17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

PROCEDURES TO ESTABLISH A SUBSURFACE VELOCITY STRUCTURE MODEL AND ITS CONTRIBUTION ON IMPROVEMENT OF GROUND MOTION PREDICTION OF KANTO REGION, JAPAN

H. Yamanaka[(1)], Y. Tono[(2)], S. Senna[(3)], M. Ohbuchi[(4)] and H. Fujiwara[(5)]

[(1)] *Professor, Tokyo Institute of Technology, yamanaka.h.aa@m.titech.ac.jp*
[(2)] *Research Assistant, Earthquake Research Institute, University of Tokyo, tono@eri.u-tokyo.ac.jp*
[(3)] *Principal Researcher, National Research Institute for Earth Science and Disaster Resilience, senna@bosai.go.jp*
[(4)] *Researcher, Ministry of Education, Culture, Sports, Science and Technology, ohbuchi@mext.go.jp*
[(5)] *Principal Chief researcher, National Research Institute for Earth Science and Disaster Resilience, fujiwara@bosai.go.jp*

Abstract

The Earthquake Research Committee of the Headquarters for Earthquake Research Promotion (ERC/HERP) as one of Japanese governmental agencies has repeatedly updated "National Seismic Hazard Maps for Japan" (Latest: 2018 Edition) [1] consisting of two types of maps: probabilistic seismic hazard maps, and scenario-based ground motion maps. The former depicts integrated hazards of strong ground motion on each map from estimation of long-term potential occurrences of various types of earthquakes, and the latter shows distributions of strong ground motion features computed with the standard procedures of ground motion simulation including fault and subsurface structural models which is called as Recipe [2]. Recipe requires a three-dimensional subsurface velocity structure model involving density, P- and S-wave velocities, Q-values, and shapes of the boundary planes for each layer. This paper presents "Procedures to establish a subsurface structure model" [2] which is being translated in English by ERC to establish a 3D velocity model, and the contribution of the new model for the Kanto region, Japan to the improvement of reliability of the seismic hazard maps. Conventional nation-wide velocity models of deep sedimentary layers in Japan (e.g., [4] have been engaged in aiming at computation of peak ground motions at periods longer than 2 seconds for the national seismic hazard maps. ERC newly applied the procedure to develop the shallow and deep layers combined model (SDLCM in the following) for the Kanto region [8]. One advantage of applying the SDLCM to the seismic hazard maps is improving accuracy of computing broadband seismic ground motion. The SDLCM consists of three domains of the shallow soil layers (Vs < 350 m/s), the deep sedimentary layers (350 ≦ Vs < 3,000m/s), and the crustal and mantle structure (3,000m/s ≦ Vs) divided by two boundaries (a surface of the engineering bedrock, and a surface of the seismic basement). Each model has developed independently, and then these were connected seamlessly, so that the hybrid computing method for broad-band ground motion whose connection period is between 0.5 to 2 seconds can be applied. Another advantage is that amplification factors of ground motion at a surface to corresponding seismic basement can directly be obtained from the SDLCM. These amplification factors were conventionally estimated only with geomorphological land classification. The comparison of the amplification factors indicates that the variation of the amplification factors proved to be underestimated in the conventional method.

Keywords: Shallow soil, Deep sediments, S-wave velocity, Ground motion prediction, 3D velocity structure

1. Introduction

A prediction of seismic ground motion is one of the important tasks in seismic hazard estimation in areas with local and regional scales. Many seismic hazard maps have been published in earthquake-prone countries. In Japan, seismic hazard maps were produced with various procedures by local and central governments. The Earthquake Research Committee of the Headquarters for Earthquake Research Promotion (ERC/HERP) in the Ministry of Education, Culture, Sports, Science and Technology of Japan has repeatedly updated "National Seismic Hazard Maps for Japan" consisting of two types of the maps since 2005. They are probabilistic seismic hazard maps, and scenario-based ground motion maps. The former depicts integrated hazards of strong ground motion on each map from an estimation of long-term potential occurrences of various types of earthquakes, and the latter shows distributions of strong ground motion proxies computed with ground motion simulation including a specified fault and subsurface structural models. The ground motion simulation for the scenario-based ground motion maps was conducted with analytical methods using a fault rupture model and a subsurface velocity model from the surface to the crust and the mantle in a target area established with a standard procedure called as Recipe [3]. The velocity structure building part of Recipe contains how to make and validate a three-dimensional subsurface velocity structure model. In particular sedimentary layers must be appropriately modeled in an area including basins or plains, because of an existence of low-velocity layers of the basins or plains which affect earthquake ground motion significantly. Accordingly the subsurface structural models of the sedimentary layers in Japan for the ground motion prediction have been updated in a working group for subsurface structure model of Subcommittee for Evaluation of Strong Ground Motion in ERC.

The first nation-wide subsurface velocity model for whole of Japan for the ground motion estimation was built in "National Seismic Hazard Maps for Japan (2006 Edition) " [5] using the old version of the procedures of Recipe which is a part of "National Seismic Hazard Maps for Japan (2006 Edition) " . This 3D model consists of two parts which correspond to the deep sedimentary layers and the layers in the crust and mantle. The deep sedimentary part of this model was furthermore improved in Koketsu et al. (2009), and the English version of Recipe (2006 Edition) was published by National Research Institute for Earth Science and Disaster Prevention, Japan [6]. The 3D model was used in the computation of strong ground motion on the top of the deep sedimentary layers at periods longer than 2 seconds with a hybrid ground motion simulation method for the national seismic hazard maps. On the other hand, short-period motion was calculated with stochastic Green's function methods using 1D velocity profiles derived from the 3D model. The long- and short-period motions were combined to the ground motion at the top of the deep sedimentary layers. Finally the shallow soil effects were calculated from empirical amplification factors of peak ground motion and seismic intensity.

One of the features of the previous procedures in the model building is the separate establishment of the deep sedimentary layers and shallow soil layers with geomorphological classification. Furthermore, the effects of the two parts of the subsurface velocity model were also evaluated separately. We have sometimes seen a discrepancy of the physical parameters, such as S-wave velocity, between the two parts of the models. When we calculate ground motion in a period range shorter than 2 seconds with the analytic methods using a 3D model, it is appropriate to use a velocity model which can smoothly connect the deep part with the shallow part without any artificial boundary in the connecting part. ERC has successively discussed to upgrade the procedures for the velocity model building used in an estimation of broad-band ground motion [7], and proposed a new procedure for an establishment of a combined velocity model of the deep sedimentary layers and the shallow soil layers [3].

This paper explains the new procedures to establish a 3D velocity model by ERC, and demonstrates the contribution of the new model for the Kanto region, Japan to the improvement of reliability of the seismic hazard maps. We also explain results of an estimation of the site amplification effects based on the new model for strong ground motion prediction in the area.

2. Subsurface model parameters required for strong motion simulation

It is supposed that the subsurface velocity model made with the procedures of ERC is used for the strong ground motion simulation with a complex fault rupture. Therefore physical parameters related with propagation of seismic ground motion must be defined in whole of Japan. Accordingly the model contains subsurface distributions of density, P- and S-wave velocities, Q-values of homogeneous layers of the shallow soil and the deep sediments, the crust and mantle with their boundary shapes.

As shown in Fig.1, the model is divided into three domains; shallow soil layers, deep sedimentary layers, the crust-mantle layers. The shallow soil domain is defined as layers from the surface to the top of the engineering bedrock layer with S-wave velocities from 300 to 700m/s. The deep sedimentary layers are characterized by layers from the engineering bedrock down to the top of the seismic basement with an S-wave velocity of about 3km/s. The shallow soil layers affect mainly an amplification of seismic wave at short-periods, while the deep sedimentary layers are responsible to long-period ground motion. The layers beneath the top of the seismic basement belong to the crust and mantle including earthquake source layers. Each layer in the three domains is defined in three dimensions with the new procedure. In the following we call a model of combination of the shallow and deep domains as the shallow and deep layers combined model (SDLCM in the following).

The flow for the procedures to establish the SDLCM is shown in Fig.2. The procedures are divided in three parts separately. The first two procedures explain how to make 3D models for the deep sedimentary layers and the shallow soil layers. The last one is prepared as an adjustment to combine the two parts for the SDLCM. The validation of the model using geophysical and earthquake data is also included in the last part. These operations in the flow will be explained in the following chapters.

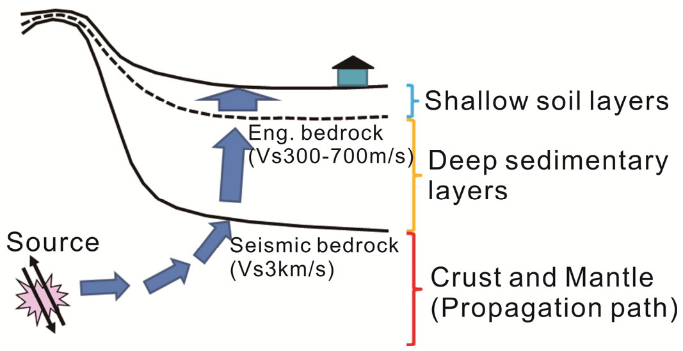

Fig. 1 – Three domains of subsurface velocity structure.

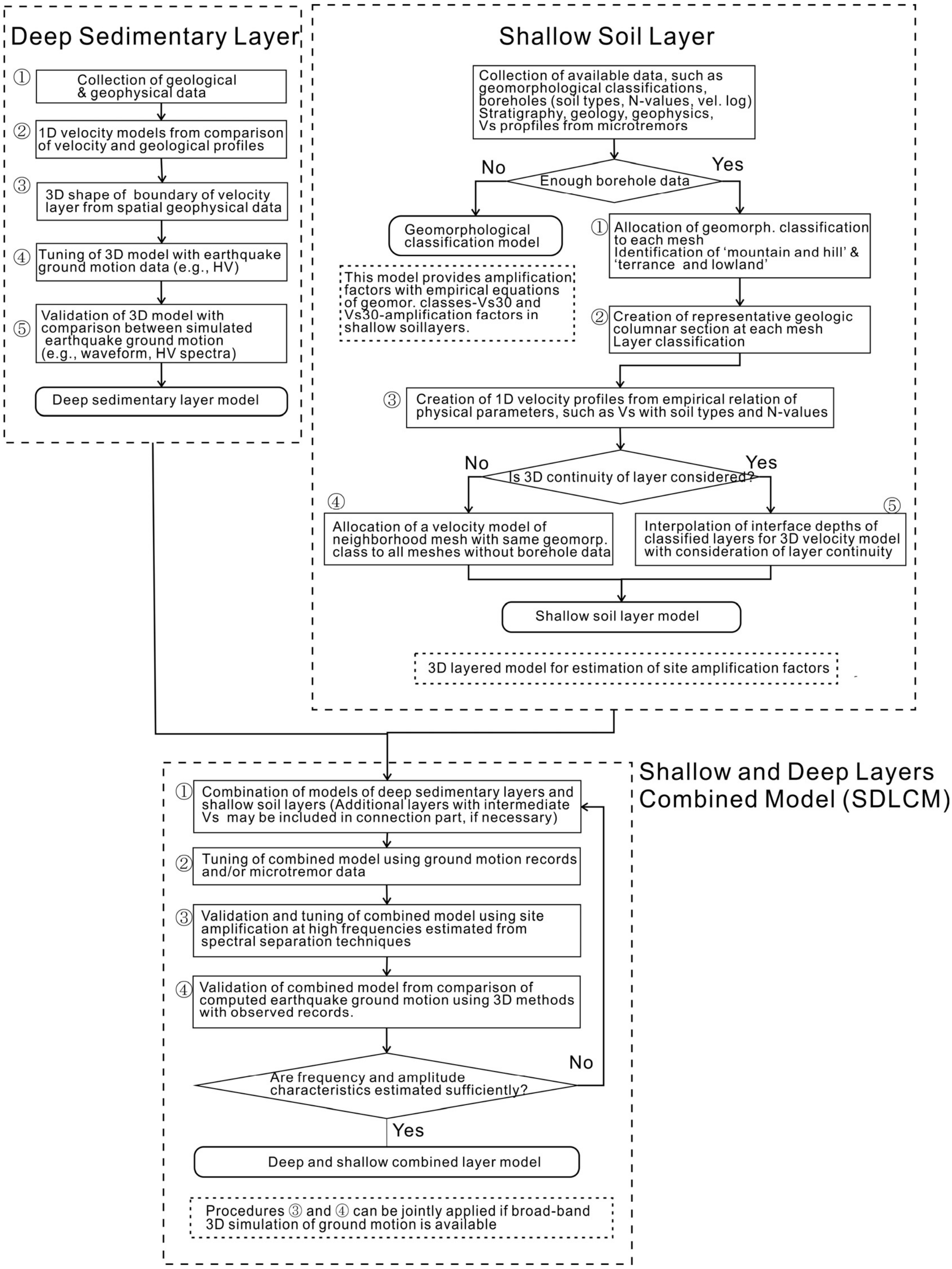

Fig. 2 – Flow for establishment of shallow and deep layers combined model.

3. Procedures for deep sedimentary layer model

We first explain the procedures for making a 3D model of the deep sedimentary layers. After collection of all the available geological and geophysical data on the deep sedimentary layers in the area, 1D profiles of the deep sedimentary layers which are expressed with major geological units are made using geological maps and borehole data. We call these 1D models as geological layer models. We compare the geological models with P-wave velocity profiles derived from existing seismic explorations for correspondence tables to know relationships between the geological units and the physical parameters, such as P-wave velocity. These tables are used to convert the 1D geological profiles to 1D velocity profiles.

Next, we classify and integrate the layers of the 1D velocity models into common layers having P-wave and S-wave velocities which are representative in an area of interest in order to develop the 1D models to a 3D layered model. Depths of each layer boundary of the 1D models with the representative velocities are interpolated spatially considering depth data of velocity interfaces derived from the collected results of seismic explorations and a spatial distribution of gravity anomaly data.

The resultant 3D model of the deep sedimentary layers must be validated from a comparison of observed earthquake records with those calculated with 1D and/or 3D computations of earthquake ground motion. We can improve the 3D model, if it is necessary at this stage.

4. Procedures for shallow soil layer model

At first, available data on the shallow soil layers such as geomorphological, geological, geophysical and borehole data, are collected. There are two kinds of the approaches to model the shallow soil layers as shown in Fig.2. One is the approach (geomorphological classification model in Fig.2) using geomorphological data to classify characteristics of amplification factors for each mesh. This approach uses the published geomorphological data for whole of Japan at every 250m interval [8]. Average S-wave velocity in the top 30 meters from the surface (Vs30 in the following) and the amplification factors was defined empirically for meshes belonging to each geomorphological unit. The other approach (①～⑤in Fig.2) is based on velocity values from the borehole data. A velocity model of the shallow soil layers was defined at each mesh for calculating amplification factors with theoretical or empirical methods. The first approach was only used in the previous Recipe. The second approach is alternatively included as one of the standard procedures in the new version of Recipe.

Shallow borehole data including results of velocity loggings and their locations are collected at each mesh in the area of interest. P-wave and S-wave velocities are defined at each mesh using the results of the logging data. For a mesh without any velocity logging data, velocities of 1D shallow soil layers are assumed from empirical equation of velocity (mainly S-wave) with N-values, soil types and geological ages. After the collection of the data, one of the two procedures (④ or ⑤) must be chosen for a 3D shallow soil model considering amount and quality of the available data.

In the first approach (geomorphological classification model) a mesh size is determined from existing geomorphological or topographical maps. When multiple geomorphological classifications are included in a mesh, one of the classifications at the central point or with major contribution is selected as a representative one. A Vs30 at each mesh is defined from an existing empirical equation of Vs30s with geomorphological classifications, elevations, slopes, and distances from mountains. Once a Vs30 is defined at each mesh, an amplification factor of PGV at the engineering bedrock is empirically calculated to obtain surface PGV (Matsuoka and Wakamatsu, 2006). This approach can be used for an estimation of the amplification factors in an area with insufficient soil data.

The second approach contains more complex procedures than the first one as shown in Fig.2.We first make a geologic columnar section at meshes with borehole data. When there are more than two borehole data in a mesh, we select data of a borehole having the deepest bottom or velocity logging. Then soil types and CPT N-values are representatively determined for each major layer considering previous geological stratigraphic and geotechnical studies including researches on CPT N-values. Then P-wave and S-wave velocities are allocated to each representative layer using logging data or empirical equations of the velocities with soil types, geological ages, and N-values to derive 1D velocity profiles at the meshes. A 1D velocity profile at every mesh without any borehole data was obtained from an interpolation of depths to the layers of the velocity profiles at the meshes with borehole data considering topographical and geological continuity of each layer.

5. Procedures for combination of shallow and deep layers model

5.1 Connection of shallow and deep layer models

When the differences (impedance contrast) between the bottom velocity of the shallow soil model and the top velocity of the deep sedimentary layer model are not so large, the two models can be directly connected for the SDLCM. However we should additionally include new layers with S-wave velocities of 400 to 500m/s between the bottom and the top of the two models as shown in Fig.3 when the differences of the velocities are so large in order to avoid artificial discontinuities in the combined model. The thickness and velocity of the additional layers can be set from logging data at deep boreholes in the area. It is also noted that the additional layers are prepared not to generate three-dimensionally lateral artificial discontinuities considering spatial variation of the depths to the seismic basement near a basin/mountain boundary.

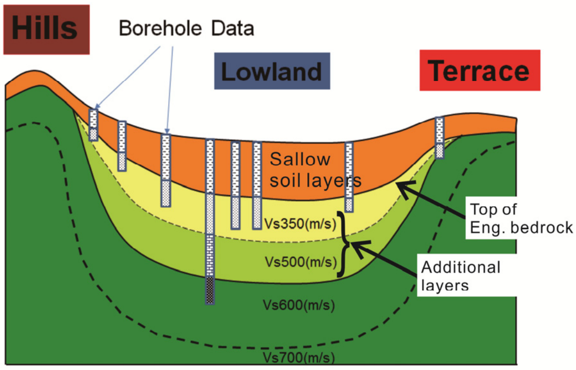

Fig. 3 – Schematic illustration of additional layers between shallow soil layers and deep sedimentary layers for SDLCM.

5.2 Adjustment using earthquake and microtremor records

The above combined model, SDLCM, is improved by adjustment with velocity data derived with earthquake and microtremor records beneath strong motion stations. It is recommended to collect additional data or to conduct new microtremor explorations in case of difficulty in the adjustment.

The combined model is validated from comparing their theoretical 1D amplification of S-waves at high frequencies (higher than 0.5Hz, for example) with observed ones estimated empirically from earthquake records due to moderate events. The SDLCM must be adjusted again with the earthquake and microtremor data if the observed 1D amplification was not well reconstructed with the calculation. Furthermore, we must validate the SDLCM by comparing overall characteristics of observed earthquake records such as travel times of P- and S-waves, amplitudes, peak periods, spectral amplitudes, time-variant features, and durations with the theoretical ones from three-dimensional computations using the model. Significant discrepancy between the calculation and the observation suggests further improvement of the SDLCM. These improvement and validation must be repeated until the sufficient fitting with an acceptable accuracy has been obtained.

6. Results of application to Kanto district, Japan

The procedures for the SDLCM were applied to establish a 3D model of the shallow and deep layers in the Kanto plain, Japan and detailed explanation of the 3D model has been published [9] The deep sedimentary layer model of the Kanto plain made with the previous Recipe was updated using the new version with new data mainly obtained from microtremor explorations. Fig.4 shows the locations of the microtremor array explorations conducted in the Kanto plain to derive 1D S-wave velocity profiles of the deep sedimentary layers. Microtremor horizontal-to-vertical ratios were also observed at the sites for the tuning a 1D S-wave velocity profile jointly with the phase velocity from the array observation. The results of the turning of the models are shown in Fig.5. The Rayleigh wave phase velocity observed in the microtremor explorations and the site amplification factors from a spectral separation analysis of earthquake records are compared with theoretical ones for the 1D models beneath the earthquake station before and after the tuning. The shallow parts are significantly improved at some of the stations as can be seen in the figure. The cross-sections of the deep sedimentary layers of the tuned SDLCM in the east-west and north-south directions are displayed in Fig.6. We can see typical basin shapes in the cross-sections in both directions. The examples of the shallow part of the tuned SDLCM are shown in Fig.7. The figure contains geomorphological classification in the areas and a shallow two-dimensional S-wave profile along the red line in the map. Thick shallow soil layers are seen along the major river in the northern part of Tokyo. The shallow soil layers with significant thicknesses are also found in small valleys in the terrace parts. Finally we confirm the appropriateness of the improved SDLCM with a comparison of observed earthquake motion with synthetic motion calculated from a 3D finite difference computation.

The SDLCM for the Kanto plain is used to evaluate site amplification characteristics. Fig.8 shows distributions of Vs30s from the SDLCM produced with the present Recipe and those from an empirical estimation based on the geomorpholgical classification [8], which was used in the previous version of Recipe. The new distribution map shows a more complex spatial variation of the Vs30s than the previous one. In particular much low Vs30s are identified in the new map along the major rivers. We furthermore calculate amplification factors of PGV between the surface and the top of the engineering bedrock using the two maps of the Vs30s. The amplification factors are shown in Fig.9. It is noted that the amplification factors are calculated using the same empirical equation of a Vs30 from different Vs30s and the S-wave velocities of the engineering bedrock of the two models. The variation of the amplification factors for the new model is much wider than that of the previous one. In particular the amplification for the two types of the terraces are so large in the new model of SDLCM.

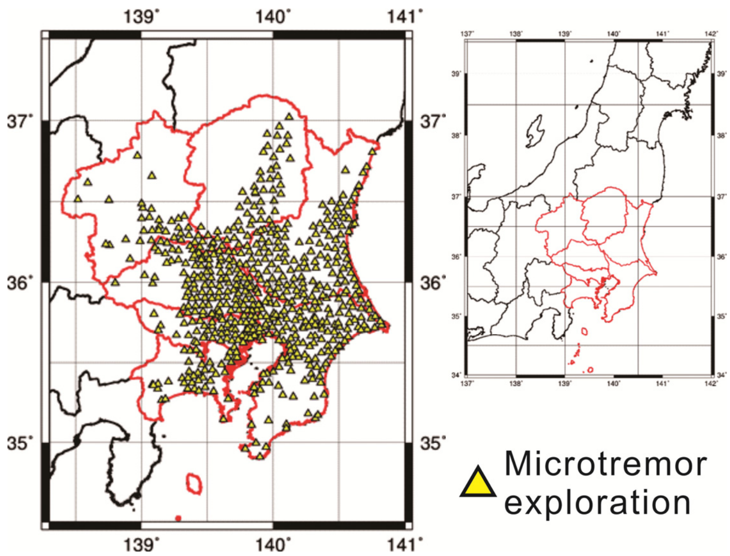

Fig. 4 – Locations of microtremor array measurements to explore deep sedimentary layers.

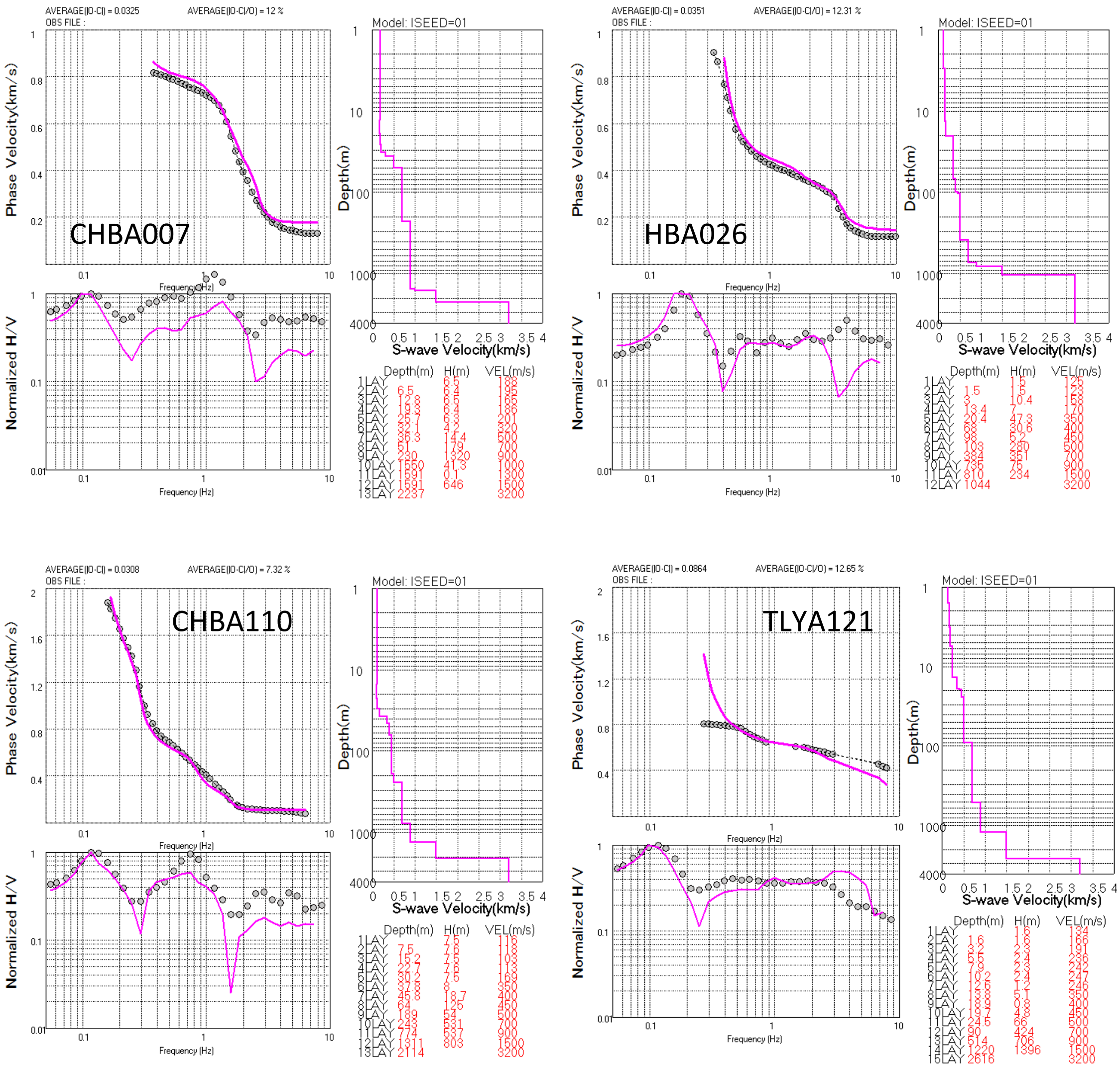

Fig. 5 – Examples of results of tuning 1D S-wave velocity models using Rayleigh-wave phase velocities and horizontal-to-vertical ratios from microtremor measurements.

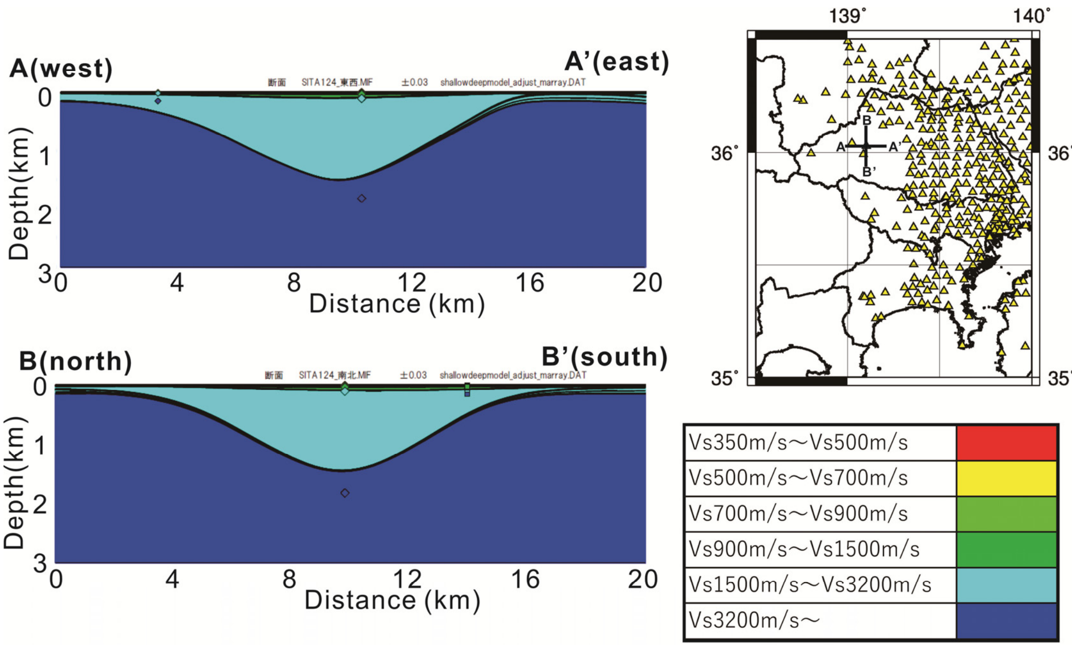

Fig. 6 – Examples of two-dimensional S-wave velocity cross sections of deep sedimentary layers along west-east (A-A') and north-south (B-B') directions.

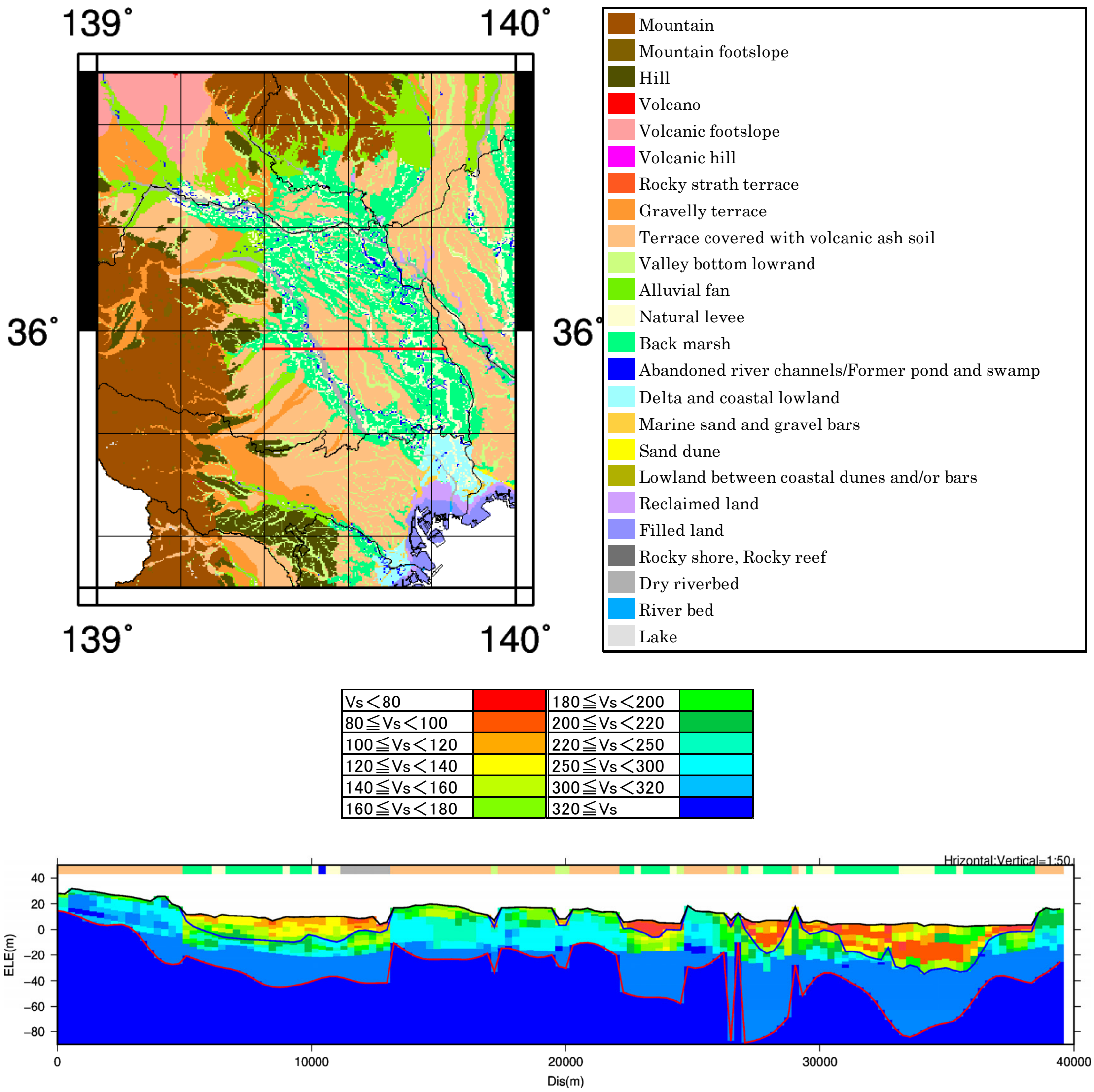

Fig. 7 – Examples of two-dimensional S-wave velocity cross section of shallow soil layers along west-east (left-right) direction with geomorphogocial map.

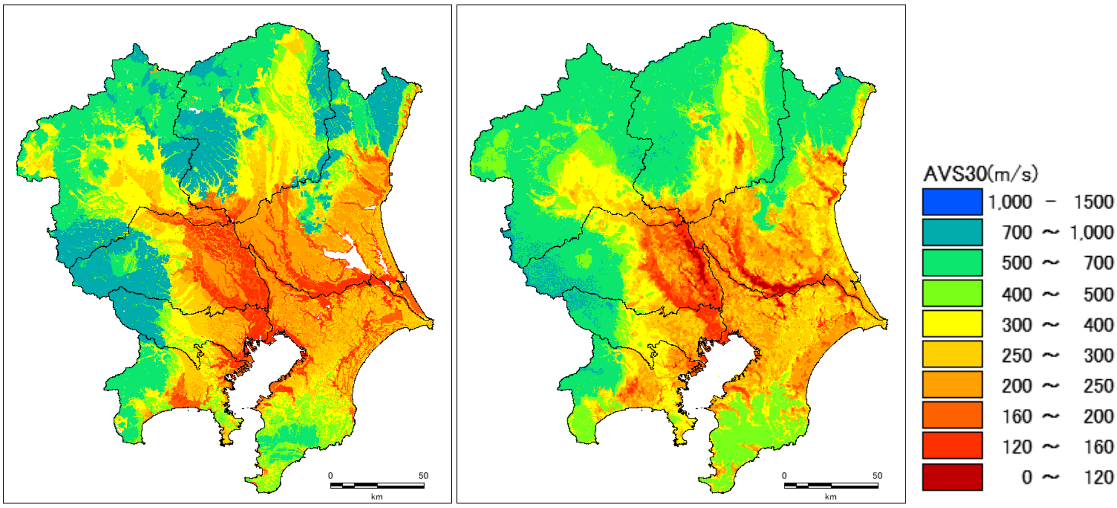

Fig. 8 – Comparison of Vs30 maps estimated from geomorphological classification (left) and SDLCM (right).

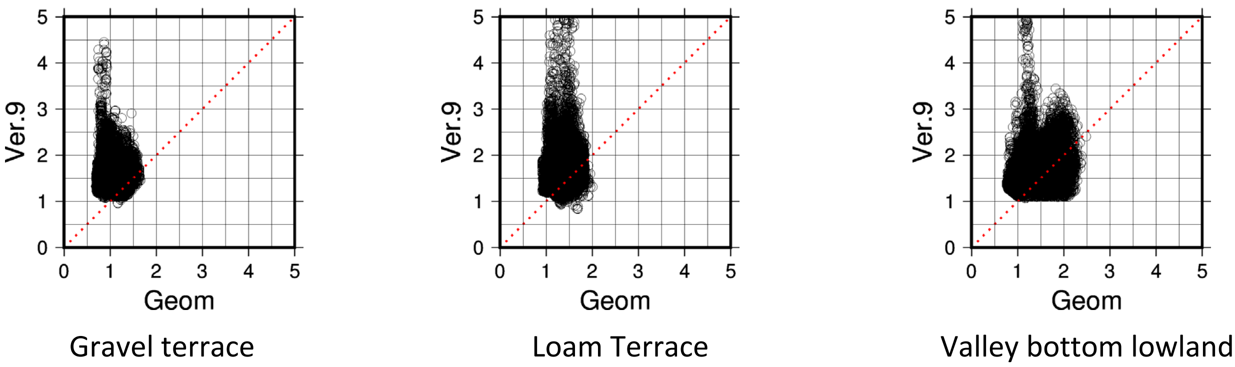

Fig. 9 – Comparison of amplification factors for shallow soil layers in new model of SDLCM (Ver.9) with those of geomorphological classification (GEOM). Left, middle and right panels are comparisons for meshes which belong to gravel plateau, loam plateau, and valley bottom lowland.

7. Conclusions

The new procedures for a 3D combined model of the shallow soil layers and deep sedimentary layers by Earthquake Research Committee, Japan, for the use in seismic hazard estimation were explained in this paper. The new procedures consist mainly of three parts for deep sedimentary layers, shallow soil layers and their connection. The part of the deep sedimentary layers is the same as the previous procedures [2]. The shallow part has been significantly improved for a 3D model. The last part is a brand new part to combine the two models of the deep and shallow layers. As an example of their application, the establishment of subsurface velocity model for the shallow soil layers and deep sedimentary layers for the Kanto plain was demonstrated. The new 3D combined model was validated using 3D simulation of earthquake ground motion due to moderate events to confirm the better performance than the previous model. The amplification factors of the shallow soil part of the combined model are compared with those of the previous one. We found the wide variation of the amplification factors in the new model. The new model can be used for a reliable seismic hazard map through prediction of strong ground motion for future large events in Japan.

References

[1] Earthquake Research Committee, The Headquaters for Earthquake Research Promiotion (2017):National Seismic Hazard Maps for Japan 2018 Edition, (in Japanese) https://www.jishin.go.jp/evaluation/seismic_hazard_map/shm_report/shm_report_2018/

[2] Earthquake Research Committee, The Headquaters for Earthquake Research Promiotion (2017): Strong ground motion prediction method ("Recipe") for earthquakes with specified source faults,

https://www.jishin.go.jp/main/index-e.html

[3] Earthquake Research Committee, The Headquaters for Earthquake Research Promiotion (2017): Procedures to establish a subsurface structure model, (in Japanese)

https://www.jishin.go.jp/main/index-e.html

[4] Koketsu, K., H. Miyake, Afnimar, and Y. Tanaka (2009): A proposal for a standard procedure of modeling 3-D velocity structures and its application to the Tokyo metropolitan area, Japan, Tectonophysics, 472, 290-300.

[5] Earthquake Research Committee, The Headquaters for Earthquake Research Promiotion (2006): National Seimic Hazard Maps for Japan 2006 Edition (in Japanese).

[6] National Research Institute for Earth Science and Disaster Prevention, Japan (2015):Technical Reports on National Seismic Hazard Maps for Japan,257..

[7] S. Senna, T. Maeda, Y. Inagaki, H. Suzuki, H. Matsuyama, H. Fujiwara(2013) : Modeling of the subsurface structure from the seismic bedrock to the ground surface for a broadband strong motion evaluation, Journal of Disaster Research, 5, 889-903.

[8] Matsuoka, M, K. Wakamatsu, K. Fujimoto, and S. Midorikawa (2006): Average Shear-wave velocity mapping using Japan Engineering Geomorphologic classificatrion map, Structural Eng./Earthquake Eng., J. Soc. Civil Eng, 23 (1), 57-68 (Translated from a paper which originally appeared on Journal of Structural Mechanicsand Earthquake Engineering., JSCE, 794/I-72, 239-251, 2005).

[9] Earthquake Research Committee, The Headquaters for Earthquake Research Promiotion (2017): Explanation of the shallow and deep layers integrated model for Kanto region, Japan, created using a " Procedures to establish a subsurface structure model", (in Japanese).

