The S-wave velocity structure and the phase velocity distribution by the Microtremor array survey

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Abstract

To conduct the geological survey in limited cost and period is one of the critical issues for civil engineering projects. The microtremor array survey(MAS) enables to obtain the S-wave velocity structure and the phase velocity distribution more quickly and economically than any other geophysical exploration method. This study presents some examples to clarify the usefulness and the preciseness of these parameters obtained by MAS. At first we introduce the chain array method as a new technique for geological survey. To our experiences , the phase velocity distribution elaborated by the chain array method is not inferior to the achievements by the other geophysical methods. And the geological layers in the sedimentary basin have its own characteristic S-wave velocity which could identify them respectively. Using this nature, it is possible to assess the geological structure and the engineering properties even to the depth of basement formation with no sufficient existing geological data by the simple microtremor array survey. We would like to discuss these advantages of MAS through some case studies.

Keywords: microtremor array survey, chain array method, SPAC, phase velocity, metropolitan

1. Introduction

Earth surface is vibrating continuously with very slight amplitude anywhere. This vibration comes from human activities such as road traffic or natural phenomenon such as ocean waves, is called the microtremors generically. This microtremors is easy to observe and there is a possibility that the motion is reflecting subsurface geological structure. For this reason, various researches of the motion have already been done since more than 100 years ago mainly in Japan. A number of researches tended to presume the subsurface geological structure from the observation of motion without the controlled seismic source (the man made one such as "vibroseis").

The microtremors array survey , especially SPAC methodology, had been put into practical use in 1980s, the basic practical use method was established in 1990s (for example Okada et al.1990 and Matsuoka et al.,1996), based on a breakthrough theory (Aki,1957) which came out more than 50 years ago. This method can be used mainly for the deep S-wave velocity structure researches in the sedimentary basin targeted the earthquake disaster prevention. Moreover some application cases detected a continuous 2D section directly using the chain array method (Mizuochi et al.,2010, Hayashi et al.,2010, est.).

2.Chain array method

2.1 Basic principle and measurement method

As a new microtremor array survey technique that evolved conventional techniques, the authors have utilized a technique called the chain array survey method that enables to show the apparent phase velocity distribution in two-dimensional section. Those images could help to understand the geological condition of the targeting area. This methodology had been introduced in details by Hayashi et al.(2010). The summary of this methodology is shown as follows.

Surface waves observed by seismometers are analyzed by a function of phase velocity and frequency, which is called the dispersion curve using SPAC or F-K methodology. Using analyzed correlation of the phase velocity and frequency in the dispersion curve, the wave length could be calculated , then apparent distribution of the phase velocity in depth is developed (Fig.1). The conversion rate between the wave length and the depth is usually presumed by the one-dimensional survey result (analyzed S wave velocity structure) conducted simultaneously and those rates are in the range of 1/2 to1/3 on our experiences.

Basically the chain array method uses the measurement technique of SPAC method which methodology has already been established (Okada 2003). Seismometer arrangement of the SPAC in circular arrays is fundamental in principle, and that can be replaced with a semi-circular array (Okada et al. 2003). According to this theory, the chain array survey method uses linear sequence of equilateral triangle arrays to detect the dispersion curves of f the every equilateral triangles. Then the dispersion curves of some continuous points positioned at every half pitch of the triangle side length, which is the intervals of seismometer, are elaborated, and the apparent distribution of the phase velocity could be created by some kriging software , which is deemed to be a reflection of the two-dimensional underground geological structure .

Since this method is characterized to express the unanalyzed original phase velocity data, it is necessary to consider that the phase velocity distribution is apparent. Therefore, the comparison with the S wave structure by the one-dimensional survey results or the existing geological data is important in quantitative interpretation.

2.3 Survey depth and Measurement time

Because of securing the homogeneity of the survey ground and the work efficiency, microtremor array survey become accurate if a small size array could detect deeper survey depth. According to previous studies, the proportion of array size and the survey depth is five times (Miyakoshi et al. 1996) and 10 times (Matsuoka et al. 1996). According to our experience shown in the table 1, more than 13 times in the chain array method, more than 11 times in one-dimensional survey is obtained. The depth in table 1 is the converted depth from the wave length, verified by the usual SPAC survey result and/or existing borehole data.

Matsuoka et al.(1996) studied about the measurement time of SPAC method and showed that the sufficient measurement time is 10 minutes when the array size is 3 to 30m , 20 minutes when the array size is more than 60 m. In our studies of the chain array measurement, the sufficient data had been obtained in about 20 minutes.

As shown in above, the chain array survey method is a technique which has a potential to obtain deeper information more simply than the other geophysical techniques. For example, if you want to survey 100m length and 30m depth, we can measure it in one or two days field work using chain array method. That survey consists of 8 times of the measurement which is composed of 6 triangles connected side-by side in the 12.5m length using 8 seismometer. As one or two measurements per hour can be conducted, 8 times measured needs only 6 to 12 hours, we can measure about 100m length (Δ 5x2.5x8 = 100m) . For the detectable depth of 3m array size measurement is 30m or more, it shows that chain array method is a very efficient and economical method.

2.3 Case studies of chain array survey

The samples of the phase velocity distribution by the chain array survey method are shown in Fig. 2.

- Urban area case

This case was carried out with the 3m side length on the sidewalk of the national highway in urban areas (Hayashi et al.2010). The difference of soil structure was observed in the center part approximately by the phase velocity that shown in white line. This result had been confirmed by S wave velocity structure analyzed by SPAC method.

- Mountain region case

This case was carried out at the canyon plane in mountain region with the array size of 30m side length (Harayama et al. 2012). It was confirmed that the river deposit thickness was supposed to be more than 200m and a fault of which vertical displacement was about 50m (shown in white line). This result had also been confirmed by SPAC method and the layers of green and blue color were Holocene sediment which had been correlated with borehole core dating data.

3- Geological structure analysis using the S-wave velocity structure

3.1 Methodology

Generally geophysical techniques is used as a method to complement the drilling data. On the other hand, the accumulation of physical quantitative data of geological formations by geophysical survey could be considerably sufficient to determine the geological structure without the drilling. Table 2 shows the S wave velocity of sedimentary layers detected by bore hole loggings implemented in the major sedimentary basin of Japan. The sedimentary rocks younger than the Neogene system have the S-wave velocity shown as follows.

Holocene: 0.1-0.4 km/s, Pleistocene: 0.4-0.9 km/s
Pliocene: 0.5-0.9 km/s, Miocene: 1.1-1.6 km/s
Basement: (1.9) 2.4-3.5 km /s

The options for the geological survey method coming up to more than several hundred meters of depth in the dense urbanized area are limited. Micretoremor array survey could be the one of those specific method. This had been demonstrated by several studies such as Matsuoka et al.(2002) and Minami et al.(2011) and a case study shown as follows. Those studies indicate a advantage of SPAC method in the metropolitan areas .

3.2 Case study in Jakarta, Indonesia

This case had been implemented in Jakarta Indonesia, was targeted to clarify the geological structure necessary for settlement of the land subsidence issues. The microtremor array survey using SPAC method had been conducted within 10 days of fieldwork in highly urbanized area, which

Table 1 Array size and survey depth of microtremor array survey method, *analyzed depth is converted from frequency of dispersion curve (see.Fig.1).

R : Maximum Triangle radius (m)	D : Analyzed depth (m)*	D / R	Target / Method
1.7	25	14.7	Glacial terrain / Chain Array
1.7	30	17.6	River dyke / Chain Array
1.7	35	20.6	Beach sediment / Chain Array
11.5	150	13.0	River sediment / Chain Array
17.3	250	14.5	Mountain canyon sediment / Chain Array
34.6	1,600	46.2	Sedimentary basin / Chain Array
30	350	11.7	Sedimentary basin / SPAC survey
90	2,200	24.4	Sedimentary basin / SPAC survey

Table 2 S-wave velocity by borehole logging in Japan (assembled from Osaka Jiban (1982) and other data)

Geological Series		Kanto			Sanin	Chugoku	Shikoku	Kinki	
		Fuchu	Iwatsuki	Shimoosa				Osaka	Kyoto
Holocene									
Pleistocene	Late	0.5–0.7	0.4	0.4		0.55	0.55	0.4–0.9	
	Middle		0.7	0.7					0.6–0.9
	Early				0.88				
Pliocene	Late					0.88	0.88		
	Early								
Miocene	Late	1.2		1.1	1.3–1.6				
	Middle		1.2						
	Early		1.5						km/s
Paleogene						1.3			
Basement		2.4	2.5	2.5	3.5	3.5	3.5	2.5–3.0	1.9–2.5

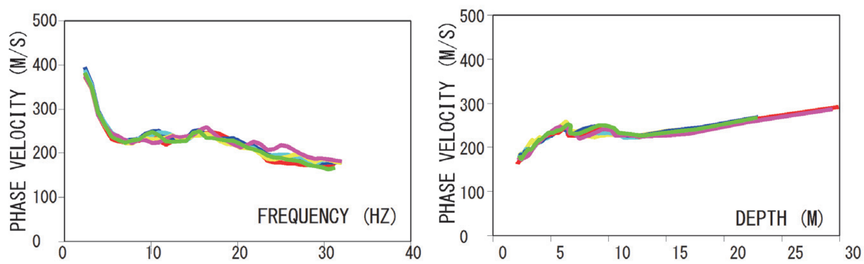

Fig. 1 Dispersion curves, frequency(left) converted to depth(right) by conversion calculation

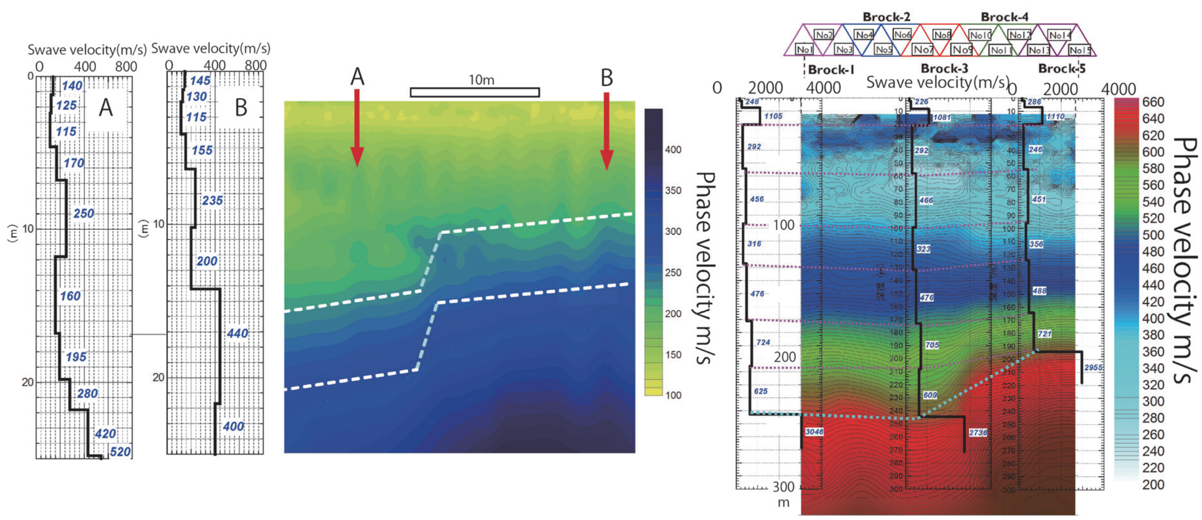

Fig. 2 Case studies of Chain array survey,
Urban area : left (Hayashi et al.2010) and Mountain region : right (Harayama et al. 2012)

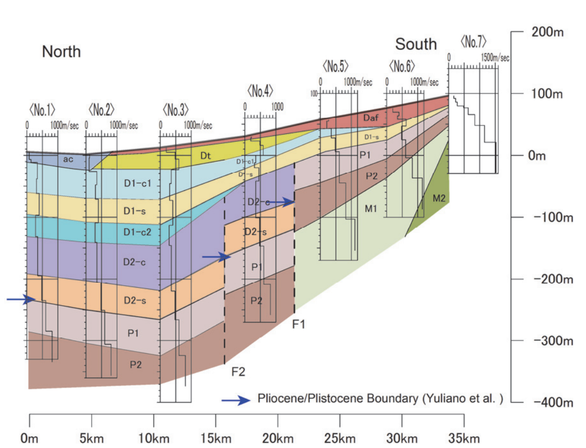

Fig. 3 Geological section analyzed by S-wave velocity distribution, SPAC method, multiple array size 1m-3m-10m-30m (Sasaki et al. 2014)

ranges 30 km by east and west and north and south. The S wave velocity structure of every survey points ware correlated with the formations of geological maps elaborated by the prior geological studiesconsidering the relationship between S wave velocity and geological age shown as Table 2. The distribution of those formations is shown in Fig. 3. This result had been correlated with the existing geological dating data (Yulianto et al.), the boundary of Pliocene and Pleistocene by the microfossil dating was coincided with our result (shown as the Blue arrow in Fig.3)

4.Conclusion

- Chain array method has been developed in practical use for several areas and purposes.
- Chain array survey can provide the image of the subsurface geological condition in several depth even with the simpler procedure than the other geological survey method.
- The preciseness of that image by chain array method were evaluated by several case studies.
- S-wave velocity structure analysis for the geological structure survey using the SPAC method had been conducted and this was found to be the one of the useful and economical method especially in the metropolitan area.

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