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ATTEMPT TO ESTIMATE LOCAL SITE EFFECT OF YAMAGATA BASIN BY DENSE MICROTREMOR MEASUREMENT

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Abstract

Yamagata basin is located in the north-east part of Japan, and 60 km in west from Sendai city where has suffered from the 2011 Tohoku earthquake. It is well known that Yamagata basin has irregular structure of seismic bedrock in earthquake engineering from the past geological investigations. In the western part of Yamagata basin, soft soil layer is accumulated in thick. Recently, the urban area of Yamagata city is expanding to west and north area, and soil conditions of newly developed area tend to be soft. Soft ground area is known to exist in the western and northern area of the basin, but the boundary of soft ground and medium or hard ground area in not so clear. Considering those conditions, seismic response of the site will significantly vary place to place in Yamagata basin. Moreover, active fault zones are there in the west of Yamagata basin. The active fault zones are estimated relatively high to occur large earthquake in the recent 30 years by Headquarters for Earthquake Research Promotion of Japanese Government. Therefore, it is important and necessary to understand the local site effect of Yamagata basin for earthquake disaster mitigation.

The authors conducted microtremor measurement at about 40 sites in Yamagata basin to estimate the local site effect and the effect of the irregular structure of engineering bedrock. Especially, the results of 25 sites in the western part of the basin significantly affected by the deep ground structure are introduced in this study. Based on the results from H/V spectral ratios, predominant frequencies of the measurement sites are estimated. The results show that predominant frequencies of sites of the northern and central area are distributed about 1.0 to 1.5 Hz. In the measurement sites of the west edge of the basin, predominant frequency tends to be estimated relatively as high as about 2.0 Hz. The predominant frequencies of southern and eastern area also tend to be estimated relatively high over 2.0 Hz, except SKD.

Based on the results of estimated predominant frequency, dynamic profile of soft soil layer and the depth of engineering bedrock of each site are estimated by comparison to the numerical simulation results of theoretical wave propagation analysis. In applying wave propagation theory, shear wave velocity of soft surface layer is assumed by SPT-*N* data of each measurement site. In some sites, predominant frequencies deduced from H/V spectral ratio show good agreement with the results of and theoretical wave propagation analysis. However, significant difference of predominant frequency is found in several sites. In order to investigate the difference, it is pointed out that the effect of the deep ground structure underlying soil layer below supporting stratum should be considered in theoretical wave propagation analysis

Along to the five measuring lines in the EW direction, spatial variation of predominant frequency of the ground is investigated more in detail by dense microtremor measurement. Spatial variation of predominant frequency is clearly shown and the effect of soil condition of back marsh, natural levee and alluvial fan is discussed.

Keywords: Local site effect; Microtremor measurment; Seismic ground response; Wave propagation; Irregular Ground

1. Introduction

Local site effect is one of the crucial factors to affect ground response subjected to strong shaking of earthquake. Deep ground structure and path effect give the significant effect to the local site effect in case that the deep ground structure like engineering bedrock has structural irregularity. The investigations of deep ground structure as well as physical properties of surface soil layers have been conducted in nationwide. Yamagata basin is located on the east-north part of Japan, and has long and narrow shape, and one of the basins with irregularity in its deep ground structure. It is known that this basin has been rarely damaged by natural disaster by ancient documents and records, however, active fault running along the west edge of this basin is estimated with relatively high probability of occurrence in the recent years.

In the eastern part of the basin, ground consists of solid alluvial fan. On the other hand, in the western part of the basin that has been rapidly urbanized in the recent years, soft ground area formed by back marsh is scattered along the large river [1]. The authors have carried out microtremor measurements to understand the vibration characteristics of the ground of the eastern part of the basin and tried to find the boundary of solid alluvial fan area and soft ground area [2, 3].

In the western part of the basin, in addition to widely expanded soft ground, and considering active fault, it is important to grasp the vibration characteristics of the ground from the disaster prevention point of view. Rigid bedrock as deep ground structure is well known to have sharp inclination from west to east edge of the basin in Yamagata basin. It means that the vibration characteristics of the basin are significantly affected by the shape of the deep ground structure. Especially, in the western part of the basin, vibration characteristics of the ground is affected by the soft surface layer thickly deposited as well as the deep ground structure irregularly varied.

In this study, the results of microtremor measurements carried out at 25 sites in the western part of the basin are introduced. Predominant frequency of each site is estimated by H/V spectral ratios and the results are visualized on the map that can easily understand predominant frequency distribution. Moreover, *N*-values of standard penetration test data (SPT-*N*) at the microtremor sites are obtained and converted into shear wave velocity profile. One dimensional wave propagation theory is applied to estimate the theoretical wave propagation characteristics of the microtremor sites. Theoretical predominant frequencies estimated by SPT-*N* data are also compared to the results of H/V spectral ratio. The effect of the deep ground structure to the surface ground response is discussed by this comparison. In addition, dense microtremor measurements are carried out along to the five east-west measuring lines. Spatial variation of predominant frequency of the ground estimated from microtremor measurement along to the east-west lines are discussed by comparison with the predominant frequency obtained by AVS30.

2. Characteristics of Yamagata Basin

Local site response characteristics of the basin structure including alluvial fan is examined by microtremor measurement in this study. The site for this study is Yamagata basin located on Tohoku district (Northeast part of Japan) that is about 60km west from Sendai city damaged by 2011 Tohoku earthquake. Location of Yamagata basin is shown in Fig. 1.Yamagata basin has the Tertiary layer with fold structure in North-South direction and the Quaternary deposits thickly accumulated. Alluvial soft soil layer is thickly and widely accumulated in the back marsh area in the western part of the basin as shown in Fig 2. Active fault line is estimated running along the western edge of the basin shown in Fig.2. The alluvial fan area is considered hard ground due to previous investigation such as standard penetration test. Toward west, ground condition changes to alluvial plain, and soft soil layer is considered thicker than around the boundary of alluvial fan area of eastern part of the basin. While the earthquake observation site (K-NET Yamagata) is on the alluvial fan area, the recently developing downtown of Yamagata city is located on the center and western part of Yamagata basin where is affected by the soft soil ground consisting of the Quaternary deposits. Therefore, local site responses of the center and western part of Yamagata basin are different from the basin edge

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eastern area including the earthquake observation site. That means it is difficult to estimate seismic vulnerability of downtown Yamagata based on the earthquake records of K-NET Yamagata.

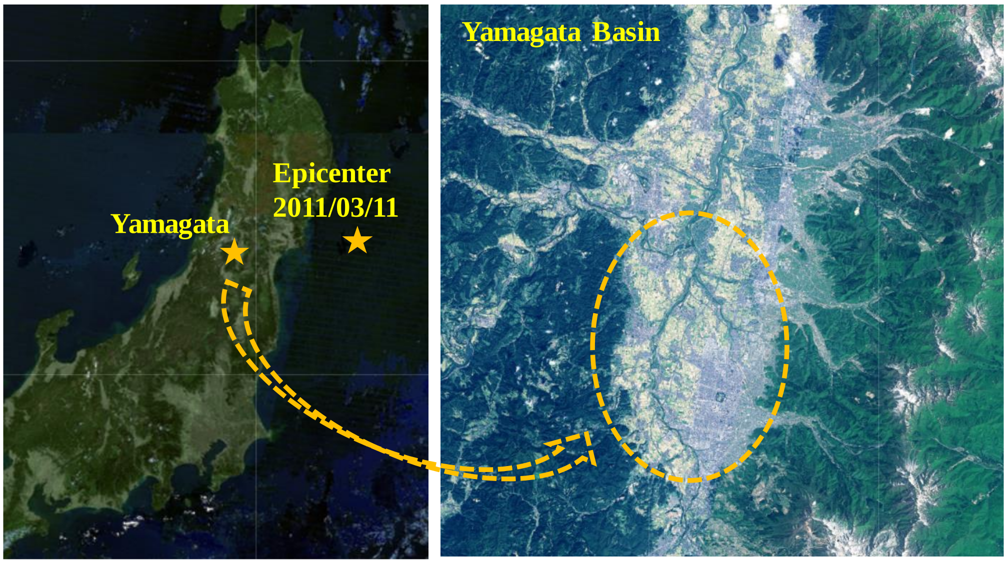

Fig. 1 – Yamagata basin (@Geospatial Information Authority of Japan)

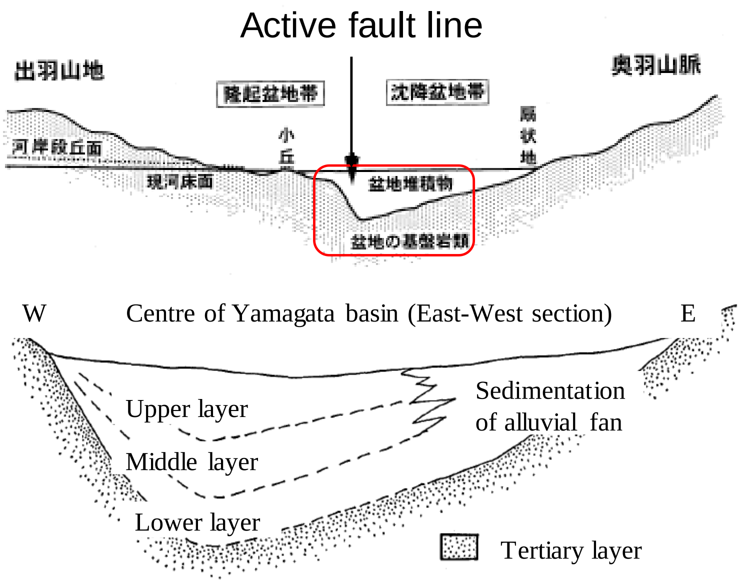

Fig. 2 – Schematic sectional view of Yamagata basin [1, 2]

Microtremor measurements are conducted at 25 sites mainly in the soft ground area of the western part of Yamagata basin. Sites are distributed from north to south of the basin which is considered to be affected by the irregular soft surface layer and the engineering bedrock structure. Distribution of measuring sites is illustrated in Fig 3. Microtremor measurement is continuously carried out in 10 minutes with sampling frequency of 100Hz. Small time window of 40.96 seconds for data analysis is applied to the entire duration

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of observed records and moving from the beginning to the end by step of which width is equal to the half of the small time window. H/V spectral ratio is derived for every small section divided by the window and the results are averaged all through the duration. Estimated predominant frequencies discussed afterwards are also described in Fig.3.

3. Estimation of Predominant Frequency from Microtremor Measurement

The results of H/V spectral ratio at 25 sites are obtained and predominant frequencies are estimated. After estimating predominant frequency of each result, distribution of predominant frequencies of the sites is organized on the map in Fig 3. Before estimating predominant frequency at each site, previous results of H/V spectra [3] are reviewed and predominant frequencies are re-estimated.

Predominant frequency of OTR and YMB at the foot of western hill area are estimated 2.1 and 2.0 Hz as relatively high frequency, respectively. Relatively high predominant frequency is estimated 2.3Hz in SGM, down from YMB along the foot of the mountain. Surface ground around OSN is inclined from west to east in the basin. Compared to the area at the foot of the mountain, the neighboring area around OSN is expanding rice field. Estimated predominant frequency of OSN is 2.0Hz.

At the sites of MIJ, DEW, DSC and OST in northern part, predominant frequencies are estimated around 1.0 Hz as relatively low frequency. Although significant peak of MIJ looks ambiguous as mentioned below, the frequency having the largest H/V spectral ratio except low frequency range less than 1.0Hz is estimated predominant frequency. Down to the center of the basin, predominant frequencies of MYU, KNS, KNC, DHC, DJS, DNC, and MNH are estimated 1.0 to 1.6Hz. The area including those sites are located in the soft ground area composed by back marsh of “Sukawa” river. The results are close each other. Especially, the locations of KNS and KNC are very close. Although estimated predominant frequency of KNS is a little bit of higher than KNC, H/V spectral ratios of both sites appear quite similar. Predominant frequencies in northern part of OST and DEW are the lowest. Predominant frequencies are turning relatively high from north to the center of the basin, however, predominant frequencies in the central area of the basin also indicate still soft ground.

The location of MKZ is on the plateau of the western hill, and predominant frequency is estimated relatively high. It is considered that the active fault runs through the area near the site of NYG and MTS. Those sites are located at the foot of mountain, and predominant frequencies are estimated 2.1Hz for NYG and MTS, respectively.

The site of MNM is located in the east side area of the basin that is considered the alluvial fan. Predominant frequency is estimated 2.0Hz. Although the location of SKD is close to MNM, predominant frequency of SKD is low as 1.2Hz, compared to MNM. As compared in the following section, SPT-*N* data of SKD support the results as mentioned above. At the south area of the basin, predominant frequency indicating surface layer characteristics of DKC is estimated 2.8Hz. At the foot of eastern mountain area, it is difficult to find significant peak in H/V spectral ratio of ZDC. Therefore, ground condition of ZDC is considered very solid as engineering bedrock.

Results of predominant frequency distribution are overall estimated low as that the northern part and down to the central part of the basin indicates soft ground consisted of back marsh of “Sukawa” river. At the western part of the basin along to mountains, predominant frequencies are relatively high as around 2.0Hz. The site of MKS is considered further high over 4.0Hz to indicate vibration characteristics of the hill. Predominant frequencies at eastern and southern area also indicate as high as western area, however, the site of SKD has relatively low frequency of 1.2Hz that is different from neighboring site of MNM. The causes of the results will be discussed in the following section through comparison to the theoretical amplitude ratios from 1D wave propagation theory using SPT-*N* data.

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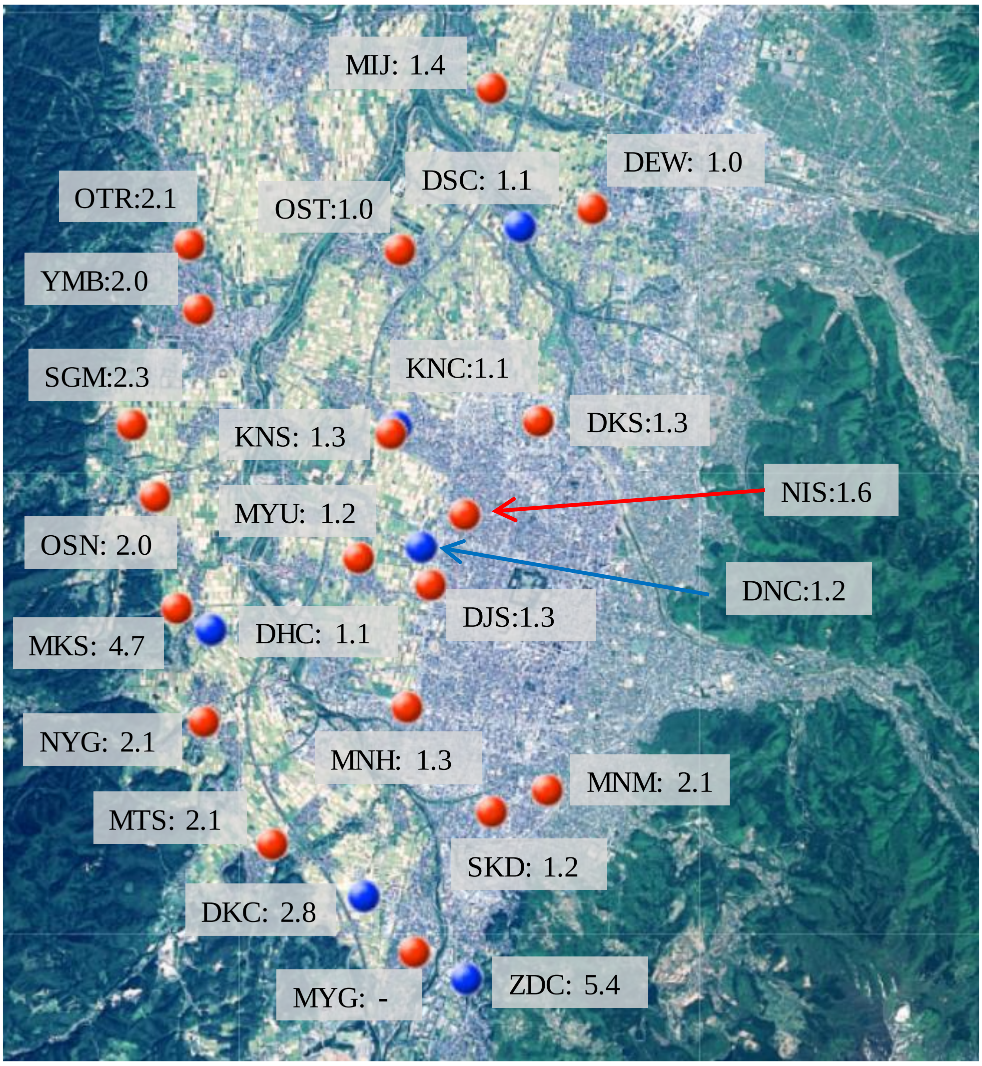

Fig. 3 – Estimated predominat frequency distribution from microtremor measurement (Unit: Hz)
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4. H/V spectral ratio and 1D Wave Propagation Theory

It is important and necessary to confirm the validity of the estimation of predominant frequency by H/V spectral ratio. Here, predominant frequency estimated by 1D wave propagation theory is compared to the result of H/V spectral ratio. In order to apply wave propagation theory, shear wave velocity profiles of the microtremor measurement sites are necessary. Here, SPT-*N* data are available from boring data around microtremor measurement sites. Shear wave velocity is estimated by Eq. 1 from SPT-*N* data [4].

$$V_s = 68.79\ N^{0.171}\ H^{0.199}\ E\ F\ (\mathrm{m/s}) \qquad (1)$$

where Vs is shear wave velocity (m/s), N is *N* value of SPT (Standard Penetration Test), H is depth of surface soil layer (m), E is factor on geological age, F is factor on soil type. When geological age is alluvial, E=1.000, and in case of clayey soil, F=1.000, and sandy soil, F=1.086.

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H/V spectral ratios of microtremor sites are shown in Fig.4 to Fig.7. Predominant frequencies found from the figures in Fig.4 to Fig.7 are already shown in Fig.3. Theoretical amplitude ratios of surface soil layers calculated from 1D wave propagation theory [5] using shear wave velocity profile described above are also illustrated in the figures by blue dashed line. In some sites, theoretical amplitude ratio are absent because SPT-*N* data are not available. It should be noted that almost all the shear wave velocity profiles are obtained from surface down to only GL-20 to 30m. This means that it is impossible to estimate the effect of deep ground structure underlying the supporting stratum described in the SPT-*N* data. At each microtremor site, two sensors are placed on the two different points on surface ground in the same site. In all the figures of Fig.4 to Fig.7, No.1 and No.2 mean results of H/V spectra of two measuring points at the same site, respectively. Blue dashed line means theoretical amplitude ratio obtained by 1D wave propagation theory.

Results are separately assigned in northern, central, western, and southern and eastern area of the basin in Fig. 4 to 7. From the northern area of MIJ, DEW, DSC, and OST in Fig. 4 to the central area of KNC, KNS, DNC, and MNH in Fig. 5 where are relatively soft ground area consisting of back marsh of “Sukawa” river, predominant frequencies estimated from H/V spectral ratios are around 1.0 to 1.6 Hz. The first spectral peaks of theoretical amplitude ratio (blue dashed line) tend to appear in relatively higher range than H/V spectral ratios. It can be considered because depth of surface soil layer obtaining SPT-*N* data is not deep enough for accurate estimation.

In Fig. 6, predominant frequencies in microtremor measurement site in western area are as high as over 2.0Hz as mentioned in previous section. Area along with western edge of the basin is estimated close to solid ground. The site of MKS which of location is on the top of small hill has predominant frequency of 4.7Hz. It can be considered the effect of vibration characteristics of the hill.

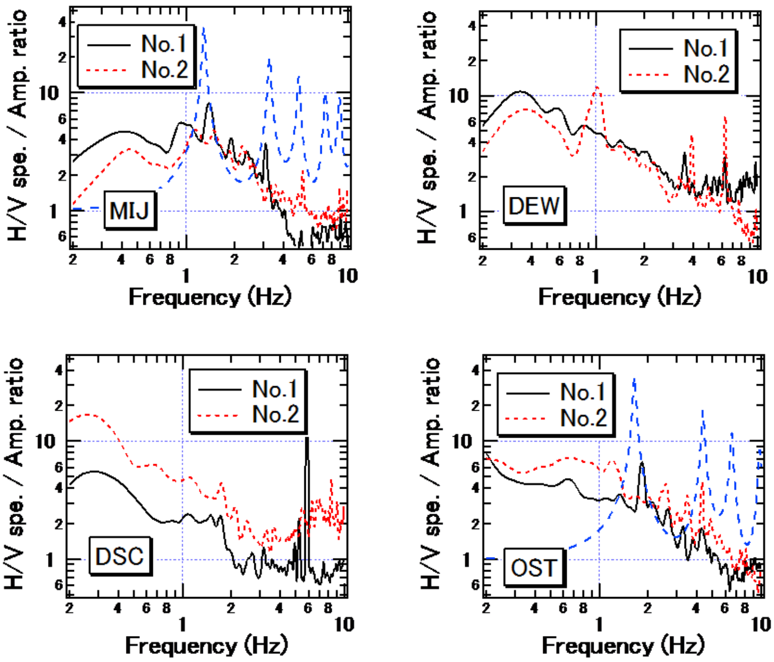

Fig. 4 – H/V spectral ratio with theoretical amplitude ratio (Northern area)

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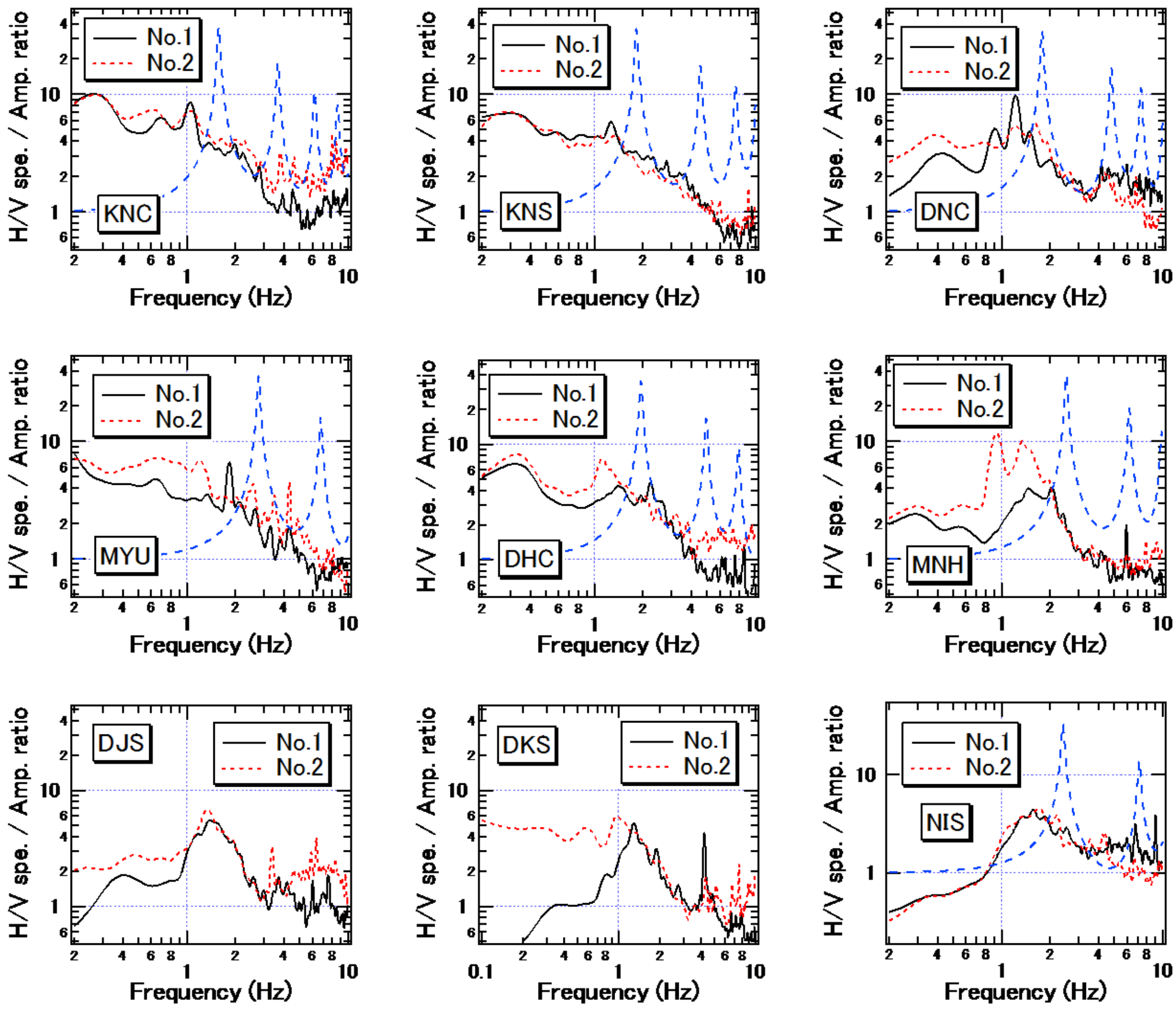

Fig. 5 – H/V spectral ratio with theoretical amplitude ratio (Central area)

Results of southern and eastern area are shown in Fig.7. Microtremor measurement sites in southern and eastern are estimated relatively solid as well as western area of which predominant frequencies are over 2.0Hz except SKD. The site of SKD indicates relatively low predominant frequency of 1.2Hz even though neighboring site of MNM has predominant frequency of 2.0Hz. Theoretical amplitude ratio of SKD shows theoretical predominant frequency is about 2.0Hz, so that further investigation is necessary to accurately understand the ground vibration characteristics of this site.

All through the figures, some amplification in low frequency range in 0.3 to 0.4 Hz can be observed. This can be assumed the effect of deep ground structure. Considering large amplitude of theoretical wave theory in lower frequency range than H/V spectra, the effect of deep soil layer underlying the solid soil stratum below supporting layer of the building should be considered for more precise estimation of local site effect. Also, microtremor is consisting of complicated wave propagation where waves are coming from lots of sources in different paths. Generally, microtremor is often assumed surface wave as Rayleigh wave, and there is a room to discussion against comparison to 1D wave propagation theory. Surface wave propagation and wave amplitude in deep ground structure should be more studied in detail.

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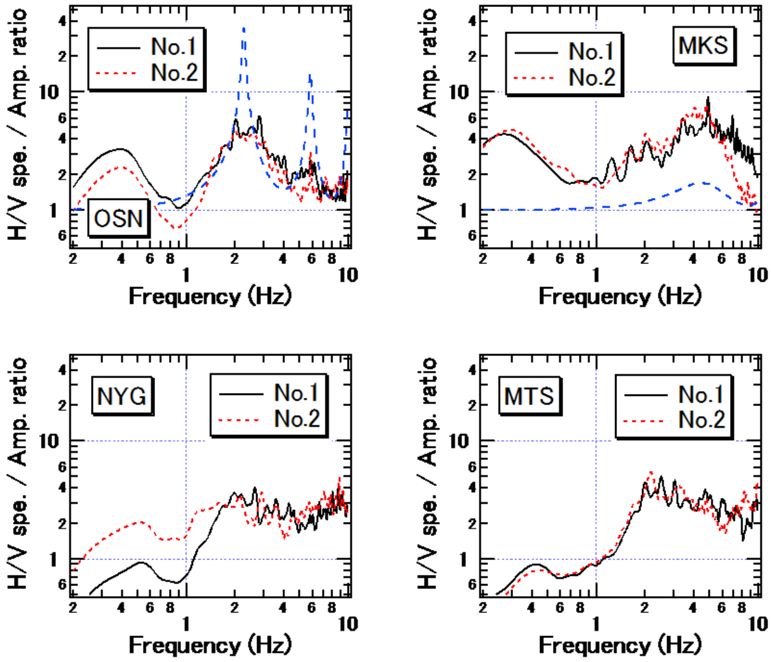

Fig. 6 – H/V spectral ratio with theoretical amplitude ratio (Western area)

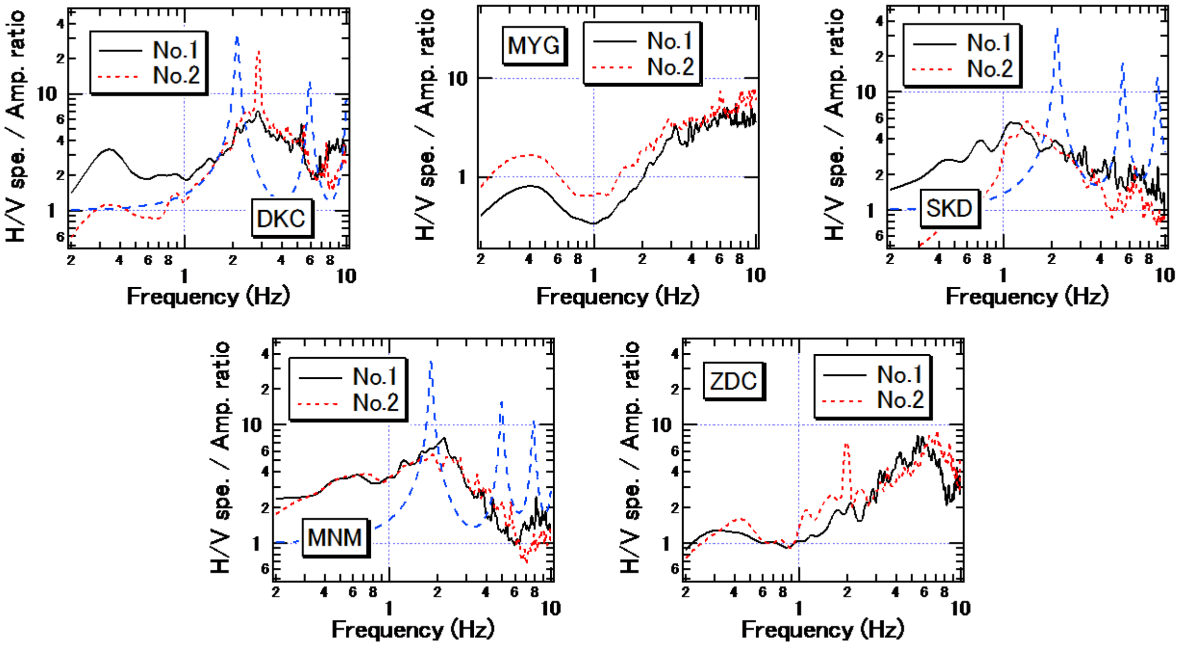

Fig. 7 – H/V spectral ratio with theoretical amplitude ratio (Southern and eastern area)

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5. Dense microtremor measurement

As one of further investigation trials of the vibration characteristics of the basin, dense microtremor measurements are conducted along to the lines crossing in the EW direction of the basin. Measuring lines (orange solid lines) of No.1 to No.5 are shown in the left figure of Fig.8. Red triangles are microtremor measurement points. Red and blue circles are the sites of microtremor measurements described in the previous section. Geomorphic classification distribution [6] of the investigated area is also shown in the right figure of Fig.8. The measuring lines locate so that they cross "Sukawa" river flowing from south to north in the basin and include wide area as much as possible from the natural levee to the back marsh and the alluvial fan.

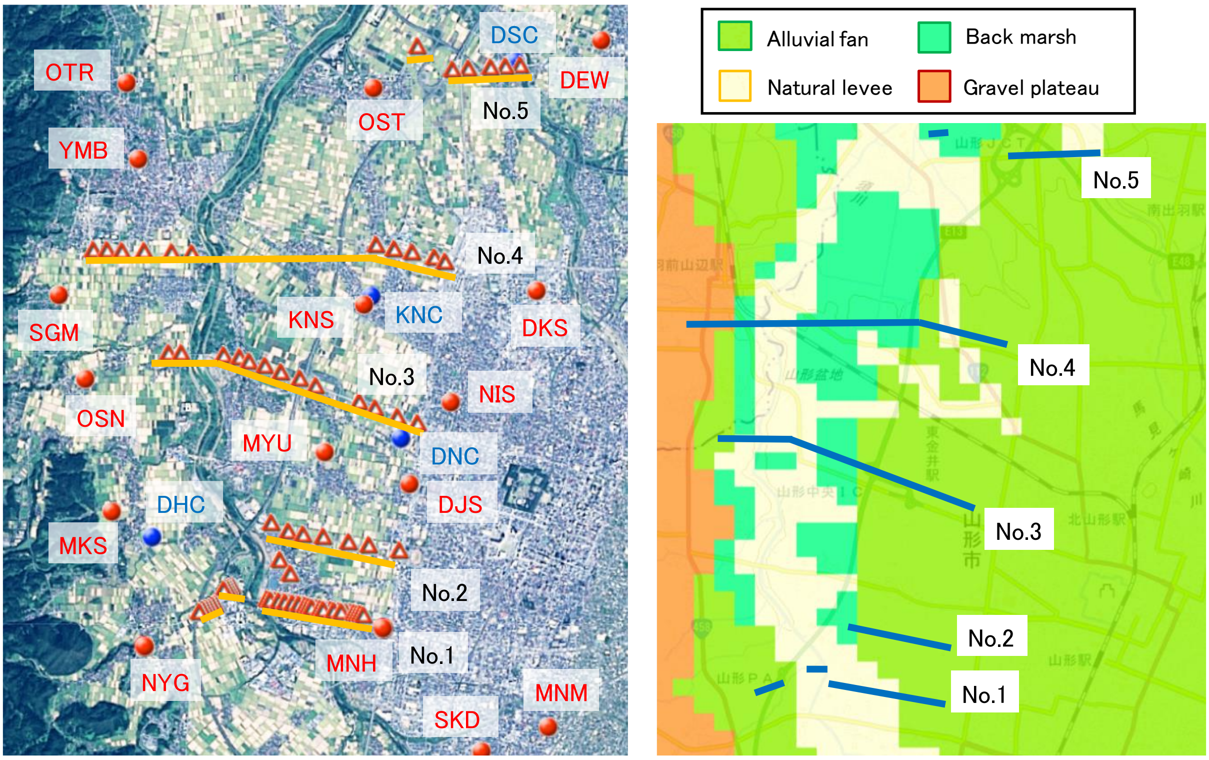

Fig. 8 – Measuring lines of No.1 to No.5 (left) and geomorphic classification (right) [6]

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In the figure, the light yellow color indicates natural levee, the blue-green color indicates back marsh, the green color indicates alluvial fan, and the orange color indicates gravel plateau. *N* values are obtained by standard penetration test (SPT) at most of the microtrmor measurement sites. Shear wave velocity profiles at the microtremor measurment sites are estimated from SPT-*N* values [4].

Fig.9 shows the spatial variation of predominant frequency along to the measuring lines of No.1 to No.5. The azimuth in the figure is east on the right and west on the left. The horizontal axis in the figure indicates the position of the microtremor measurement on the measuring line. Predominant frequency of the ground estimated from the H/V spectral ratio of the microtremor measurement is represented by solid circles and solid lines along to each measuring line. In addition, the results obtained by calculating the predominant frequency of the surface ground from the 1/4 wavelength theory using AVS30 [6] estimated from the geomorphic classification are represented by the red triangle and red solid line.

Regarding the spatial variation of the predominant frequency of the ground, at the area of the east side of "Sukawa" river along to the measuring line No.1, predominant frequency can be found about 2.0 Hz at

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natural levee. Predominant frequency descends to about 1.0 Hz in back marsh as it moves away from the river towards east, but indicates fluctuating around 1.5 Hz as it approaches into the area of alluvial fans. Measuring line No. 2 is placed on the east side of "Sukawa" river. Predominant frequency of the ground is about 1.0 Hz at back marsh, and 1.5 Hz at alluvial fan.

Geomorphic classification along to the measuring line No.3 changes in a complicated manner from the west coast to the east coast of "Sukawa" river. Predominant frequency of the ground is about 2.0 Hz at natural levee of the west of "Sukawa" river. On the east side, the results show that predominant frequency varies between 1.0 and 1.5 Hz from back marsh to alluvial fan. Along to the measuring line No.4, the geomorphic classification on the west side of "Sukawa" river changes from gravel plateau to alluvial fan, back marsh, and natural levee, but variation of predominant frequency of the ground estimated from the microtremor measurement is in the range of 1.5 to 2.0 Hz. On the east side of the measuring line, predominant frequencies are distributed about 1.3-1.5 Hz from the end of back marsh to alluvial fan. Measuring line No. 5 is the northernmost line of the microtremor measurements, and it is the area from the eastern end of Sukawa's back marsh to natural levee of the "Mamigasaki" river flowing in the eastern part of the basin. Predominant frequency about 1.0 Hz in the area of the natural levee on the eastern side is found, but at most of measuring points, predominant frequencies are estimated slightly higher than 1.5 Hz.

When the predominant frequencies of the ground estimated from the H/V spectral ratios of microtremor measurements are compared with the results using AVS30 estimated from the geomorphic classification over all the measuring lines, it can be said that predominant frequencies from the H/V spectral ratios and AVS30 meet good agreement at about 1.0-1.5 Hz at the area of back marsh. On the other hand, at area as natural levee and alluvial fan in the geomorphic classification, the predominant frequencies estimated from the H/V spectral ratios tend to be lower than the results from AVS30. Shear wave velocity profiles estimated by SPT-*N* at the sites near the measuring lines are shown in Fig.10 where AVS30 is drawn for the comparison. The sites of MNH, DHC, DNC belong to alluvial fan, and KNC and OST locate on natural levee. As shown in Fig.10, AVS30 is larger than estimated one from SPT-*N*, and estimated as high as 300m/s or more at the site assumed to be alluvial fan in the geomorphic classification. On the other hand, shear wave velocity profile estimated from SPT-*N* indicates lower as about Vs=100m/s from surface to GL-5m, and Vs=200m/s or larger in deeper than that. Therefore, estimation of shear wave velocity in natural levee and alluvial fan should be more paid attention. As described in this section, microtremor measurement will be one of the most effective technique to enhance the estimation.

6. Conclusions

Results of microtremor measurement conducted at 25 sites in the western part of Yamagata basin are discussed, and predominant frequencies at each site are estimated by H/V spectral ratios. Results are compared to theoretical amplitude ratios calculated by 1D wave propagation theory.

Predominant frequencies of soft ground consisting of back marsh of "Sukawa" river are estimated about 1.0 to 1.6 Hz in northern and central area. At the west edge of the basin, several sites show relatively high predominant frequency over 2.0Hz. In the sites of southern and eastern area of the basin, predominant frequencies from H/V spectral ratios are estimated as high as western area about 2.0Hz or higher like ZDC, except the site of SKD.

In general, distribution of predominant frequency reflects the thickness of soft soil layers of surface ground and the deep ground structure irregularity. Theoretical amplitude ratios derived from 1D wave propagation theory in this study tend to have predominant frequency in lower frequency range than H/V spectral ratios of microtremor measurement. This may be considered because SPT-*N* data profile is not deep enough for theoretical estimation. Soil data collection should be more conducted and soil properties of underlying layers below supporting stratum of the building should be required in detail. In many of the results of H/V spectral ratio, spectral amplitude in low frequency range from 0.3 to 0.4Hz is observed indicating the effect of deep ground structure like engineering bedrock or seismic bedrock.

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Dense microtremor measurements are conducted along to the measuring lines of No.1 to No.5. Results of spatial variation of predominant frequencies are shown along to the sections of the EW direction. Estimated predominant frequencies are also compared to the predominant frequencies estimated by AVS30 obtained from geomorphic classification data. Estimated frequencies meet good agreements in the back marsh area, however, in the area of natural levee and alluvial fan, predominant frequency estimated by microtremor measurement tends to be lower than AVS30. It is because AVS30 is estimated as high as 300m/s in the alluvial fan that is larger than estimated shear wave velocity by SPT-*N* data.

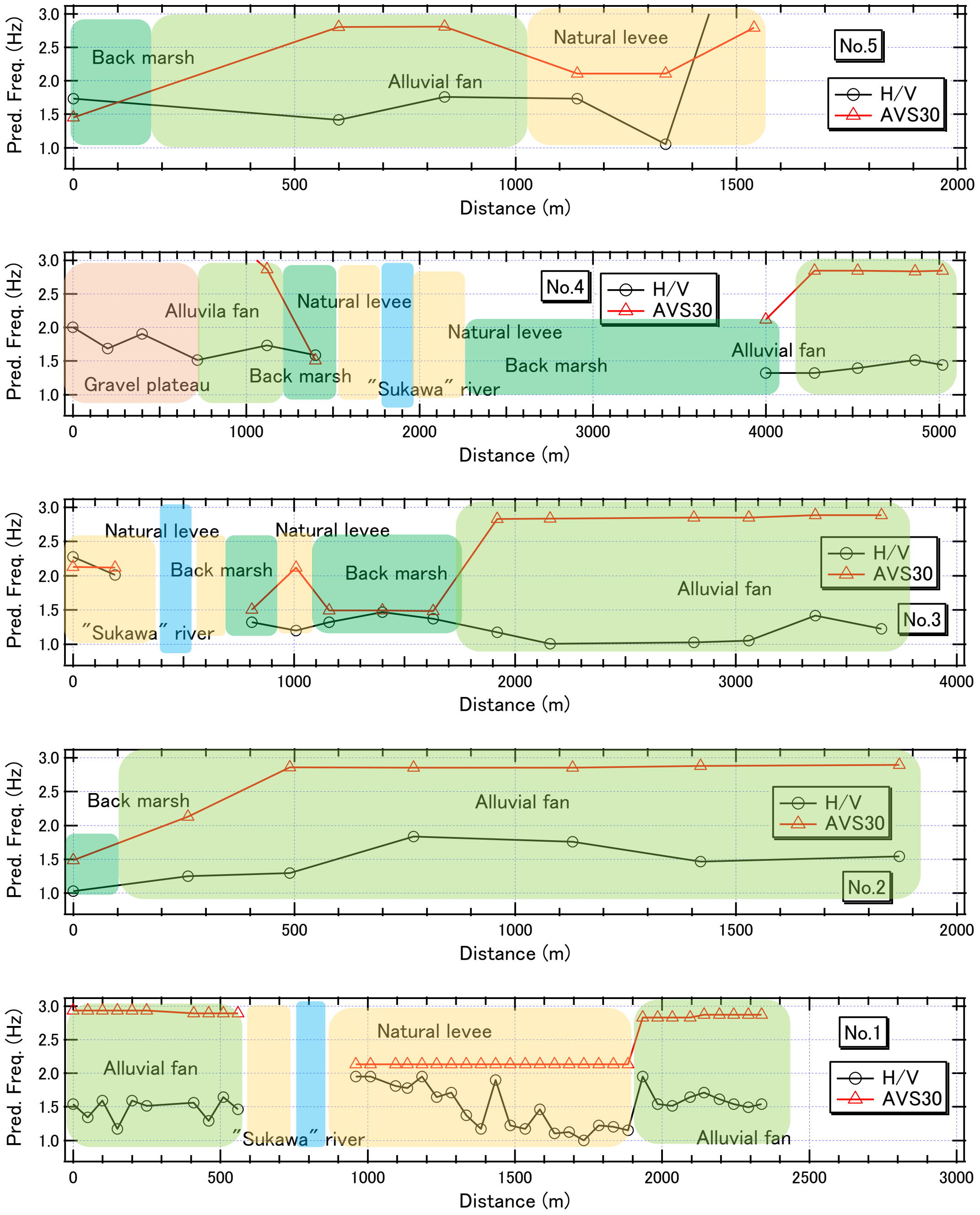

Fig. 9 – Spatial variation of predominant frequency along to the measuring lines of No.1 to No.5

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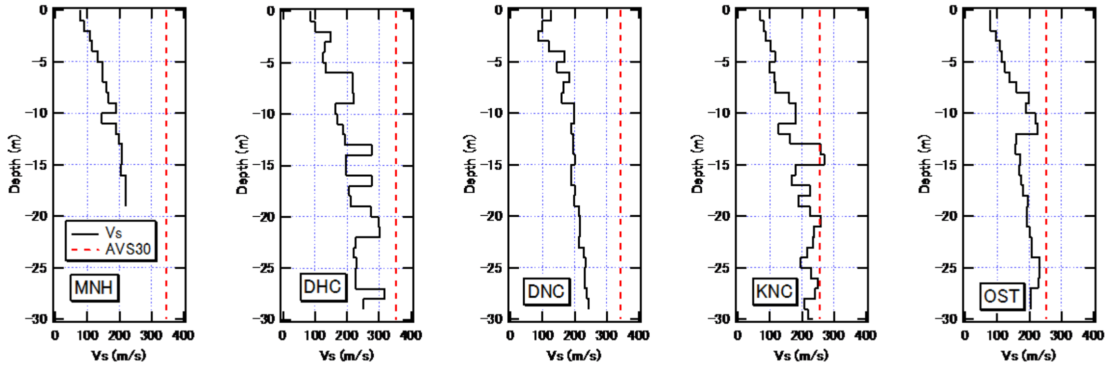

Fig. 10 – Estimated Vs profile and AVS30 at the sites near the measuring lines of No.1 to No.5

7. Acknowledgements

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