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Modeling of the subsurface structure from the seismic bedrock to the ground surface for a broadband strong motion evaluation in Kanto Area, Japan

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Abstract

We have collected a lot of boring exploration and physical property data (mainly microtremor observation ones) in the past, which are important to especially evaluate seismic ground motion in period range from 0.5 s to 2.0 s, and have studied combining a shallow part with a deep one on a subsurface structure model, for the purpose of modeling subsurface structure so that we can evaluate broadband earthquake ground motion from 0.1 Hz to 10 Hz. In this paper, we will report the methods of modeling initial subsurface structure and S-wave velocity structure which incorporate period and amplification characteristics based on earthquake and microtremor observation records, in the whole area of Kanto including Tokyo, Japan.

Keywords: Broadband strong motion evaluation, S-wave velocity, Real-time earthquake damage estimation, Microtremor observation

1. Introduction

In order to advance the accuracy of strong motion prediction, it is one of the important problems to develop a subsurface structure model which enables us to evaluate broadband seismic ground motion from 0.1 s to 10 s. It is necessary to integrate shallow subsurface structure models [1] and deep ones [2] which have ever been modeled separately and to improve those models so that observed records can be reproduced.

In this study, first, all over Kanto area, we constructed geological and soil structure models from engineering bedrock to ground surface with boring exploration data we had collected from the local governments etc. in the past. Then we developed initial subsurface structure models (geological models) by integrating the shallow models described above into the deep ones developed in the past. Next, we collected earthquake observation records obtained at seismic ground motion stations of K-NET, KiK-net, JMA (Japan Meteorological Agency) and the local governments etc. and microtremor observation records obtained by a lot of array and single surveys. After that, S-wave velocity structure models, Q values and amplification factors etc. were evaluated based on the initial models. As a result, subsurface structure models were sophisticated. In addition, a planar interpolation method was investigated and subsurface structure from seismic bedrock to ground surface were modeled by meshes with the size of 250 m.

By the way, model verification of the previous models were conducted in the following way. On the range of shorter period than 2 s, we compared earthquake observation records with site amplification factors etc. obtained through the use of 1 dimensional multiple reflection theory. On the range of longer period than 2sec, we compared earthquake observation records with results obtained by FDM computation [3].

Here, we will mainly report the results in the whole area of Kanto.

2. Outline on modeling of subsurface structure

In this study, in order to develop "wide-area version" subsurface structure models by the prefecture using subsurface structure models in the past research described above, we have studied a modeling method of subsurface structure from seismic bedrock to ground surface by meshes with the size of about 250 m used in micro-topography classification. Before now, we have studied subsurface structure models about Chiba, Ibaraki and Niigata prefecture [4, 5]. We also referred to the modeling method of "local-area version" subsurface structure from seismic bedrock to ground surface by meshes with the size of 50 m we had developed by the municipality in our previous research [6].

By the way, it is significant that the initial integrated subsurface structure models based on boring survey data are constructed at the same quality level in the whole of target area. In this study, geological stratigraphy was read 3-dimensionally and initial shallow subsurface structure models, on which spatial continuity was taken into consideration in the whole of target area except mountainous region, were constructed. Besides, about mountainous area, subsurface structure were modeled in other simple way. That's how, subsurface structure all over Kanto area were modeled. Flow of subsurface structure modeling is shown in Fig.1.

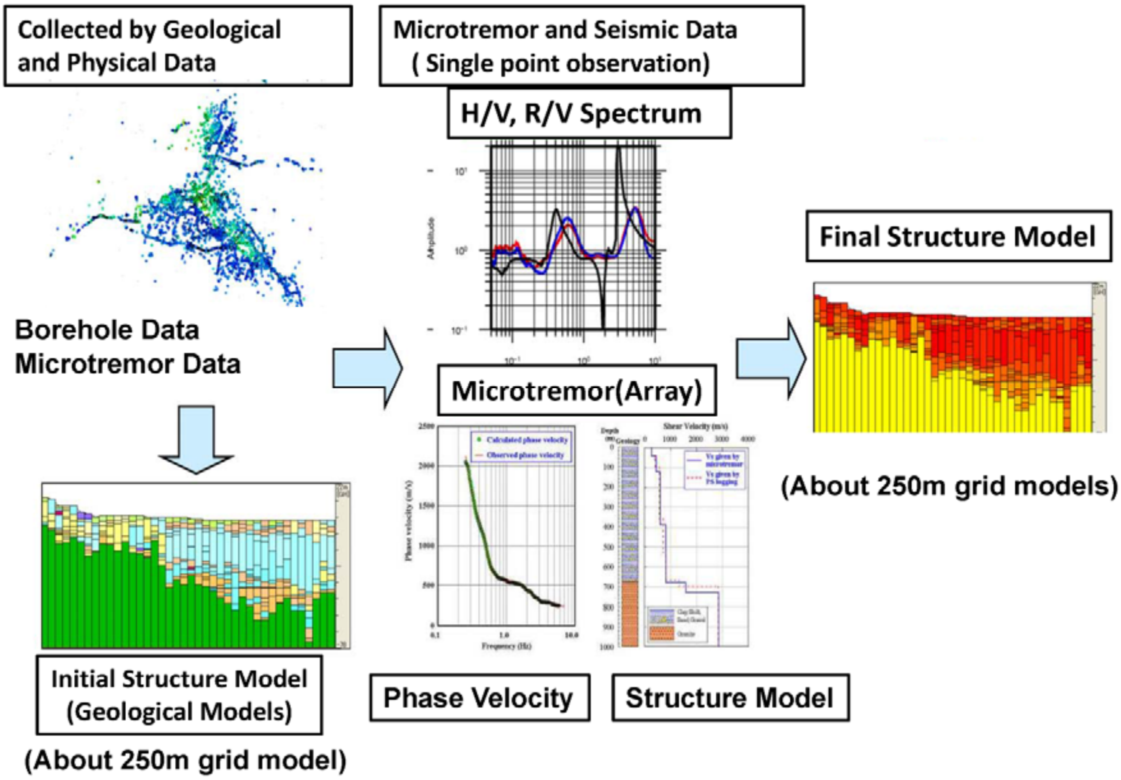

Fig.1 Flow of subsurface structure construction from seismic bedrock to ground surface creation.

3. Collection of boring survey and microtremor observation data for modeling subsurface structure

In this study, we collected boring survey data, which the local governments have as the fundamental information on subsurface structure, earthquake and microtremor observation records. Boring survey data, which were collected from "Geo Station [7]" of NIED or which were collected from the local governments and digitalized into XML format, were mainly used for modeling shallow subsurface structure. Earthquake observation records were collected from the seismic ground motion stations of K-NET, KiK-net, JMA and the local governments (which are mainly prefectures). The target time is from April 1, 2000 to December 31, 2014.

On microtremor observation, two kind of array observations have taken place in mainly lowlands and plateaus. One is miniature array and irregular array observation. It has taken place on premises of public buildings or on the public streets at about 12,000 sites as of May, 2016. The other is larger-scale array observation. It has taken place in the vicinity of seismic motion stations of K-NET, KiK-net and the local governments at about 440 sites as of May, 2016. All-in-one microtremor observation devices, which are called JU210, JU215 and JU410 manufactured by Hakusan Kogyo Co., Ltd., were used during observations. The miniature array observation consists of a triangular array with a radius of 60 cm and a triangular array from 5 m to 10 m on a side (Fig. 2), and took place at intervals of around 1 km for 15 minutes. The larger-scale array observation consists of a triangular array with a radius of 400 m, 200 m and 100 m, an L-shape array 75 m, 50 m and 25 m on a side, and miniature array. It took place at intervals of around 5 km, for an hour on a triangular array and for 30 minutes on smaller arrays like L-shape array.

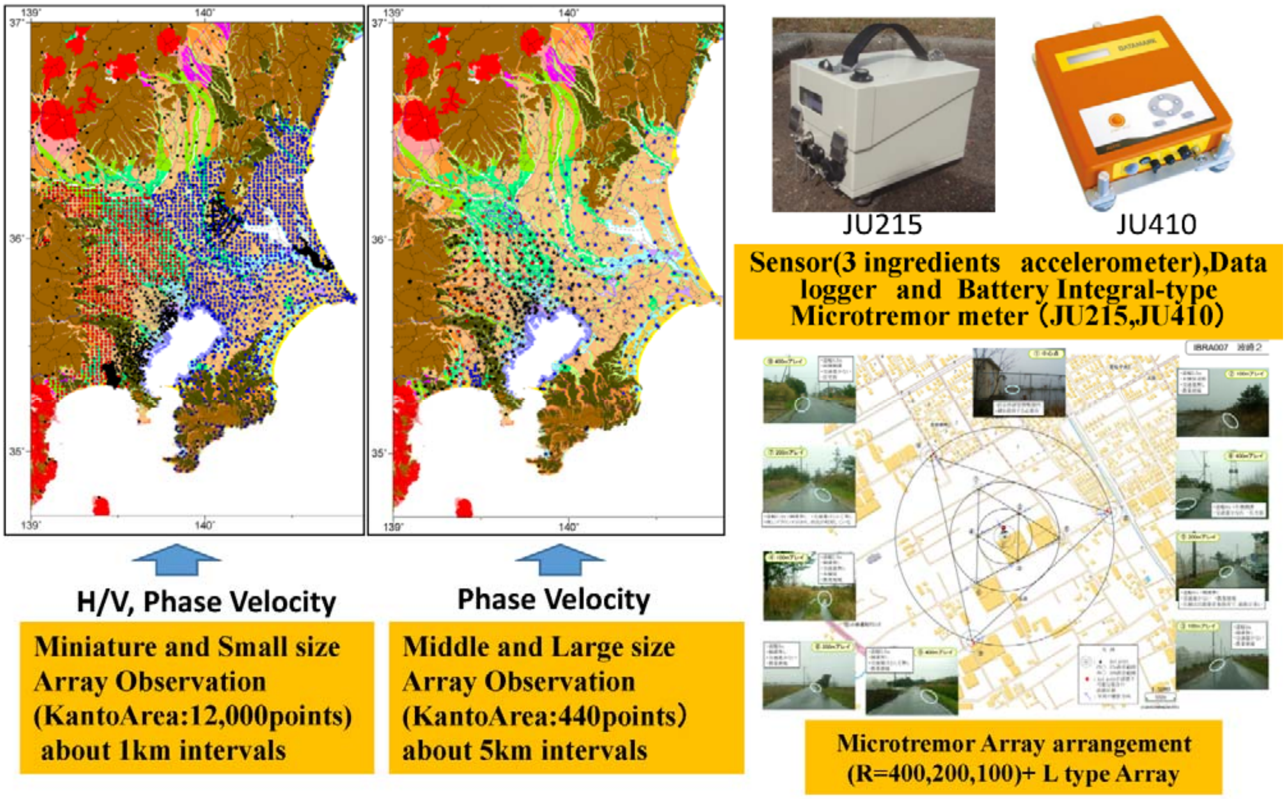

Fig.2 Microtremor observation methods of this study.

4. Modeling of initial subsurface structure (geological modeling)

4.1 Shallow subsurface structure model

Development of shallow initial geological models is divided into two ways. One is on lowlands and plateaus for which stratigraphic successions are developed. The other is on hills and mountains for which weathered layers are set. An outlined procedure on development of shallow initial geological models is shown in Fig.3. Here, classification like lowlands, plateaus, hills and mountains depends on micro-topographic classification with the 250 m mesh size by world geodetic system.

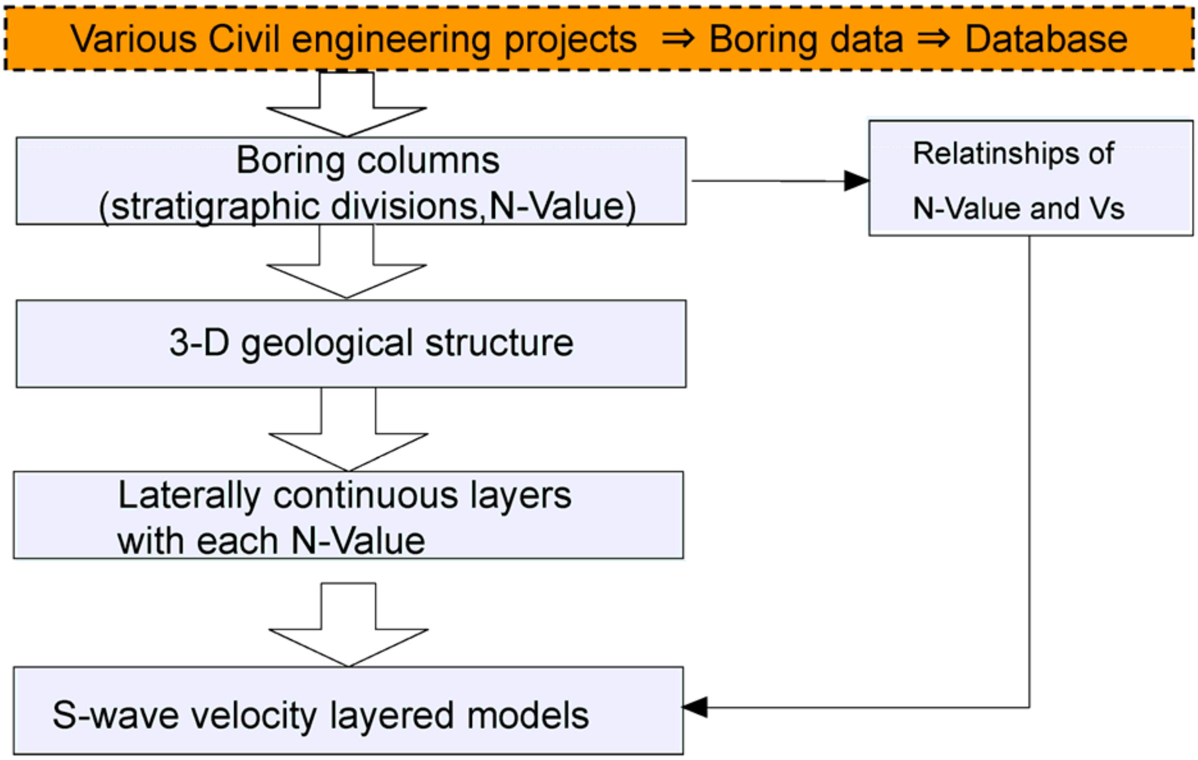

Fig.3 Flow chart of modeling the Shallow subsurface structure models.

By the way, geochronological classification of shallow subsurface structure by boring survey data (procedure 2 in Fig.3) took place by using an idea about stratigraphic successions in the target area indicated in the past research. Generally, on shallow subsurface structure in sedimentary plane, strata are classified based on sedimentary facies change involved with eustatic change of see level. On the Pleistocene, which is the Simousa layer group or corresponding layers in Kanto area, strata were classified based on sedimentary facies change in the vertical direction of two layers described below. One was a silt-based layer which have fine-grained soil N value smaller. The other was a sandy, rudaceous layer with N value 50 or more. On plateau area, terrace and loam layers over the Pleistocene were classified. On coastal area and river basin, the Holocene, that is alluvium, ranged over the Pleistocene or older strata. Strata and sedimentary facies around there were basically classified based on sedimentary facies change involved with eustatic change of see level. Based on these basic elements, stratigraphic succession in lowlands and plateaus was made a table of for each prefecture in Kanto area. Profiles of geological and soil columns are shown in Fig.4 just for reference. On geological and soil models, the information was employed for the sites where boring data existed and strata boundary was interpolated by means of surrounding boring data so as not to contradict the micro-topographical classification with geological consideration for the sites where boring data did not exist. In addition, using interpolated strata boundary data, strata boundary data and depth distribution data of N value were created for each mesh of the subsurface structure models. In the process of these modeling, boundary areas of lowlands with plateaus, hills and mountains were modeled considering landform and taking into account continuity of strata corresponding to a scale of subsurface structure models (that is, an employed mesh size).

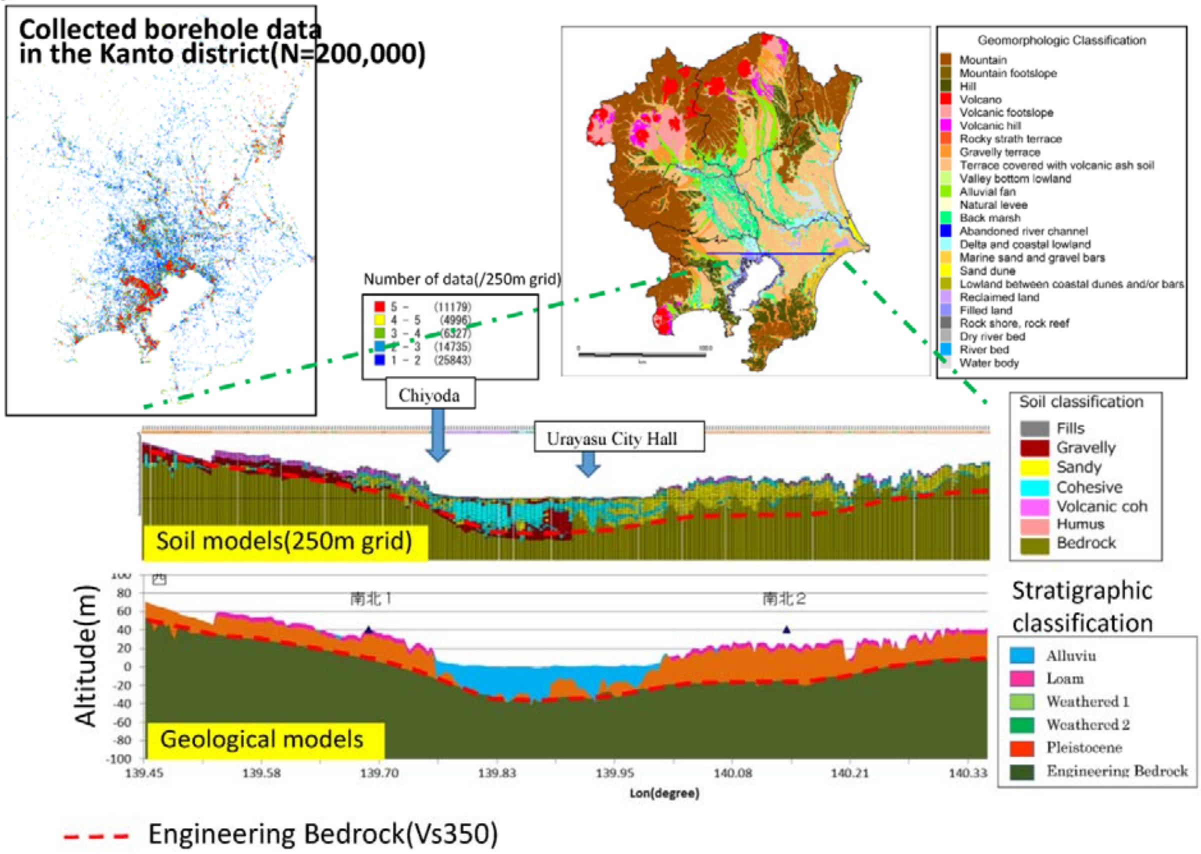

Fig.4 Example of the initial geologic models(shallow part) made in Kanto area.

4.2 Deep subsurface structure model

About deep initial subsurface structure models, in the near future, we will develop and evaluate them in the whole area of Japan. Therefore, here, we employed the national subsurface structure model (J-SHIS model) which had been developed and evaluated uniformly throughout the country. Integrated with shallow subsurface structure models shown in 4.1, initial integrated models were developed. An example of initial integrated models is indicated in Fig.5. Initial value of physical properties of shallow models is indicated in Fig.6.

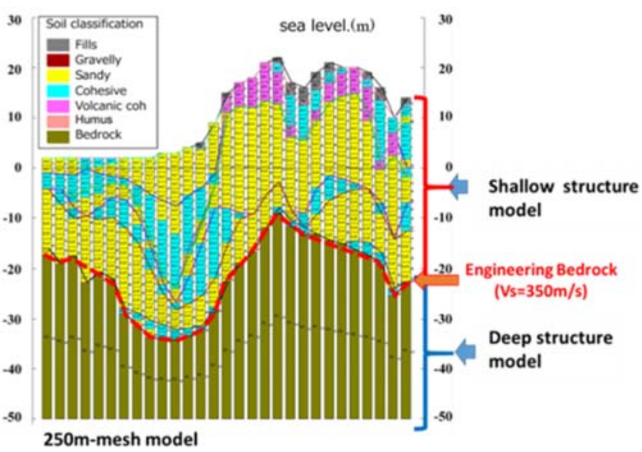

Fig.5 Example of initial integrated models.

<Shallow model>
Central Disaster Prevention Council(2001)

	S-WAVE VELOCITY(m/s)
Alluvium	$Vs = N^{a}\begin{Bmatrix} Alluvial \\ Dilvial \end{Bmatrix}\begin{Bmatrix} \text{COHESIVE SOIL} \\ \text{SANDY SOIL} \\ \text{GRAVEL SOIL} \end{Bmatrix}$
Loam	
Pleistocene	$Vs = 112.73^{0.256}\begin{Bmatrix} 1.000 \\ 1.223 \end{Bmatrix}\begin{Bmatrix} 1.000 \\ 0.885 \\ 0.900 \end{Bmatrix}$
Engineering Bedrock	Set for each area Vs350:Pleistcene distribution Vs400:Hill Vs500:Mountaion, Volcanic

Division of geological		SOIL No.	N-value	Density(g/cm3)
Alluvium	Landfill	B1	0~4	1.6
		B2	4~10	1.7
		B3	10~	2
	Peat	Ap1	0~1	1.2
		Ap2	1~	1.3
	Cohesive	Ac1	0~2	1.4
		Ac2	2~4	1.5
		Ac3	4~8	1.6
		Ac4	8~15	1.7
		Ac5	15~30	1.8
		Ac6	30~	1.8
	Sandy	As1	0~4	1.7
		As2	4~10	1.8
		As3	10~30	1.9
		As4	30~50	1.9
		As5	50~	1.9
	Gravell	Ag1	~20	1.9
		Ag2	20~30	2
		Ag3	30~50	2
		Ag4	50~	2
Dilvial	Loam	Lm1	0~4	1.4
		Lm2	4~	1.5
	Cohesive	Dc1	0~2	1.5
		Dc2	2~4	1.6
		Dc3	4~8	1.7
		Dc4	8~15	1.8
		Dc5	15~30	1.8
		Dc6	30~	1.8
	Sandy	Ds1	0~4	1.8
		Ds2	4~10	1.8
		Ds3	10~30	1.9
		Ds4	30~50	1.9
		Ds5	50~	2
	Gravell	Dg1	~20	1.9
		Dg2	20~30	2
		Dg3	30~50	2
		Dg4	50~	2.1

Fig.6 Initial value of physical properties of shallow models.

5. Analysis for improvement of subsurface structure models with microtremor observation records

5.1 Improvement of subsurface structure models with larger-scale array microtremor and earthquake observation records

In case of larger-scale array microtremor surveys, an inversion analysis was conducted for disperse curves calculated from observed data, and subsurface velocity structures were evaluated. On the inversion analysis, R/V(Radial /Vertical) spectral ratios were calculated using S-coda parts of seismic ground motion observed at strong motion stations, and joint inversion, which is a simultaneous inversion analysis of observed R/V spectral ratios and disperse curves, were conducted. About the simultaneous inversion analysis method, we used the method proposed by Arai and Tokimatsu (2004) [9] and Suzuki and Yamanaka (2011) [10] as a reference. Flow of the inversion analysis is shown in Fig.7. On R/V spectral ratios of seismic ground motion, waveforms after 20 s from first arrival of S wave were extracted, and then Fourier spectra of radial and vertical component were respectively calculated. Fourier spectra were smoothed using Parzen window with 0.05 Hz band width.

We defined residual errors for phase velocity as follows,

$$E_{PV} = \left(1/N^{PV}\right)\sum_{j=1}^{N^{PV}}\left[w(f_j)\left(C^O(f_j) - C^C(f_j)\right)\Big/C^O(f_j)\right]^2 \tag{1}$$

$$\begin{aligned} w(f_j) &= 1.0(f_j > 1.0Hz) \\ w(f_j) &= f_j * 0.5 + 0.5\,(f_j \leq 1.0Hz) \end{aligned} \tag{2}$$

Here, N^{PV}, $C^O(f_j)$ and $C^C(f_j)$ are respectively the number of phase velocity data, observed phase velocity and theoretical one corresponding to a frequency f_j. $w(f_j)$ is a weight function and weighting is larger at higher frequency.

Similarly, residual errors for R/V spectral ratios as follows,

$$E_{RV} = \left(1/N^{RV}\right)\sum_{j=1}^{N^{RV}}\left[\left(RV^O(f_j)\Big/RV^O_{\max} - RV^C(f_j)\Big/RV^C_{\max}\right)\right]^2 \tag{3}$$

Here, N^{RV}, $RV^O(f_j)$ and $RV^C(f_j)$ are respectively the number of R/V spectral ratio data, an observed R/V spectral ratio and a theoretical one corresponding to a frequency f_j,. RV^O_{max} and RV^C_{max} are respectively maximum value of an observed R/V spectral ratio and that of a theoretical H/V spectral ratio.

These residual errors were employed and a residual error for all the observed data was defined as follows,

$$E = 0.5E_{PV} + 0.5E_{RV} \tag{4}$$

A Conceptual diagram and an example of results are indicated in Fig.8.

By the way, the average of ratio of Rayleigh wave over Love wave were calculated based on R/V spectral ratios of observed waveforms and calculated ones. R/L ratio was 0.58 in the range of shorter period than 2 s, and was 0.90 in the range of longer period than 2 s. These results are harmonious in comparison with R/L ratio in Narita city, Chiba prefecture, reported by Kobayashi et al. (2011) [11].

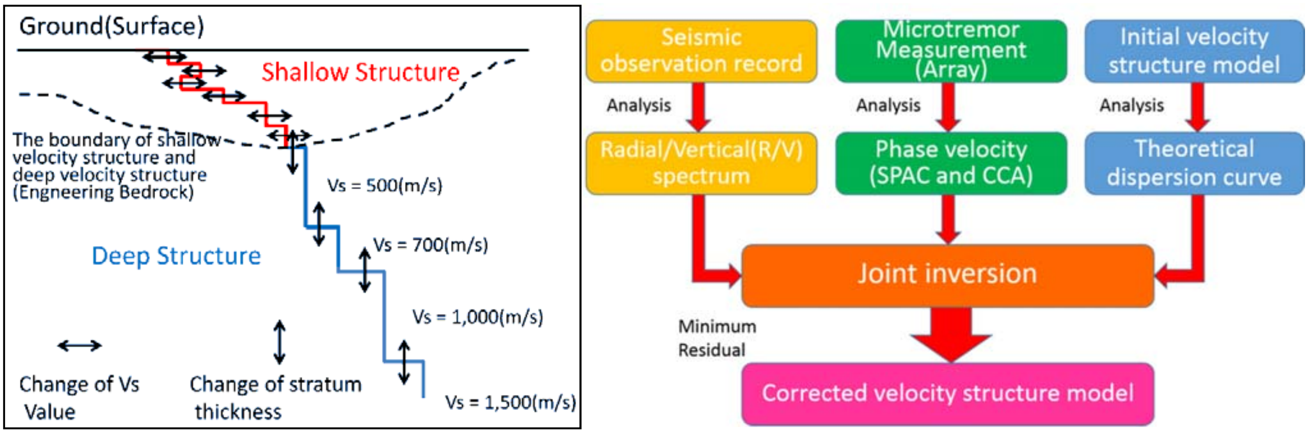

Fig.7 Correction of subsurface structure models using joint inversion method.

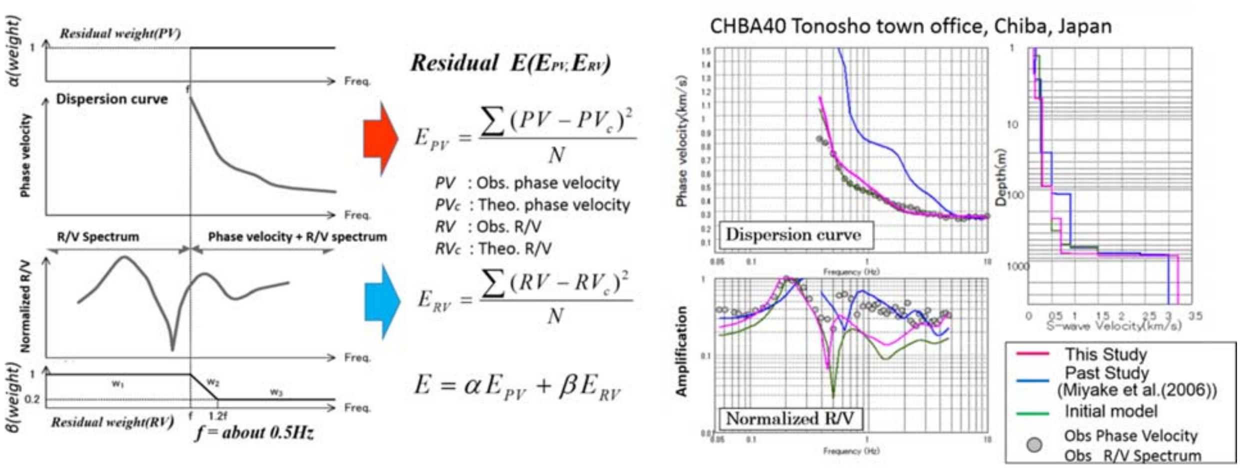

Fig.8 Correction of subsurface structure models using joint inversion method(Example).

5.2 Improvement of subsurface structure models with miniature and irregular array microtremor observation records

For the purpose of evaluating S-wave velocity structure of shallow ground and engineering bedrock accurately, it is better that models are improved so as to be fit phase velocity calculated from miniature and irregular array observation records by using the method shown in 5.1 based on initial geological models. In this research, however, for efficient analysis and judgement of a great deal of observation data, automatic processing of S-wave velocity structure evaluation was applied to modeling, especially, top of engineering bedrock surface (Vs350 m/s). We employed the following method (Cho et al. (2013) [12] and Senna et al. (2014) [13]) among some theoretical and statistical methods. A disperse curve, which is indicated with relation between frequency and phase velocity, is transformed into relation between wave length and phase velocity, and then the transformed relation is regarded as relation between depth and S-wave velocity. We also used the way that phase velocity corresponding to wave length of 40m on a disperse curve was regarded as the mean S-wave velocity from ground surface to the depth of 30m (Konno and Kataoka (2000) [14]). An example of AVS30 and S-wave velocity structure obtained in the way described above is shown in Fig.9.

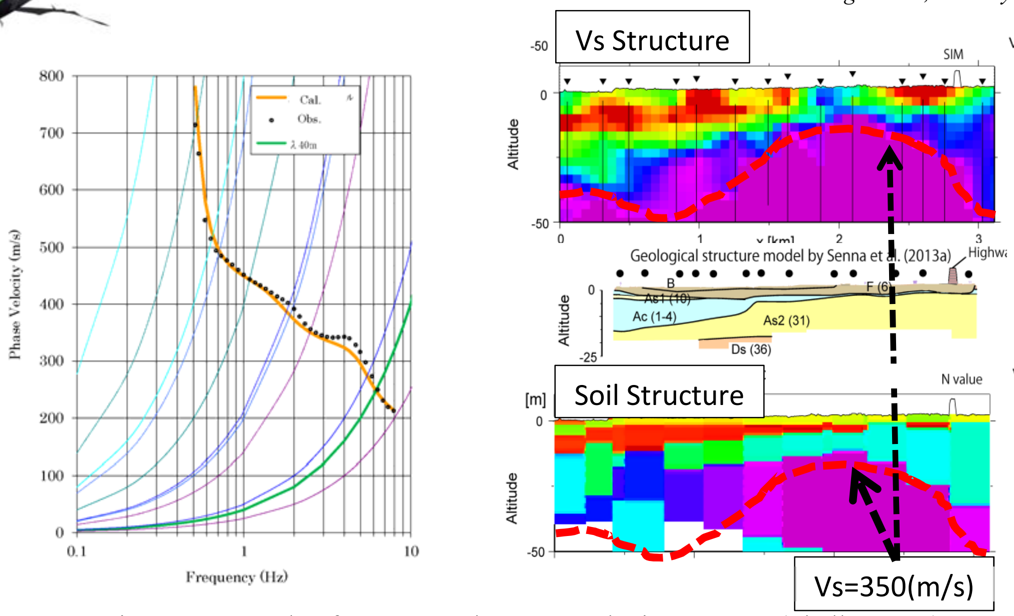

Fig.9 An example of AVS30 and S-wave velocity structure(Shallow part).

5.3 improvement of subsurface structure models with H/V spectral ratios of microtremor observation records

Inversion analysis was executed for shorter period than 2 s, or for shallower subsurface structure than engineering bedrock surface, with subsurface structure models interpolated in 5.1 and 5.2, by using phase velocity calculated from miniature array observation data and H/V spectral ratio calculated from all single-point microtremor observation data. The way of inversion with single-point microtremor is shown in equation (5). As is the case with 5.1, joint inversion was conducted for theoretical, observed phase velocity and H/V spectral ratio based on the method proposed by Arai and Tokimatsu (2004).

$$F = \frac{w_R}{I_R}\sum_{i=1}^{I_R}\left(\frac{c_{mi}^R - c_{Si}^R}{c_{mi}^R}\right)^2 + \frac{w_{HV}}{I_{HV}}\sum_{i=1}^{I_{HV}}\left(\frac{(H/V)_{mi} - (H/V)_{Si}}{(H/V)_{mi}}\right)^2 \tag{5}$$

Here, C^R, (H/V) are respectively Rayleigh wave theoretical phase velocity and H/V spectral ratio (R/L=0.72; 4th mode synthesis) and I_R, I_{HV} are the number of data for each one. Index m and S represent observed data and theoretical ones. w represents weight with w_R=1.0 and w_{HV}=1.0. With equation (5), minimum value problem of F was solved. Some examples of modified models by means of joint inversion are indicated in Fig.10. Models obtained in this study had the best agreement with H/V spectral ratio.

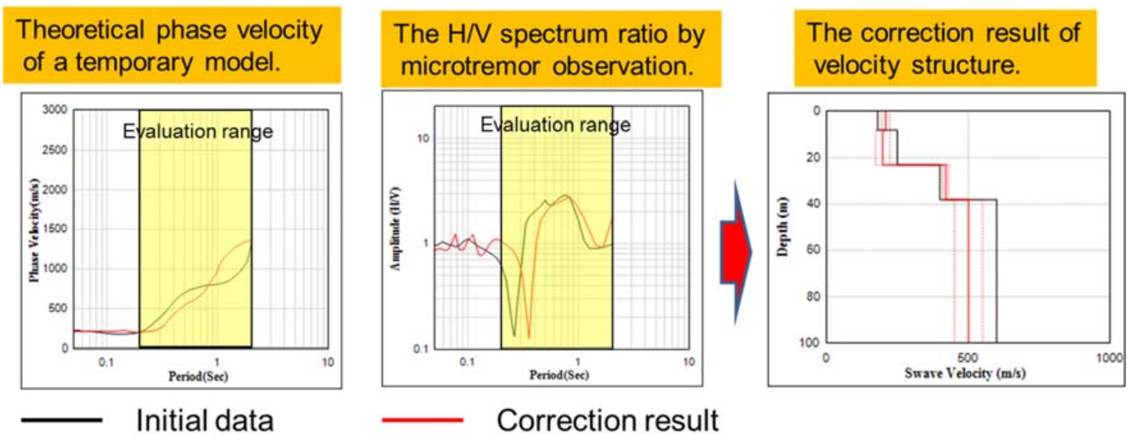

Fig.10 The joint inversion technique using the H/V spectrum ratio of microtremor, and the phase velocity of the structure model

6. Developed subsurface structure model

Indexes of a seismic ground motion, which were calculated with subsurface structure models in the whole area of Kanto, were shown in ground plan. AVS30, which was calculated with integrated subsurface structure models, and ΔI, PGV, ΔSI, etc. for checking the improved depth of engineering bedrock surface are shown in Fig.11. On the whole, about shallow subsurface structure (refer to a figure corresponding to AVS30), S-wave velocity in this study was more explicit than that in the past research (AVS30 based on micro-topographic classification [21] or the previous subsurface structure models to ground surface). Fig.11 is indicated the gain from the engineer bedrock (Vs400 (m/s)) to the ground surface. AVS30 is average S-wave velocity to depth of 30m. The increment by which *ΔI* is the Japan Meteorological Agency seismic intensity (JMA). *ΔSI* is an increment of spectrum intensity value (Spectral Intensity) (G.W.Housner (1961)).

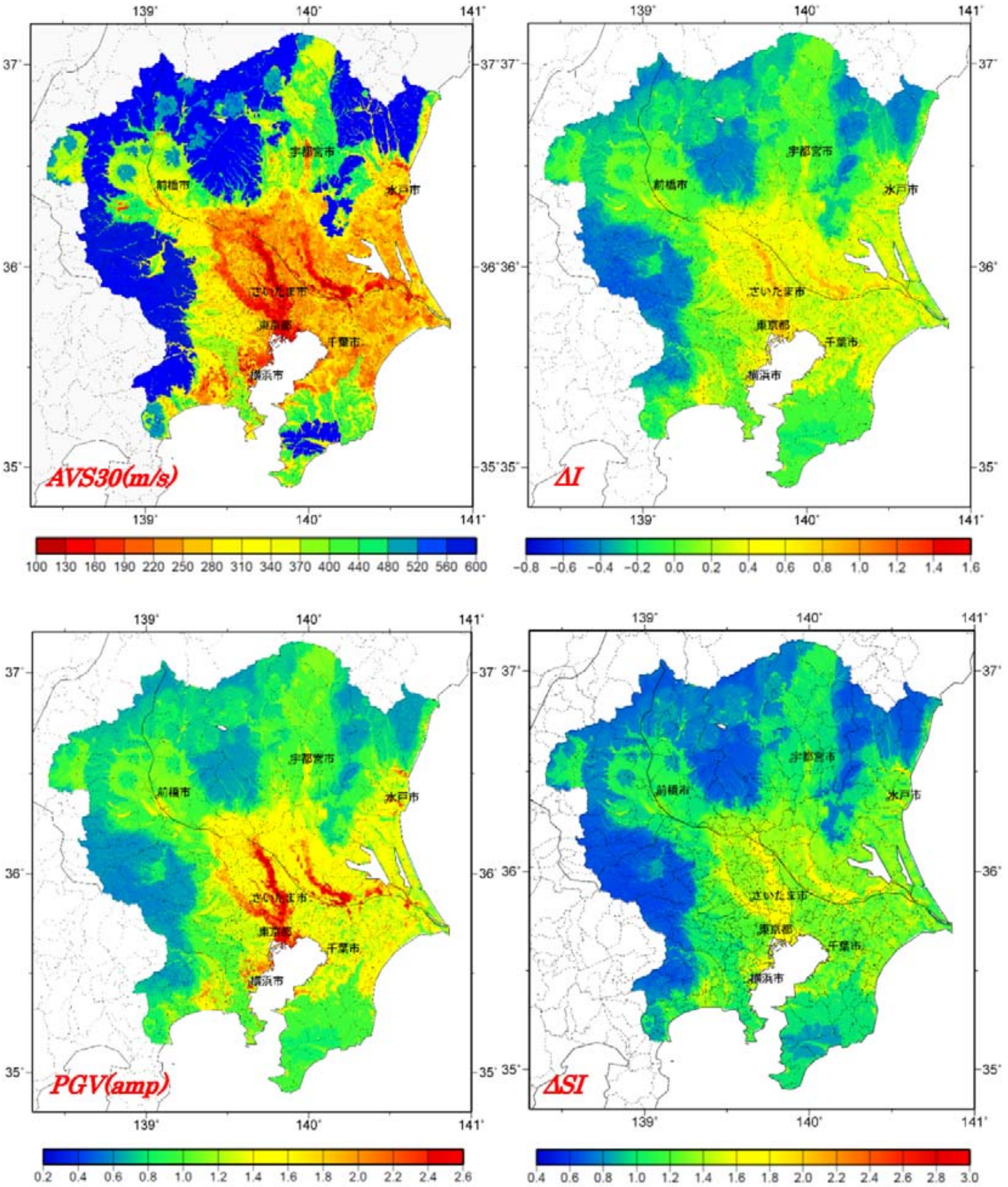

Fig.11 Calculated with integrated subsurface structure models(AVS30, ΔI, PGV, ΔSI)

7. Conclusions

In this research, initial geological models were developed and then subsurface structure models from seismic bedrock to ground surface were constructed by using records of earthquake observation and microtremor array observation. These models in Kanto area were improved in terms of broadband period characteristics in comparison with the previous integrated models. In addition, about computation with FDM(Finite-Difference Methods) and 1D multiple reflection method executed separately, the results were considerably improved in the vicinity of period 1 s which was important from the standpoint of disaster prevention. It can result from not only detailed modeling of shallow subsurface structure by collecting soil columns data, but also improvement of models by evaluating phase velocity and H/V spectral ratio based on microtremor observation, for the structure around engineering bedrock from Vs300 m/s to Vs700 m/s which were boundary layers between shallow and deep subsurface structure.

There are a number of problems in terms of model quality variability by region due to collection density of boring data at the time of development of initial geological models. But the method, which has using miniature array observation etc. and modifying the depth of engineering bedrock surface with geological information, can enable an S-wave velocity model to be stably improved around engineering bedrock in any region. In the near future, we will develop subsurface structure models in Tokai area and all over Japan.

8. Acknowledgments

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