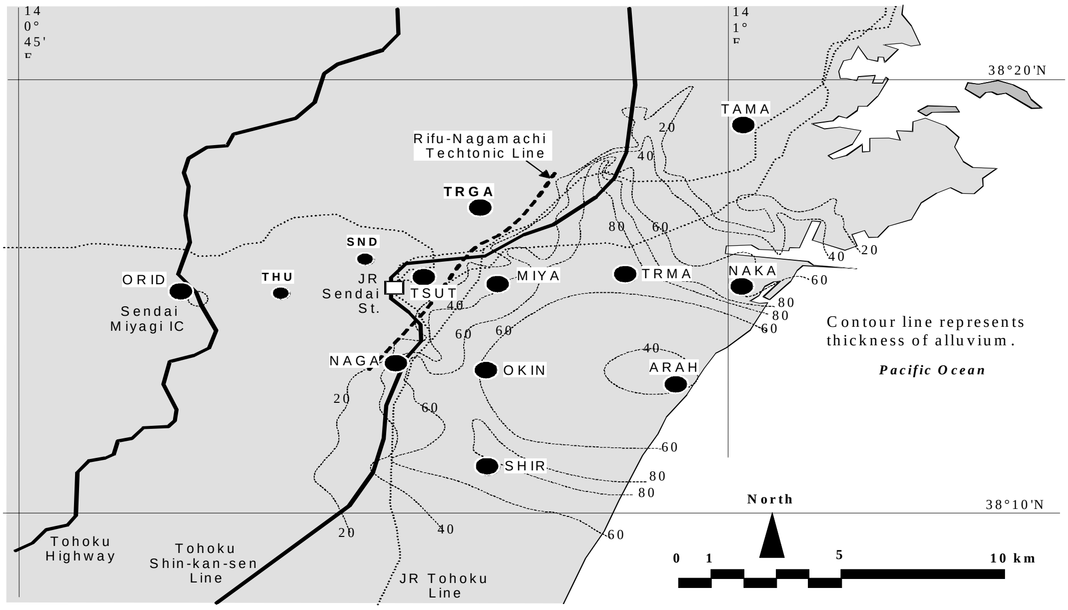


Figure 1: Location of recording sites and control station with thickness of alluvium

It is seen that the average spectral ratio ranges from 0.5 to 2.0 for horizontal surface motions and from 0.6 to 1.5 for horizontal bottom motions. The sites MIYA, NAKA, TAMA were established at the beginning of the observation, and therefore the number of records are the largest among sites. These three sites, in addition, can be representative of the three soil classifications. The variation varies for period reflecting the soil properties of sites. For TAMA site, the ratio varies less for different source regions, whereas larger variation is seen for NAKA site. For surface vertical motion, there is less variation among sites. The variation due to source region increased. There is a tendency that the closer sources raises the ratio for three sites.

CHARACTERISTICS OF EARTHQUAKE MOTIONS

With the constructed database, we examined the effectiveness of the one-dimensional amplification theory to apply to the soil conditions of these recording sites. The amplification 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 Figures 3 to 13. All Fourier spectra are smoothed using the Parzen window with a width of 0.2 Hz.

Table 2: Recorded Major Earthquakes (Intensity larger than 3)

EQ No.	M	Dep (km)	Dis (km)	Ijma
8608	5	53	135	3
8615	6.0	51	108	3
8701	6.6	72	191	4
8702	7.0	119	505	3
8704	5.5	50	112	3
8708	6.4	30	178	3
8709	6.4	30	167	4
8717	5.6	29	166	3
8719	6.6	44	136	4
8721	6.1	45	151	3
8724	6.5	47	145	3
8734	5.7	50	125	3
8739	5.8	41	185	3
8740	5.8	42	125	3
8911	4.9	52	98	3
8915	4.1	14	11	3
8926	7.1	0	256	3
9217	6.9	0	269	3
9234	5.9	34	160	3
9305	7.8	101	594	3
9325	5.5	36	154	3
9327	5.9	112	51	4
9409	6.0	42	136	3
9410	6.0	22	154	3
9413	8.1	23	806	3
9414	5.1	48	111	3
9417	7.5	0	343	3
9502	7.2	48	261	3
9602	6.5	6	178	4
9604	5.2	76	117	3
9701	5.3	88	99	3
9705	5.5	54	137	3
9712	6.5	6	96	4
9713	5.2	76	61	3
9820	5.0	13	13	4

M: Earthquake magnitude in JMA scale

Ijma: Intensity for Sendai published by JMA.

The first two digits in EQ No. indicates the year of occurrence, e.g., 87 means 1987.

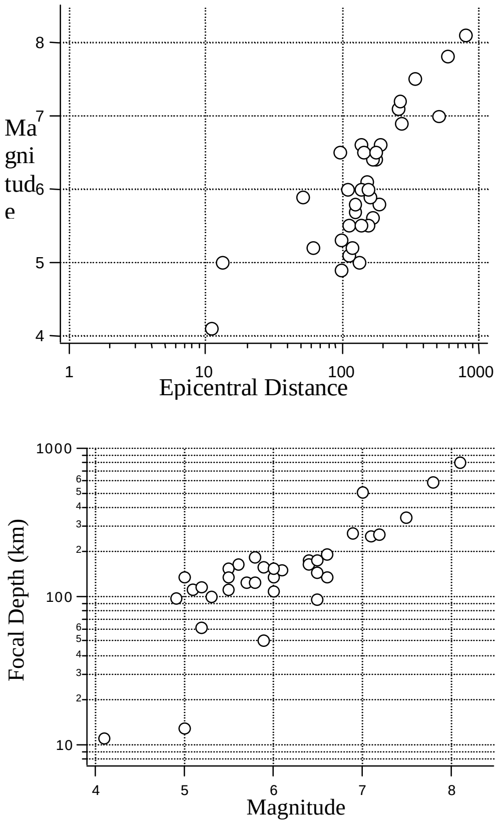


Figure 2: Magnitude, Focal Depth and Epicentral Distance for the Major Earthquakes

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 Figure 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 Figure 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.

Althrough the comparison between observed and theoretical results in Figure 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 Figure 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 Figure 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 Figure 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 frequency of transfer functions is 1.22 Hz as shown in Figure 13. This is the softest ground condition in our observation sites. Although number of records is few, a degree of accordance is satisfactory.

CONCLUSIONS

In this paper, the studies conducted thus far using the recorded motions in Sendai were firstly summarized. Most of the related studies have targets of obtaining the realistic evaluation methodology for soil amplifications. The figures 3 through 13 show that the properties can be uniquely evaluated.

Looking back the years since the installation, the project duration is not enough to get the data that we had desired in the beginning. It is not enough either to obtain the records with intensity levels useful for nonlinear effect of soils. For all that data is not sufficient yet, there had been plenty of understandings and findings on the soil amplifications and variation of surface motions within the area among researchers and engineers through this project. Time is necessary either to continue the earthquake recordings for new data or to integrate the data and methodology with more advanced recently developed technology such as the high speed computing environment and the GIS technology.

ACKNOWLEDGMENT

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 the Building Research Institute (BRI) of the Ministry of Construction and the Association for Promotion of Building Research (APBR). 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 the APBR. The authors wish to express their sincere thanks to the committee members for their cooperation.

The earthquake observation project with dense accelerometer array configuration is now continued. 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 advanced in the future.

REFERENCES

Building Research Institute, (1978), *Report on the Damage by 1978 Off-Miyagi Prefecture Earthquake* (in Japanese), Research Report of BRI, 86, pp75-81

Kitagawa, Y. et al., (1987, 1988, 1989), *Dense strong motion earthquake seismometer array at site with different topographic and geologic condition (part 1,2-1987), (part 3-1988), (part 4-1989), (part 5- 1990)*," (in Japanese) Summaries of technical papers of AIJ Annual Meeting.

Okawa, I. et al., (1990), *Variation patterns in amplitude and spectrum of records from array observation sites*, Proceedings of the 8th Japan Earthquake Engineering Symposium, Dec., pp565-570.

Kashima, T. et al., (1990), *The earthquake observation using dense array of accelerometers at sites with various topographic and geologic conditions*, (in Japanese), Proc. of the 8th Japan Earthquake Engineering Symposium, Dec., pp487-492.

Okawa, I. et al., (1992), *Site effect characterization using records of dense strong motion earthquake seismometer array in Sendai*, Proc. of the Tenth World Conference on Earthquake Engineering, Madrid, Spain

Kitagawa, I., et al., (1992), *Observation and Analyses of Dense Strong Ground Motions at Sites with Different Geological Conditions in Sendai*, Proceedings of the International Symposium on the Effects of Surface Geology on Seismic Motion, Odawara, Vol.1, pp311-316

Kitagawa, Y. et al., (1994), *Dense Array Observation and Analyses of Strong Ground Motions at Sites with Different Geological Conditions in Sendai*, BRI Research Paper 139, July

Okawa, I., et al., (1995), *Variation and Consistency of the Property of the Earthquake Motions and Site Amplifications from the Dense-Seismometer Array Observation*, Proceedings of the Fifth International Conference on Seismic Zonation, Vol.3, Nice, France, pp2247-2254

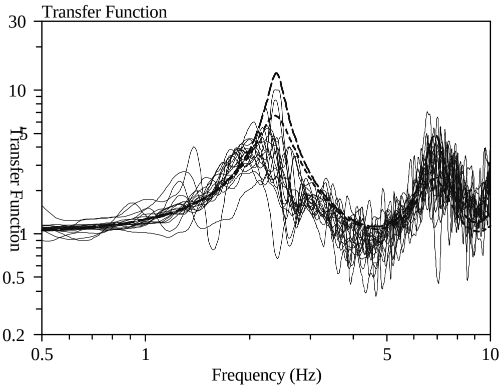


Figure 3: Fourier spectral ratio at MIYA site

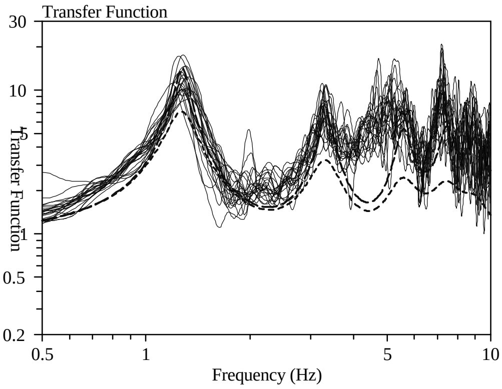


Figure 4: Fourier spectral ratio at NAKA site

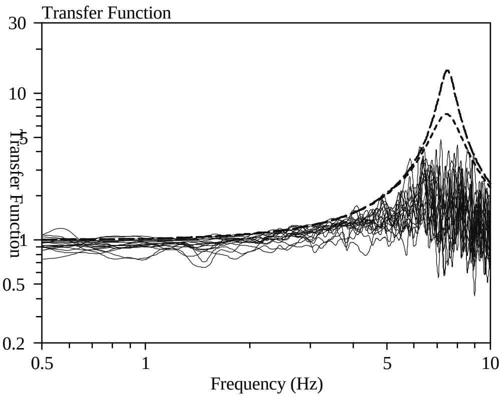


Figure 5: Fourier spectral ratio at TAMA site

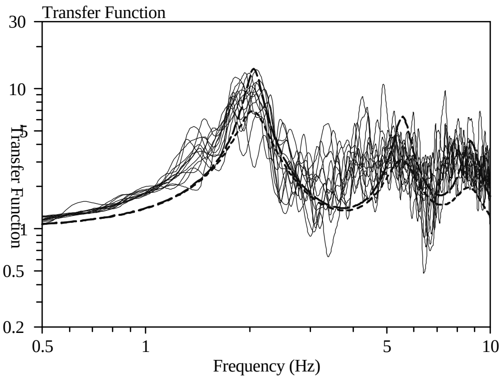
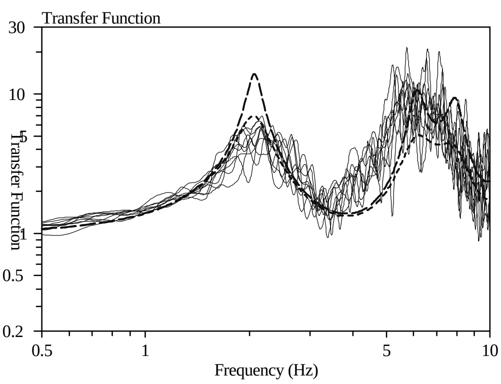


Figure 6: Fourier spectral ratio at ORID site



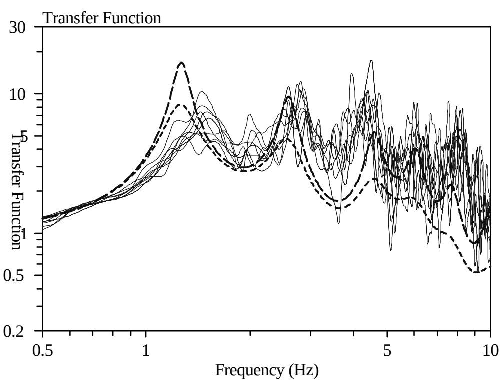
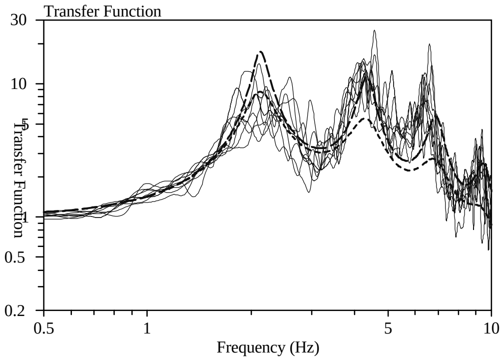


Figure 7: Fourier spectral ratio at TSUT site **Figure 8: Fourier spectral ratio at TRMA site**



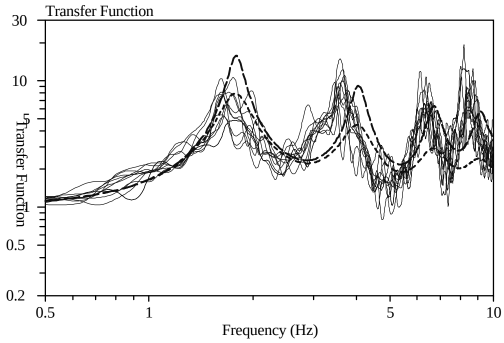
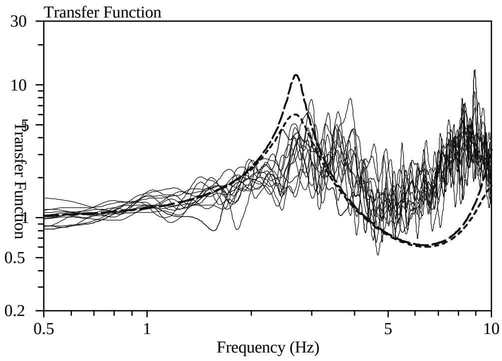


Figure 9: Fourier spectral ratio at OKIN site **Figure 10: Fourier spectral ratio at SHIR site**



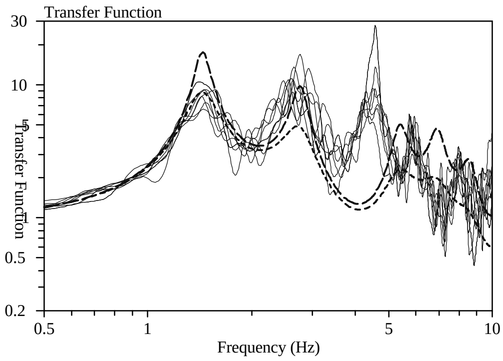


Figure 11: Fourier spectral ratio at TRGA site **Figure 12: Fourier spectral ratio at NAGA site**

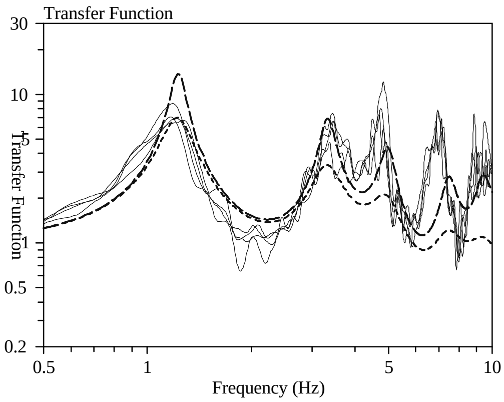


Figure 13: Fourier spectral ratio at ARAH site