MICROTREMOR SURVEYS IN LARGE SEDIMENTARY BASINS ON THE COAST OF THE SEA OF JAPAN

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Abstract

Many sedimentary basins or plains were formed during the Tertiary and Quaternary periods on the coast of the Sea of Japan. These sedimentary basins would be struck by large earthquakes occurring at nearby active fault systems. Because reliable S-wave velocity structure model is required for quantitatively evaluating seismic hazard, available information on the S-wave velocity structure model needs to be enriched in such sedimentary basins. As a part of Integrated Research Project on Seismic and Tsunami Hazards around the Sea of Japan (2013-2020), we have conducted large-scale microtremor array surveys in sedimentary basins on the coast of the Sea of Japan. The surveyed sites include two sites in the Kaga Plain, two sites in the Ochigata Plain, fifteen sites in the Toyama Plain (including the Niikawa, Tonami, and Imizu Plains), four sites in the western part of the San'in region (Masuda, Hagi, and Nagato cities), five sites in the Hakodate Plain, and seven sites in the Tsugaru Plain. Each array consists of several circular arrays of different radii ranging from ten meters to about one thousand meters in order to obtain phase velocities representing velocity structure from the near-surface sediment layers to the seismic bedrock. The vertical component of microtremor was analyzed by the spatial auto-correlation method (SPAC) to obtain the phase velocity dispersion curve. Then, the S-wave velocity structure was modeled by inverting the obtained phase velocity data. We also additionally measured H/V spectra by single-station microtremor observations at many sites in the Kaga, Ochigata, Masuda, Hagi, Senzaki (Nagato), and Tsugaru Plains to investigate the spatial variation in the bedrock depth. The depth of the seismic bedrock is approximately 5–6 km in the Toyama and Tonami plains, which is consistent with existing reflection and refraction survey results. The Tsugaru Plain also has relatively thick sediments, and those thicknesses are about 3 km in the central part of the plain. This paper summarizes the results of our microtremor surveys conducted in the last seven years (2013-2019).

Keywords: microtremor array, SPAC method, H/V spectral ratio, S-wave velocity structure model, sedimentary basin

1. Introduction

Many sedimentary basins were formed during the Neogene and Quaternary periods on the coast of the Sea of Japan. These sedimentary basins would be struck by large earthquakes occurring at nearby active fault systems. A reliable S-wave velocity structure model is required for quantitatively predicting strong ground motions from such earthquakes. For that purpose, nation-wide three-dimensional velocity structure models for ground motion simulations such as J-SHIS [1, 2] and JIVSM [3] have been developed in Japan by compiling available geophysical and geological information. Thus, available information needs to be enriched to validate and improve the models. However, S-wave velocity structure is not investigated well for sedimentary basins on the coast of the Sea of Japan except some well-studied areas such as Niigata [4, 5], Fukui [6], Tottori [7], and Fukuoka [8] basins. As a part of Integrated Research Project on Seismic and Tsunami Hazards around the Sea of Japan (2013–2020), we have conducted large-scale microtremor array surveys to obtain information on the S-wave velocity structure down to the seismic bedrock in those unexplored sedimentary basins.

2. Microtremor Array Observation

Microtremor array observation has been conducted at 35 sites in sedimentary basins on the coast of the Sea of Japan (Fig.1). Most of those sites were selected referring to the locations of permanent strong motion stations. The surveyed array sites are composed of two sites in the Kaga Plain, two sites in the Ochigata Plain, fifteen sites in the Toyama Plain, which includes the Niikawa, Tonami, and Imizu Plains, four sites in the western part of the San'in region (Masuda, Hagi, and Nagato cities), five sites in the Hakodate Plain, and seven sites in the Tsugaru Plain. Each array observation consisted of several equilateral triangle arrays of different radii ranging from ten meters to about one thousand meters in order to obtain phase velocities representing velocity structure from the near-surface sediment layers to the seismic bedrock (Table 1). One small array observation (r = 10 m) was additionally carried out at MCH (Masuda city hall) because MSD is apart from a strong motion station located at Masuda city hall. We also measured H/V spectra by single-station microtremor observations at many sites in the Kaga, Ochigata, Masuda, Hagi, Senzaki (Nagato), and Tsugaru Plains to investigate the spatial variation in the bedrock depth.

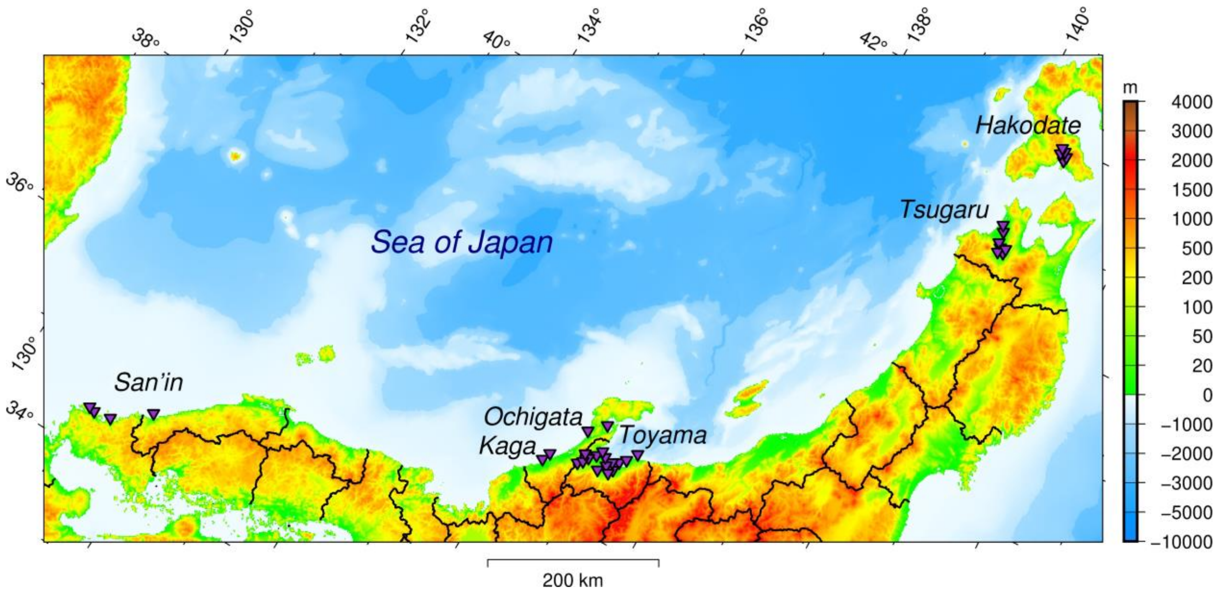

Fig. 1 – Map of microtremor array observation sites

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The observation system consisted of a three-component velocity sensor Lennartz LE-3D/5s having a natural period of 5 s and a data logger Hakusan LS-8800 with 24 bits A/D converter. All recorders in an array were synchronized by the clock of Global Positioning System. The field works were carried out from December 2013 to November 2019. The recording duration depends on the size of an array and traffic noise in the surrounding area.

Table 1 – List of microtremor array observation

Region	Site	Latitude (°N)	Longitude (°E)	Array radii (m)	Year
Kaga	KMT	36.39902	136.44376	200, 400, 800, 1600	2013
	MKH	36.49061	136.49177	200, 400, 800, 1600	2013
Ochigata	HKI	36.89380	136.77949	200, 400, 800, 1600	2013
	NNO	37.04567	136.96867	37, 110, 200, 400	2014
Toyama	NYZ	36.93481	137.50228	130, 350, 770, 1540	2014
	UOZ	36.82314	137.41153	81, 243, 500, 1000	2015
	NMK	36.76432	137.34198	17, 51, 180, 360, 705, 1410	2014/2015
	TTY	36.66225	137.31854	30, 137, 300, 710, 1450	2014
	TYB	36.72944	137.26300	120, 285, 750, 1500	2014
	TYF	36.66900	137.21208	95, 315, 750, 1500	2014
	OYM	36.60897	137.28242	35, 105, 300, 600	2014
	YTO	36.58531	137.13992	140, 300, 666, 1370	2014
	SIM	36.74025	137.14874	30, 143, 300, 675, 1540	2014
	DIM	36.71374	137.03644	20, 60, 235, 470, 750, 1500	2014
	SNM	36.78046	137.08285	78, 234, 500, 1000	2015
	TNM	36.64767	136.96264	125, 280, 676, 1260	2014
	OYB	36.67167	136.89547	26.7, 80, 240, 500, 1000	2015
	NNT	36.58838	136.91946	75, 225, 510, 1020	2015
	FKM	36.54680	136.86649	75, 225, 500, 1000	2015
San'in	MSD	34.69414	131.83235	10, 30, 110, 220	2016
	MCH	34.67466	131.84351	10	2016
	HAG	34.40722	131.39887	10, 30, 116, 232	2016
	NGT	34.37418	131.18038	10, 30, 100, 200	2016
	HEK	34.39028	131.10141	10, 30, 140, 280	2016
Hakodate	HAK	41.77032	140.73830	10, 40, 120, 380, 760	2017
	MHR	41.81762	140.75182	10, 28, 92, 310, 620	2017
	NNE	41.86187	140.70154	10, 58, 174, 444, 888	2017
	KMI	41.82532	140.65311	12, 29, 83, 249, 690, 1380	2017
	OON	41.88390	140.64473	10, 30, 90, 180, 490, 980	2017
Tsugaru	HRK	40.61458	140.57196	15, 45, 75, 150, 500, 1000	2018
	HRS	40.60127	140.49829	15, 45, 155, 310, 600, 1200	2018
	FJS	40.65510	140.50381	15, 45, 160, 320, 700, 1400	2018
	IYG	40.69692	140.45653	15, 45, 175, 350, 700, 1400	2018
	GSW	40.81570	140.50381	15, 45, 125, 250, 500, 1000	2018
	ING	40.88019	140.39669	20, 60, 145, 290, 640, 1280	2019
	KRI	40.66417	140.57972	20, 60, 147.5, 295, 590, 1180	2019

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3. Data Processing

The vertical component of the observed microtremors was analyzed to obtain the spatial autocorrelation (SPAC) coefficients [9] after dividing the records into small segments (20.48s, 40.96s, or 81.92 s). The phase velocity dispersion curve was estimated by the extended SPAC method [10, 11] using the obtained SPAC coefficients. Then, we estimated the one-dimensional layered S-wave velocity structure model at each site by assuming that the phase velocity could be modeled as the fundamental mode of the Rayleigh wave. The S-wave velocity of each layer was fixed at the value given in the layered model of J-SHIS V2 [2] except for some additional layers, which was necessary for reproducing the observed dispersion curves. The thickness of each sedimentary layer and the S-wave velocity of the additional layers were estimated by using the genetic algorithms [12] or the Markov chain Monte Carlo method [13].

4. Results and Discussions

4.1 Kaga and Ochigata Plains

The observed phase velocity (blue circles) and the estimated S-wave velocity structure model (red line) at two sites in the southern part of the Kaga Plain and two sites in the Ochigata Plain, central Japan, are shown

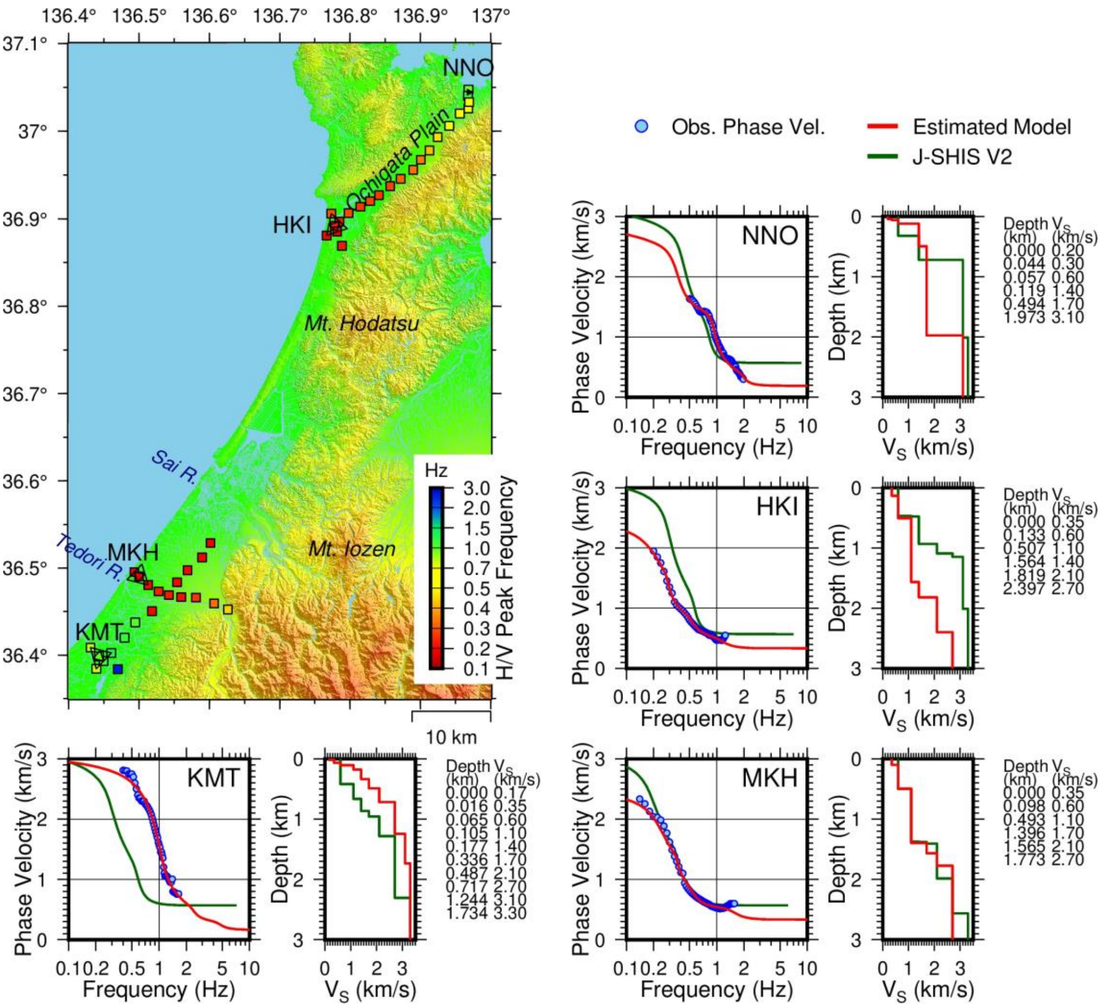

Fig. 2 – Phase velocity dispersion curves, S-wave velocity models, and H/V peak frequencies (colored squares on the map) in the Kaga and Ochigata Plains

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in Fig.2 together with the model of J-SHIS V2 (green line). The depth in the list within the figure refers to the top depth of each layer (The same applies hereinafter). The detail of the survey in this area has been published in our previous paper [14]. The S-wave velocity model for NNO was revised by another field observations conducted after that study. The estimated S-wave profiles at KMT and MKH and the spatial variation in the peak frequency of H/V spectral ratio indicate that the thickness of the Quaternary deposits changes at around the Tedori River. The peak frequency of H/V spectra decreases gradually along the line from Nanao (NNO) to Hakui (HKI) in the Ochigata Plain, indicating gradual change in the bedrock depth. It is also consistent with the Bouguer anomaly in this area [15].

4.2 Toyama Plain

The observed phase velocity (blue circles) and the estimated S-wave velocity structure model (red line) at fifteen sites in the Toyama Plain, central Japan, are shown in Fig.3. The present J-SHIS V2 model (green line) reproduces well at several sites particularly in the lower frequency range (< 1 Hz). The observed phase velocity in the higher frequency range (> 1 Hz) is relatively low at alluvium sites in the Izumi Plain (SNM and SIM) and NMK compared to other surveyed sites mainly covered by fan and terrace deposits. The bedrock depth is deep (5–6 km) at most of the surveyed sites in Toyama, Izumi, and Tonami Plains. The deep seismic reflection profile across the Tonami Plain and the Kureha Hills by Ishiyama *et al.* (2017) shows that the Neogene sedimentary basin deposits fill up to approximately 5 km depth beneath the plain [16], and that result is quite consistent with our microtremor surveys at OYB and TNM.

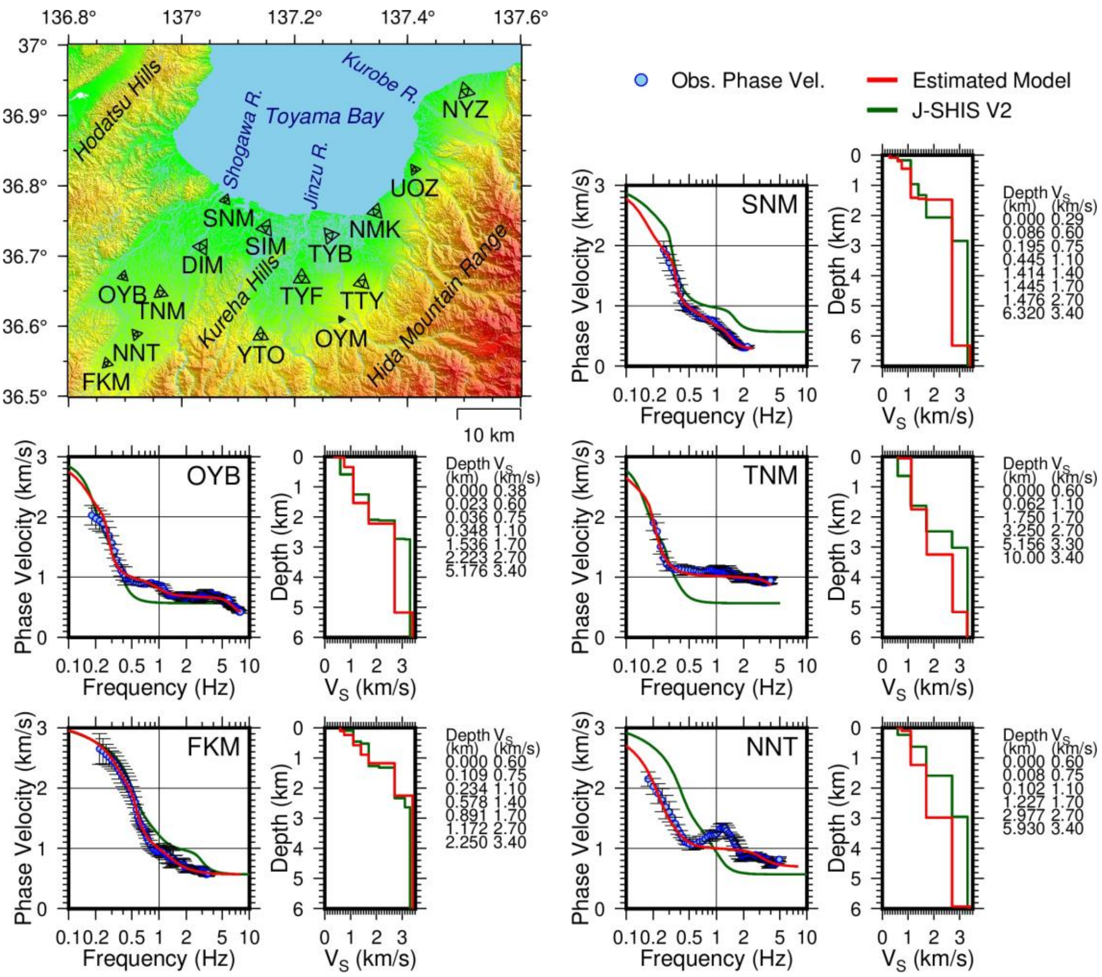

Fig. 3 – Phase velocity dispersion curves and S-wave velocity models in the Toyama Plain

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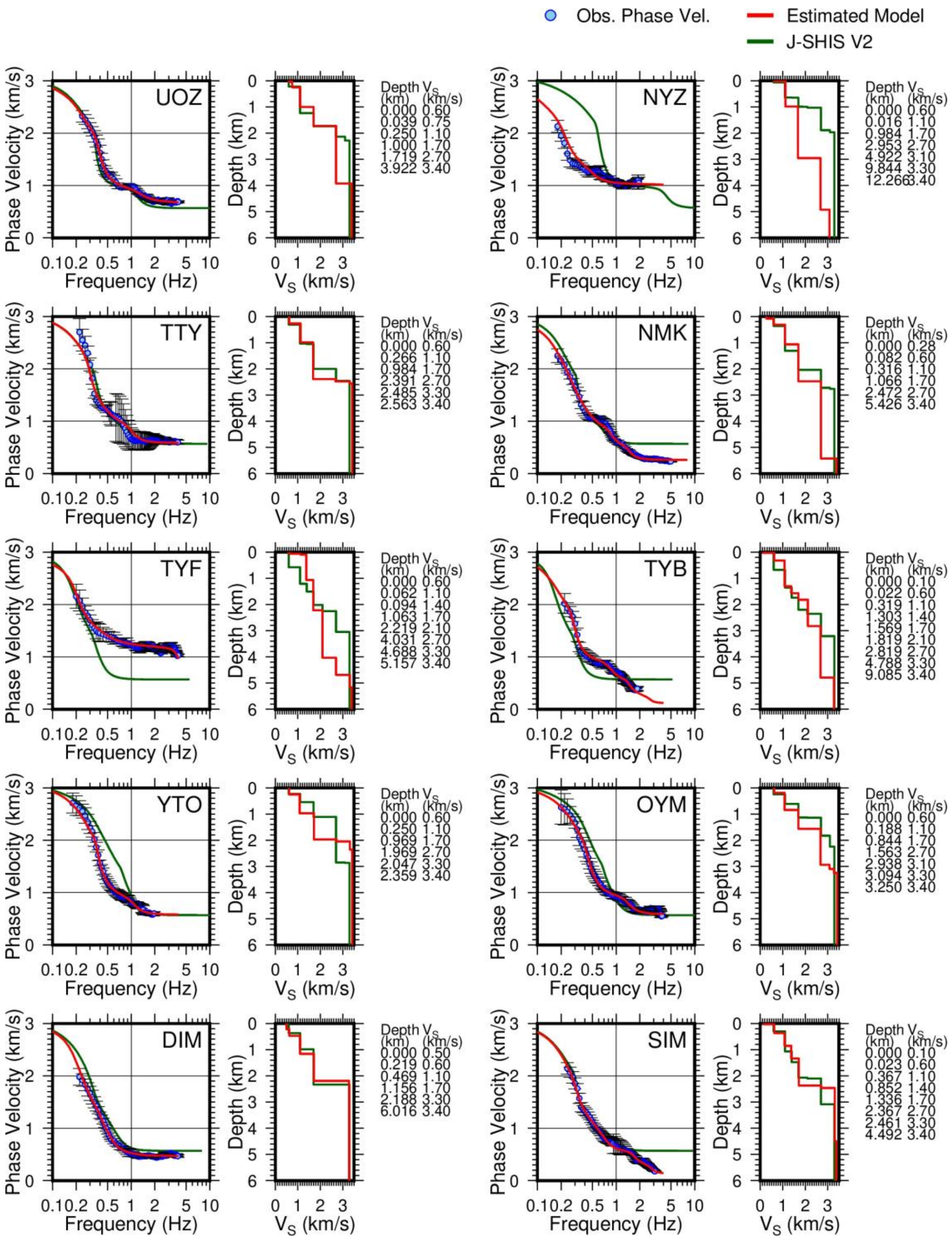

Fig. 3 – Continued

4.3 Western San’in region

The observed phase velocity (blue circles) and the estimated S-wave velocity structure model (red line) at five sites in the western part of the San’in region, western Japan, are shown in Fig.4. The estimated phase velocity is limited in the frequency range at NGT and HEK due to extremely low power spectra of the observed microtremors. The S-wave velocity of the topmost layer is 0.12–0.20 km/s in the Masuda plain (MSD and MCH) and the Hagi plain (HAG), indicating existence of Holocene delta deposits. The estimated

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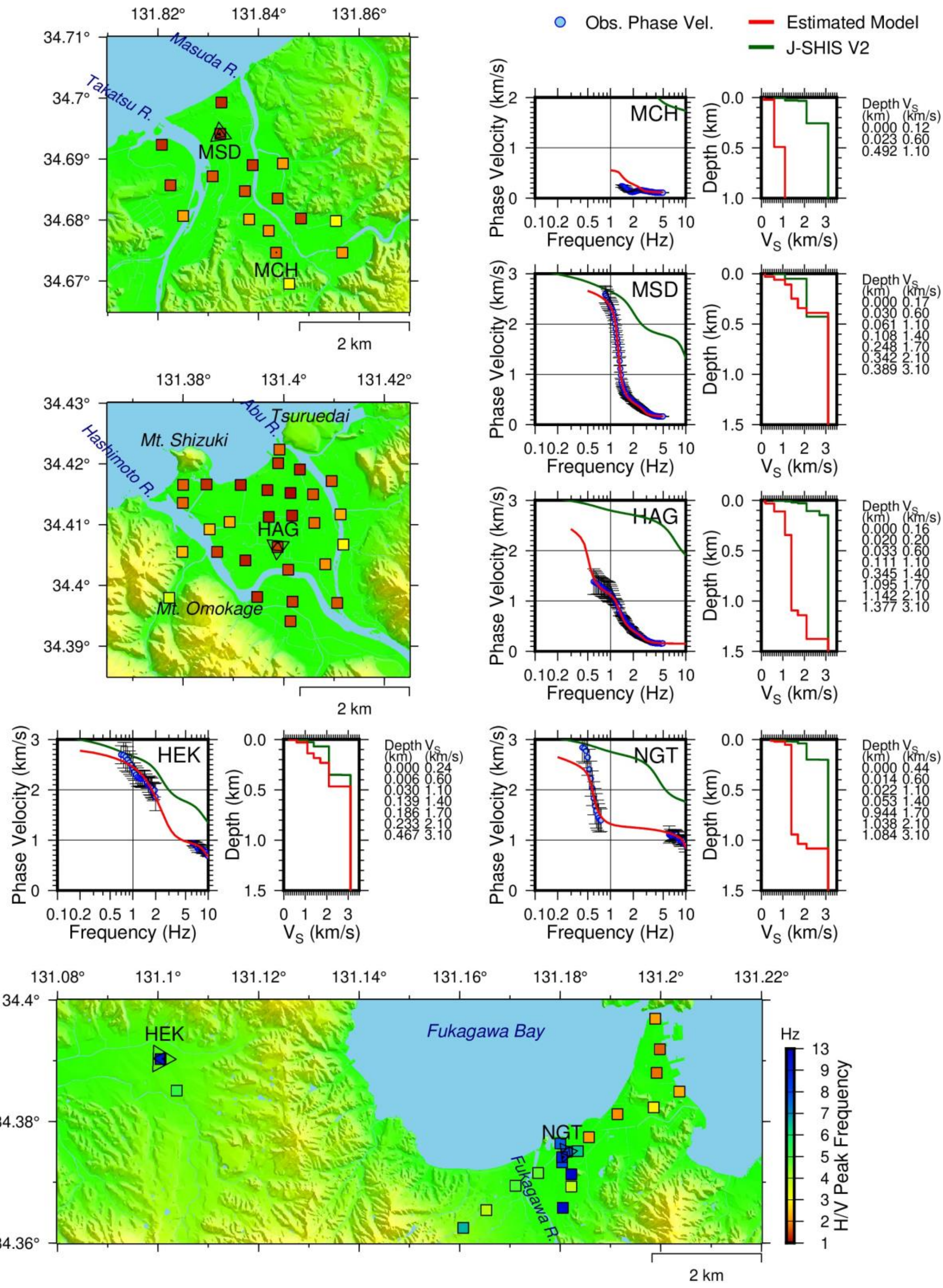

Fig. 4 – Phase velocity dispersion curves, S-wave velocity models, and H/V peak frequencies (colored squares on the map) in Masuda, Hagi, and Nagato cities, western San'in region

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S-wave velocity model at each site has thicker sediments than the present J-SHIS V2 model (green line). The spatial distribution of the peak frequency of H/V spectra is relatively complicated in the Senzaki (Fukagawa) plain (NGT) compared to the Hagi and Masuda plains.

4.4 Hakodate Plain

The observed phase velocity (blue circles) and the estimated S-wave velocity structure model (red line) at five sites in the Hakodate Plain, southern Hokkaido, are shown in Fig.5. MHR is located on the middle terrace, and the other stations are located on the alluvium. The estimated velocity model explains the observed phase velocities better than the J-SHIS V2 model (green line). The thickness of Quaternary and Neogene sediments at MHR is relatively thin, which reflects its higher phase velocity in the low frequency range (<3 Hz) compared to the other sites. The layers with S-wave velocity ranging from 1.1 to 1.7 km/s dominates in the sedimentary layers, that is, the Hakodate Plain is mostly filled by Miocene sediments. The S-wave velocity of the topmost layer at NNE is very small (0.07 km/s), which is might be due to peat in this area. The active reverse fault zone along the western margin of the Hakodate Plain [17] makes thickness of Quaternary sediments deepen in the western part of the plain (KMI and OON) compared to the eastern part (NNE).

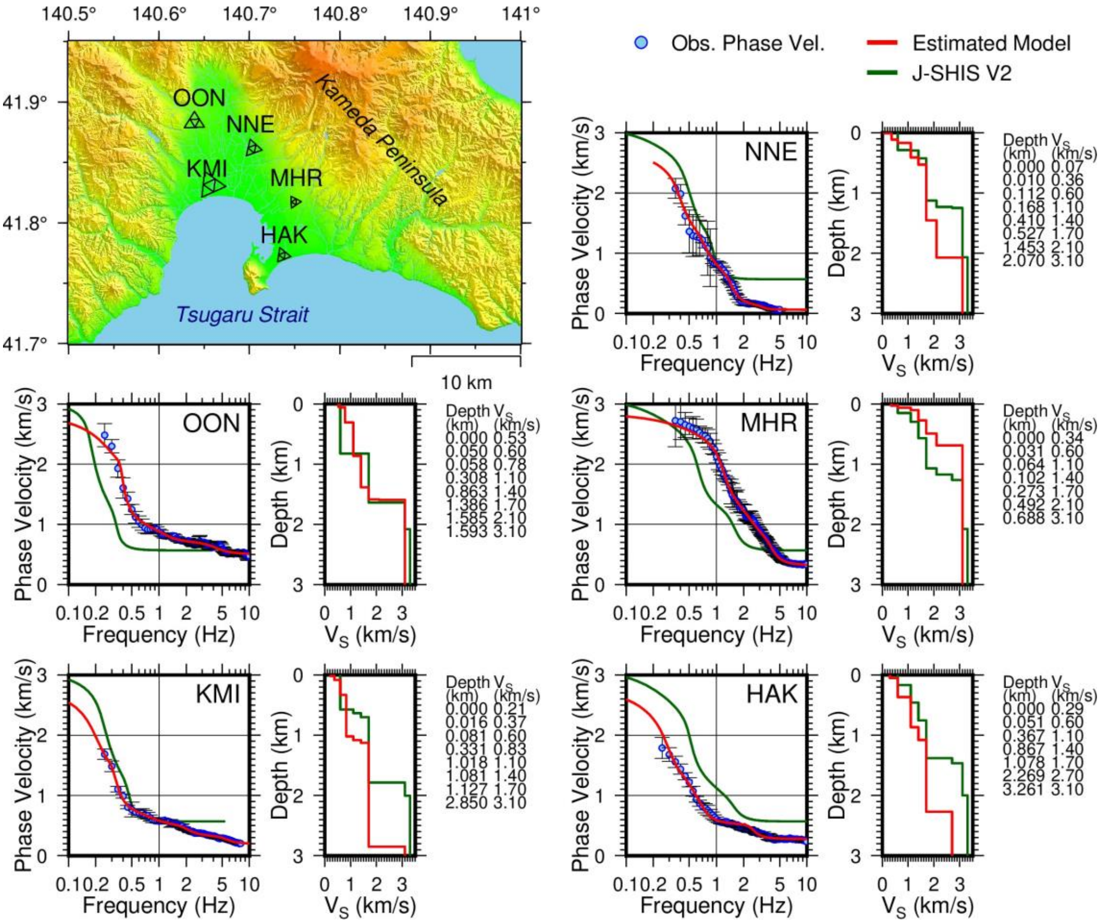

Fig. 5 – Phase velocity dispersion curves and S-wave velocity models in the Hakodate Plain

4.5 Tsugaru Plain

The results at seven sites in the Tsugaru Plain, northeastern Japan, are shown in Fig.6. The estimated model (red line) explains the observed phase velocities (blue circles) much better than J-SHIS V2 model (green

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line). The bedrock depth is estimated to be about 1.5–1.6 km in the northern part of the Tsugaru Plain (ING and GSW), and it is more than 3 km in the central part of the plain (IYG and FJS). The top depth of V_S 0.6 km/s is shallow in the central part of the plain (FJS and HRS). The layers with V_S 1.1–1.7 km/s are relatively thick among sedimentary layers, and they are more than 1 km at most sites. This fact indicates Miocene

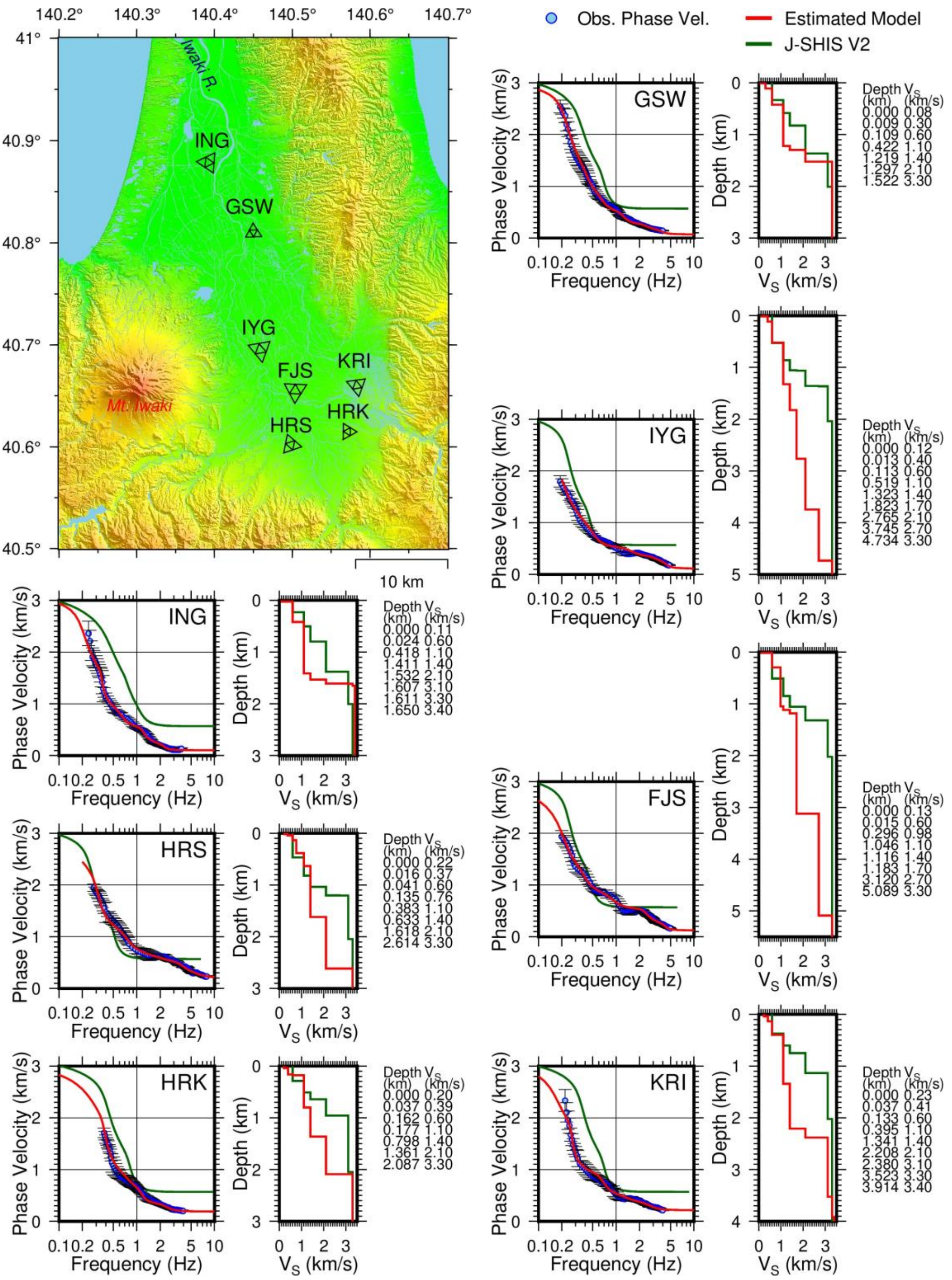

Fig. 6 – Phase velocity dispersion curves and S-wave velocity models in the Tsugaru Plain

sedimentary layers are thick in the Tsugaru Plain. The S-wave velocity of the topmost layer is small (0.08–0.13 km/s) at sites on alluvium deposits (Jusanko Formation) along the Iwaki River (ING, GSW, IYG and FJS) and relatively large (0.20–0.23 km/s) at the other sites (HRS, HRK, and KRI). The results of H/V spectra by single-station microtremor observations will be used to interpolate the structure model over the Tsugaru Plain.

5. Conclusions

We have carried out large-scale microtremor array surveys at 35 sites in the sedimentary basins on the coast of Sea of Japan to investigate S-wave velocity structure model down to the bedrock. We also additionally measured H/V spectra by single-station microtremor observations at many sites in the Kaga, Ochigata, Masuda, Hagi, Senzaki (Nagato), and Tsugaru Plains to investigate the spatial variation in the bedrock depth. The estimated depth of the seismic bedrock is approximately 5–6 km in the Toyama and Tonami plains in central Japan, which is consistent with existing reflection and refraction surveys. The Tsugaru Plain in northeast Japan also has relatively thick sediments, and those thicknesses are more than 3 km in the central part of the plain. The sedimentary layers having S-wave velocity ranging from 1.1 to 1.7 km/s, which might be correspond to Neogene sedimentary rocks, are relatively thick compared to Quaternary sediments (Vs < 1 km/s) in the sedimentary basins studied during this project. These survey results would be quite useful for revising the nation-wide and regional three-dimensional velocity structure models in near future.

6. Acknowledgements

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