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ESTIMATION OF A DEEP SHEAR WAVE VELOCITY STRUCTURE OF CHIBA CITY BASED ON ARRAYS OF ACCELEROMETERS

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ABSTRACT: During the 2011 Tohoku earthquake, strong ground motions have been recorded at a number of stations in Chiba City that were installed by the authors and other institutions. From the viepoint of its magnitude and the epicentral distance, it is possible to make an assumption that the surface wave is dominant in the record. In this study, seismic records have been analyzed to obtain a phase velocity dispersion curve based on the high resolution F-k analysis and the CCA analysis. The results match well with the existing results found in a literature.

Key Words: 2011 Tohoku earthquake, array of accelerometers, deep soil profile, phase velocity dispersion curve, F-k analysis, CCA analysis

INTRODUCTION

A long period ground motion during an earthquake sometimes has a serious impact on large structures such as bridges, high-rise buildings and oil storage tanks. During the 2011 Tohoku earthquake (Great East Japan earthquake), Chiba City, which is located east of Tokyo, has been hit by a fairly strong ground motion with a very long duration time and has suffered from serious damage. An explosion in flames of a liquefied petroleum gas tank is one of the most hazardous incidents that occurred during the event, as shown in Photo 1.

It is well known that the evaluation of ground motion is critical when estimating damages due to earthquakes. Since the ground motion during an earthquake is largely affected by the so-called site effect which is determined by the soil structure, it is important to obtain its profile, especially the shear wave velocity profile. There are a number of methods available that are used for this purpose. Among others, microtremor array measurement is one of the most popular ways and has been conducted extensively. This measurement gives phase velocity dispersion curves from which it is possible to estimate the soil profile through an inversion process. This process, however, is very sensitive to changes in dispersion curves (Kurose and Yamanaka 2006). In addition, it is believed that the power of microtremors in the longer period range is in a low level compared to shorter period ranges. To overcome this limitation, the joint inversion of more than one function has been pursued by a number of researchers (e.g., Arai and Tokimatsu 2005, Kurose and Yamanaka 2006).

Photo 1 An explosion in flames of a liquefied petroleum gas tank (Asahi.com 2011)

In this study, an attempt has been made to estimate an shear wave velocity profile by seismometer array measurements (Tomishima et al. 2010) during the 2011 Tohoku earthquake and its after shocks in addition to the earthquakes prior to it, in which Chiba area was chosen as a target area. The result was compared with that of microtremor measurement and the existing profile for deep soils.

OBSERVATIONS

Target area

The area of study is Chiba City, which is located about 50 kilometers east of Tokyo, Japan, as shown in Fig. 1. Fig. 2 shows a map of landform classification in this area, in which the location of the censors used in this study is also plotted. As can be seen in Fig. 2, the landform of this area consists of three categories: terrace, river valley and reclaimed ground.

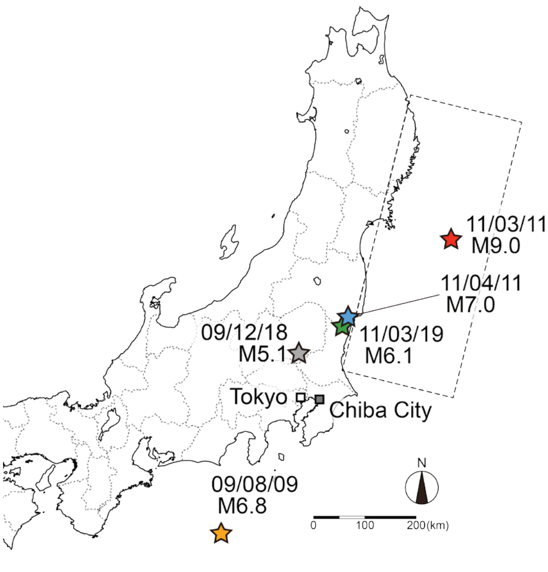


Fig. 1 Locations of Chiba City and epicenter of the earthquakes considered in the study

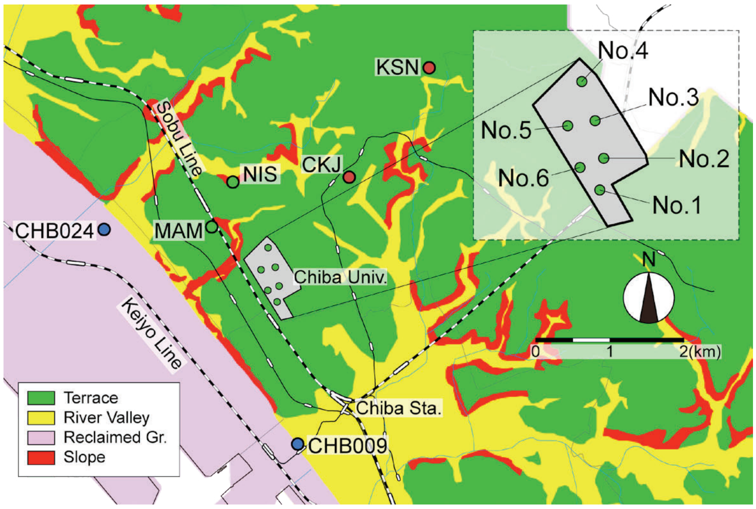


Fig. 2 Map of landform classification and sensor location

Earthquake observations

A total of 12 sensors (accelerometers) are deployed in this area, their locations are shown in Fig. 2. Of these, two sensors marked as CHB009 and CHB024 are installed by the National Research Institute for Earth Science and Disaster Prevention, or NIED, and are called K-NET sensors, while other two of them denoted by CKJ and KSN are installed by Japan Meteorological Agency, or JMA, and are called seismic intensity meters. The rest of the sensors have been installed by the authors. As can be seen from the figure, these sensors are deployed in such a way that the distances between the sensors vary from 0.2 to 2 kilometers, which makes it possible to form a different size of array of sensors that can cope with the measurement of phase velocities of the wave in the period range of 1 to 5 seconds. Recording time of our sensors is set to 300 seconds so that the coda part of the ground motion can be recorded.

Microtremor measurements

Although we are interested in a deep soil profile, it is believed that the shallow soil profile at the site plays an important role when looking at the dynamic characteristics of the ground such as the phase velocity dispersion curve. In addition, it is worthy of consideration to compare the earthquake observation-based results with those from microtremors. From this point of view, a series of microtremor array measurements were also conducted in the Nishi-Chiba campus of Chiba University (Tomishima et al. 2010). The array consists of five sensors on the circumference of a circle and one at its center with the radius ranging from 22 to 222 meters.

Sensors we have used to measure microtremors are velocimeters.

ANALYSIS AND DISCUSSIONS

Theoretical dispersion curves

Fig. 3(a) shows the shear wave velocity profile of deep soils at Nishi-Chiba campus of Chiba University found in literatures (J-SHIS 2010, Sato et al. 1999), while Fig. 3(b) shows that of shallow soils constructed from a PS-logging carried out in the campus. Fig. 4 compares the two of the dispersion curves based on the theory of surface wave propagation in an elastic medium (Tokimatsu et al. 1992), in which each soil profile consists of the shallow part, i.e. Fig. 3(b), and the deep part, i.e. one of the two plots in Fig. 3(a). Fig. 5 shows the phase velocity and the medium response

(Harkrider 1964, Saito et al. 1993) of each mode of Rayleigh wave for the soil model with deep soils from J-SHIS.

From Fig. 4, it is found that the two dispersion curves are slightly different depending on the difference between the corresponding deep soil profiles. It is also worthy of note that the first higher mode of Rayleigh wave dominates over its fundamental mode in some of the period ranges such as near 0.1 seconds, 2 to 4 seconds and 6 seconds or longer, in which the synthesized dispersion curve in Fig. 4 shows fluctuation.

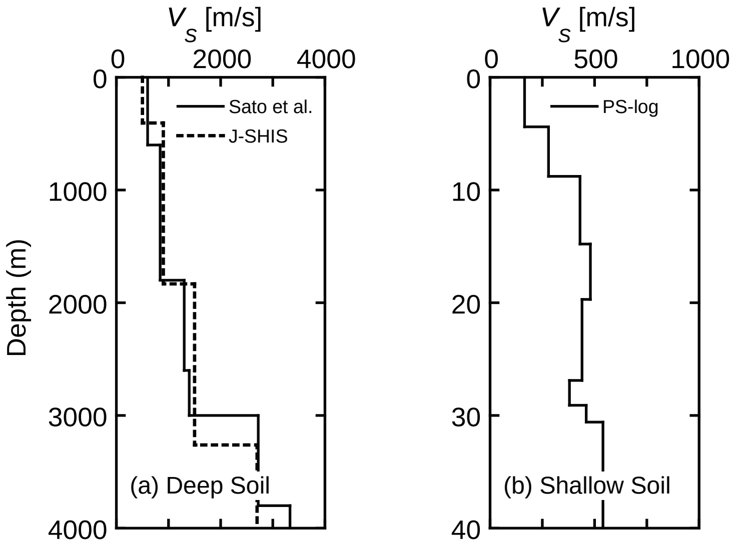


Fig. 3 Shear wave velocity profile of the target site (Nishi-Chiba campus of Chiba University)

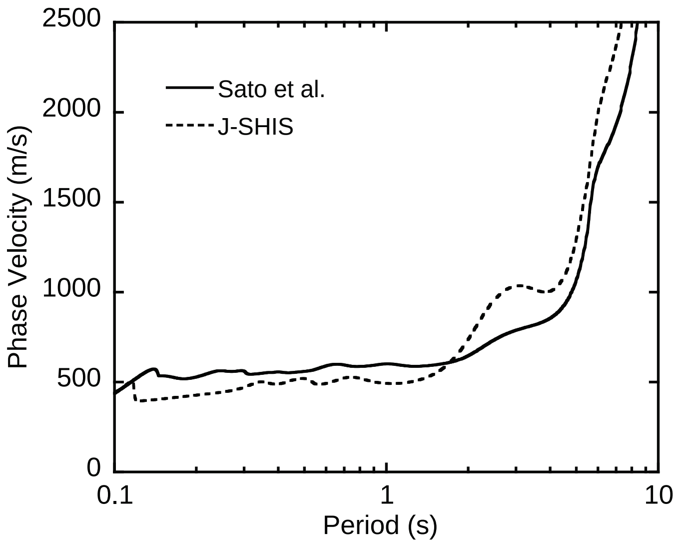


Fig. 4 Theoretical dispersion curves

Recorded ground motions

From the last two and a half year of observation, we have recorded a number of seismic activities including the 2011 Tohoku earthquake and its after shocks in addition to the earthquakes prior to the main shock. The locations of the epicenter of the earthquakes along with their magnitudes (M_j) are also indicated in Fig. 1. It is seen that most of the earthquakes occurred in the region north to northeast of the target area except the one which occurred in the region southwest of the target area.

Table 1 summarizes the maximum accelerations and velocities (PGA and PGV) of the ground motions recorded within this time period. If you take a closer look at the peak values of the 2011 Tohoku earthquake and then compare them with landform classification of the sensor locations shown in Fig. 2, it is understood that PGA's observed on terrace and in lowland are of the same order, but that PGV's at lowland are larger than those at terrace. This implies that soil nonlinearity occurred in the soft soil found in lowland.

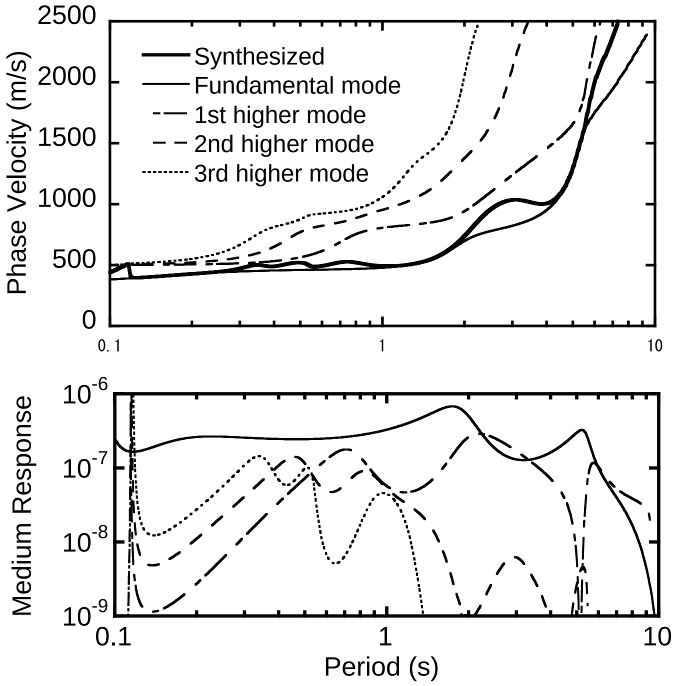


Fig. 5 Phase velocity and medium response for each mode

Method of analysis for estimating phase velocities

There are a number of methods for estimating phase velocity of the soil. In this study, two methods were used: high resolution F-k and CCA methods. The high resolution F-k spectrum analysis (Capon 1969) together with the SPAC analysis (Aki 1957) is one of the most popular methods to calculate the dispersion curve of Raleigh waves. There is another method called the centerless circular array analysis, or CCA, that is an extension to the SPAC analysis and is proved to be robust in the computation of this curve (Cho et al. 2006).

These analyses have their base on the correlation between the vertical recordings of the sensors that constitute an array. The vertical recordings are used since they contain Rayleigh waves. This notion is widely accepted in the case of microtremor. Seismic ground motion, however, contains not only surface waves but also body waves. Thus, in order to apply these methods, a portion of data has to be extracted from seismic recordings so that it contains surface waves.

We have looked at non-stationary spectra of the vertical component of the seismic record for this purpose. A portion of the recorded accelerogram has been extracted where the spectrum shows a dispersive nature which the surface wave is characterized by. Some of the example time histories and their corresponding non-stationary spectra are shown in Fig. 6. Fig. 6(a) shows the ground motion recorded at CHB024 and Fig. 6(b) shows the recordings at MAM, both during the main shock. From the viewpoint of landform, CHB024 is located in the reclaimed ground and MAM is located on the terrace as shown in Fig. 2.

Array configuration

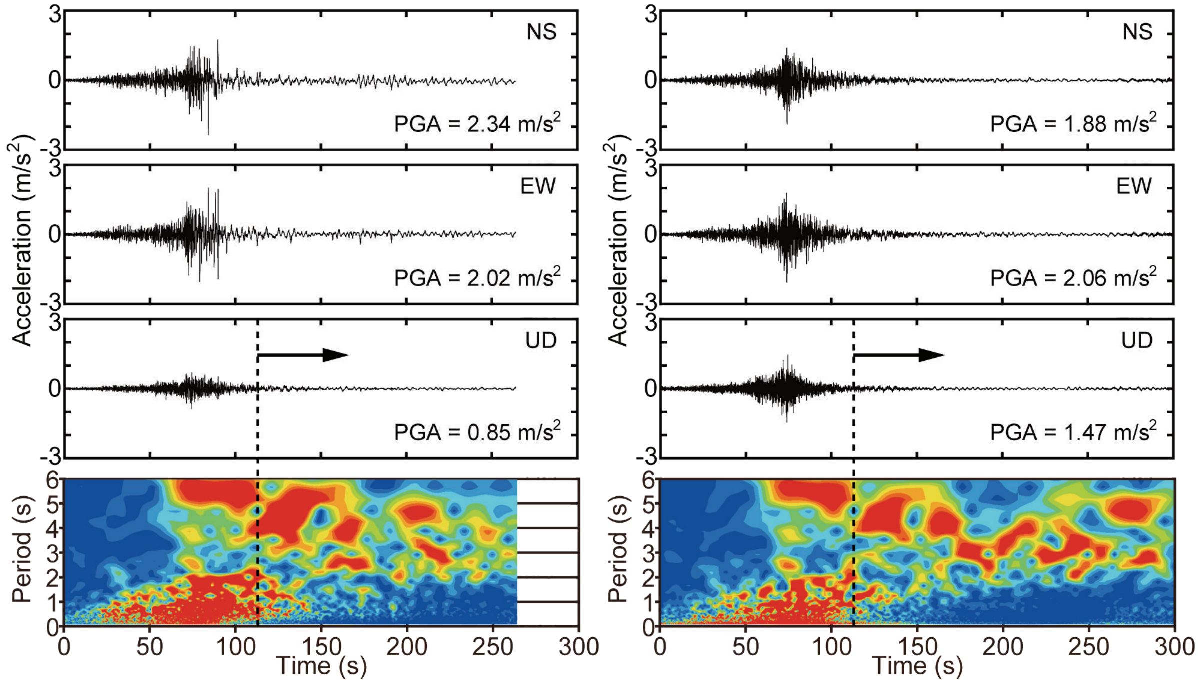
Both F-k and CCA methods require an array of sensors to be configured. As mentioned earlier, there are a total of 12 sensors deployed in the target area. Unfortunately, however, not all the sensors have been functioning properly during the events. Fig. 7 shows the array configuration during the event of the 2011 Tohoku earthquake. As illustrated in the figure, a total of four sensor arrays were configured, each of which is composed of four sensors with different sensor distances ranging from 1,500 to 4,500 meters. As for other events, one to four arrays were configured in each event.

Table 1 PGA and PGV of recorded ground motions

EQ	Censor	PGA (cm/s^2)			PGV (cm/s)		
		EW	NS	UD	EW	NS	UD
090809	No.2	-	-	25.1	-	-	0.5
	No.3	44.7	37.8	12.0	1.4	1.3	0.5
	No.4	25.1	31.4	13.4	1.2	1.2	0.5
	No.6	42.8	34.2	16.7	1.5	1.2	0.5
091218	MAM	10.1	8.4	6.0	0.3	0.3	0.2
	NIS	14.6	22.0	12.6	0.4	0.9	0.2
	No.1	9.7	9.9	5.6	0.3	0.3	0.1
	No.2	11.9	14.4	7.4	0.3	0.4	0.2
	No.3	14.2	12.0	4.7	0.3	0.4	0.1
	No.4	8.3	8.4	6.8	0.3	0.3	0.1
	No.6	12.0	12.6	5.7	0.4	0.4	0.1
110311	CHB009	139.7	178.7	77.1	22.1	35.0	10.7
	CHB024	202.5	234.4	85.6	31.5	30.7	14.0
	MAM	206.4	188.2	147.0	21.5	24.3	12.6
	NIS	343.6	480.5	203.3	23.5	29.8	14.6
	No.3	172.1	157.6	90.7	22.6	22.8	11.1
	KSN	282.3	177.4	119.8	21.7	15.4	10.3
	CKJ	163.8	306.0	126.5	22.8	20.1	12.1
110319	MAM	24.7	35.7	16.4	1.2	1.2	0.5
	NIS	63.2	71.0	27.4	2.4	2.9	0.7
	No.3	30.2	22.0	9.2	1.1	1.0	0.5
	No.4	26.4	23.7	10.5	1.0	1.1	0.5
	No.5	27.5	-	10.9	1.2	-	0.5
	No.6	39.1	29.0	11.8	1.5	1.4	0.5
110411	CHB009	26.4	32.0	14.4	3.5	3.4	1.2
	CHB024	43.1	34.9	16.2	3.4	2.8	1.5
	NIS	79.1	90.4	44.8	3.7	4.7	1.4
	No.3	39.6	34.4	15.6	3.0	2.9	1.1
	No.4	33.7	34.3	25.8	2.5	3.1	1.2
	No.6	54.3	39.5	24.8	3.4	2.6	1.1

F-k spectra

The extracted portion of an accelerogram has been further divided into a number of data segments, each of which consists of 8,192 data points. These data segments are averaged so as to compute F-k spectra by following the high-resolution F-k analysis procedure. Fig. 8 shows some of the F-k spectra for several frequencies in the case of the Tohoku event. According to the figure, it is seen that clear peaks are found in most frequencies within the scope of frequency intervals corresponding to the size of an array. In some cases, however, the shape of a spectral peak contour is an ellipse rather than a circle due probably to an irregular or flat shape of the sensor array. It is also noted that the arrival direction of each F-k spectrum roughly coincides with the direction toward the epicenter of the main shock.



(a) CHB024 (b) MAM

Fig. 6 Accelerograms and non-stationary spectra of the ground motion during the main shock

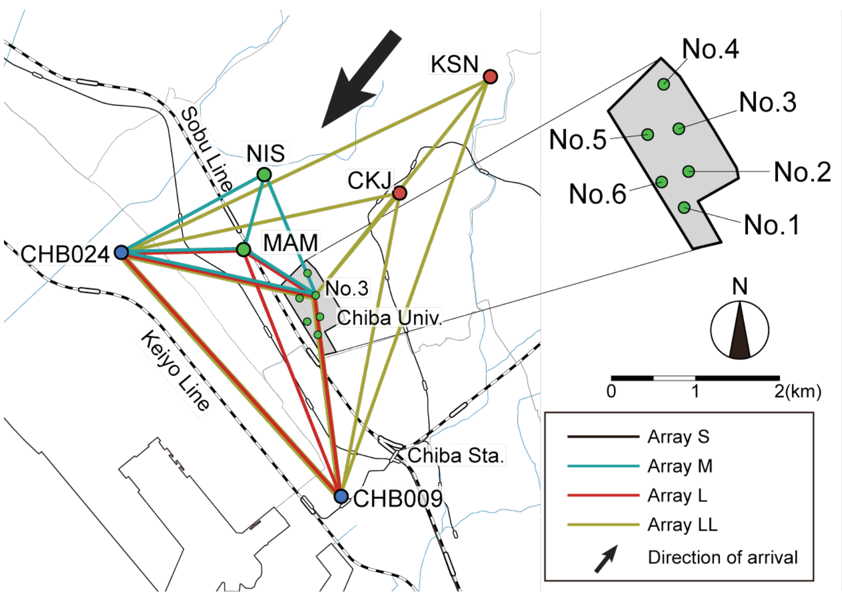
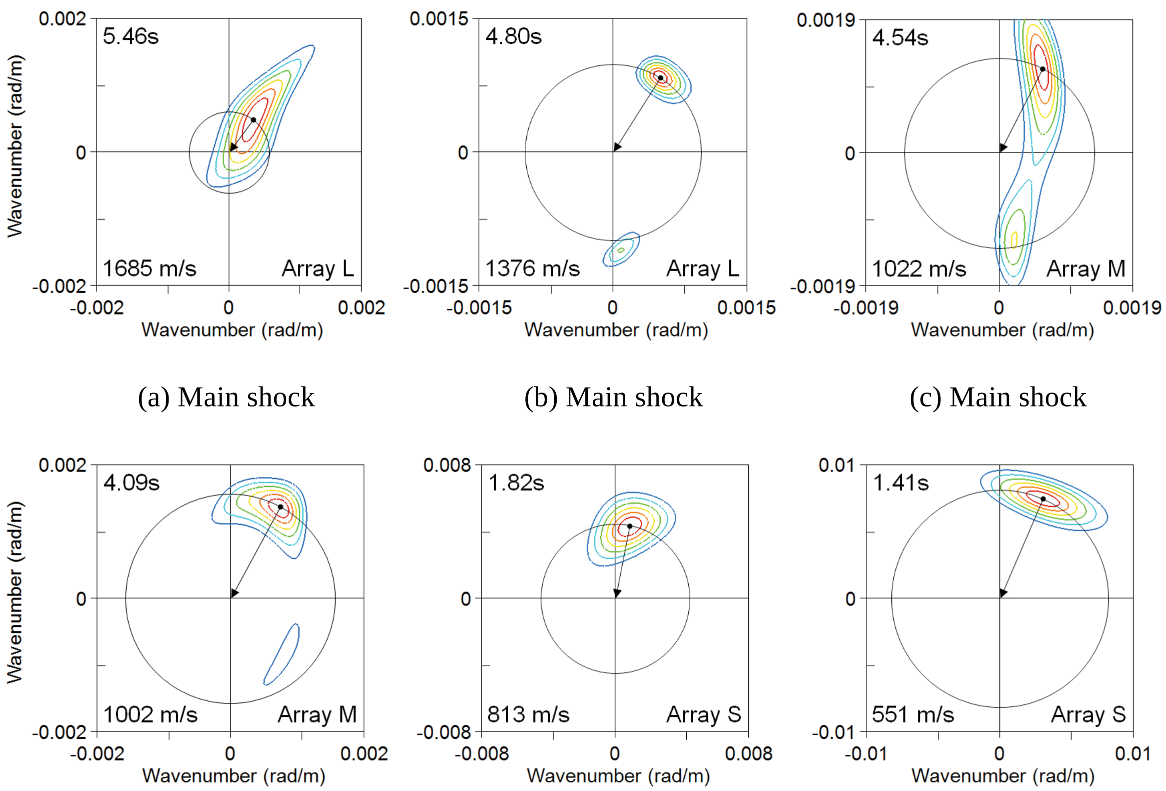


Fig. 7 Configuration of array of sensors for the main shock



(a) Main shock (b) Main shock (c) Main shock

(d) Main shock (e) After shock / 110319 (f) After shock / 110319

Fig. 8 F-k spectra

Phase velocity dispersion curve

Fig. 9 shows the phase velocity dispersion relationship obtained from both microtremor measurement and earthquake observation results. Theoretical dispersion curves are also plotted in the figure. Of the two theoretical plots, the one denoted as J-SHIS is computed based on the deep soil model which was taken from the J-SHIS web site (J-SHIS 2010) and the shallow soil model given by a PS-logging. The other one marked as Sato et al. is computed based on the deep soil model found in a literature (Sato et al. 1999) along with the PS-logging shallow soil model. In both cases, the dispersion curve was computed by considering higher modes of Rayleigh wave in addition to its fundamental mode.

It can be pointed out from the figure that:

- In the period rage from 2 seconds to 4 seconds, the plot shows some variations, which may be explained by the influence of the higher modes of Rayleigh wave.
- The phase velocity relationship based on microtremor measurements and earthquake observations agrees very well with the theoretical dispersion curves.
- The observation-based result better matches with the theoretical one with the deep soil model taken from J-SHIS when compared with the one with the Sato et al. model.
- The relationship obtained from microtremor measurements and that from earthquake observations overlap for a period range between 1.5 seconds and 3 seconds and are found to be continuous.

From this result, it is possible to say that an array of seismometers can effectively be used to estimate the deep soil structure.

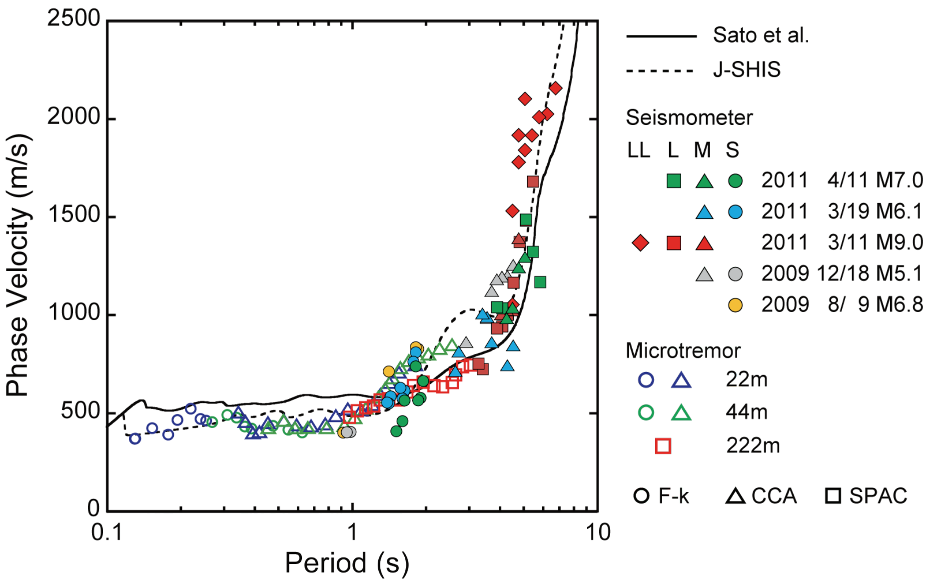


Fig. 9 Phase velocity dispersion curves for the target area

CONCLUSIONS

In this study, an attempt has been made to estimate a shear wave velocity profile by seismometer array measurements during the 2011 Tohoku earthquake and its after shocks in addition to the earthquakes prior to the main shock. The result was compared with that of microtremor measurement and the existing soil profile. It was found from the study that:

- The phase velocity dispersion curve obtained from earthquake observations overlaps smoothly with that from microtremor measurements.
- The observation-based phase velocity agrees fairly well with the theoretical one computed based on the previously reported soil profile.
- An array of seismometers can effectively be used to estimate the deep soil structure.

ACKNOWLEDGMENTS

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