Procedures to build a subsurface velocity structure model

English version
Translated in March, 2022

Earthquake Research Committee, The Headquarters for Earthquake Research Promotion

This document is a translation from Japanese to English of “地下構造モデル作成の考え方”（地震調査研究推進本部地震調査委員会） published in April, 2017.

1. A subsurface velocity structure model in strong ground motion prediction

To evaluate seismic ground motion hazards as a measure for earthquake disaster prevention, the Headquarters for Earthquake Research Promotion (HERP) has released National Seismic Hazard Maps, which contain the results of ground motion estimation obtained with the strong ground motion prediction method for earthquakes with specified source faults ("Recipe[1]").

This "Recipe" indicates that one can define a seismic velocity structure model for earthquake ground motion evaluation as a three-dimensional velocity structure with the main physical parameters of density, P-wave and S-wave velocities, their Q-values, and the shape of a layer boundary for each layer. The seismic velocity structure model is built independently by dividing the structure into the following three domains bounded by the top-surface of the engineering bedrock[2] and the top-surface of the seismic basement[3]. The three domains are characterized as follows.

- Shallow soil layers are the sedimentary layers from the surface to the top-surface of a firm layer having an S-wave velocity of 300–700 m/s, which is regarded as the engineering bedrock. The thicknesses of these layers are between zero and several tens of meters. Mainly, these layers influence the amplification of seismic waves in a short-period range of less than 2 s.
- Deep sedimentary layers are the layers from the top of the engineering bedrock to the top-surface of a layer with an S-wave velocity of approximately 3 km/s, which is known as the seismic basement. Their thicknesses are between several tens of meters and approximately 34000 m. These layers influence the amplification of seismic waves in a wide-period range (0.1–10 s) that are of interest in the evaluation of broadband ground motion, including long-period components at periods longer than 2 s.
- Crustal structure is the structure deeper than the top-surface of the seismic basement. This structure influences the characteristics of the seismic wave propagation path effect. Because seismic waves propagate in the upper mantle in some cases, depending on epicentral distances of earthquakes considered, it is necessary to include the upper mantle in modeling this structure. Here, this is referred to as the crustal structure.

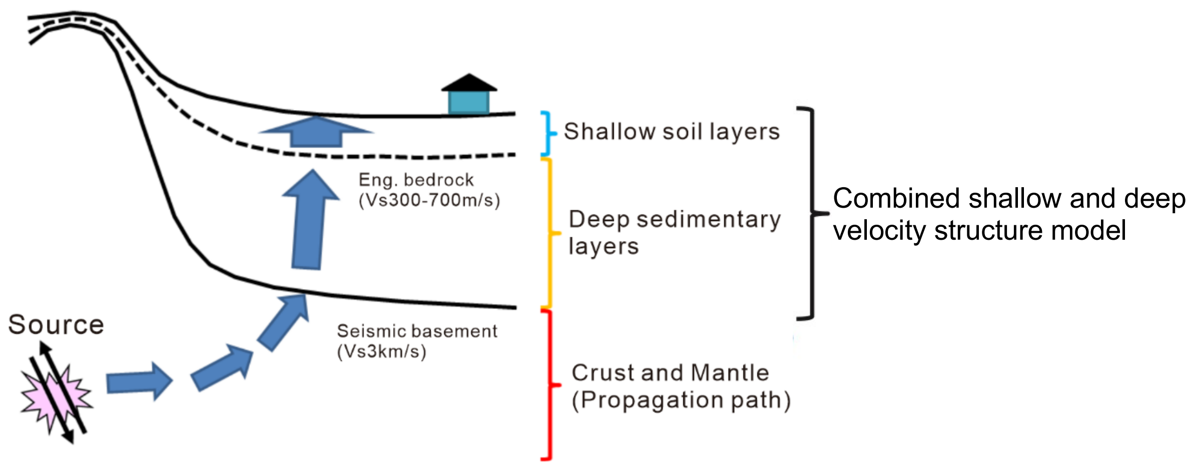

Figure 1-1. Schematic diagram of seismic velocity structure model

[1]The published "Recipe" contains an idea for building a seismic velocity structure model, and a subsurface velocity structure model in whole Japan made with this idea has been released in J-SHIS. For the previous development of seismic velocity structure models, see Appendix 1 (in the following, a reference to the Appendix is denoted by a superscript).

[2]This is a firm layer in which design earthquake ground motion is defined for a structural seismic design in construction engineering fields. Its S-wave velocity varies depending on the kind of designed structures, in a range of 300–700 m/s[A2] in many cases.

[3]This is a bedrock located at the top of the crust, which has an S-wave velocity of approximately (over) 3 km/s (Architectural Institute of Japan, 2009).

Simulation of earthquake ground motion in a wide frequency range is firstly performed for a calculation of ground motion at the top-surface of the engineering bedrock by using a hybrid method considering an amplification of seismic waves in the propagation path from the source fault to the top-surface of the engineering bedrock. By adding the amplification effects caused by the shallow soil layers to the simulated results, it is possible to obtain the earthquake ground motion on the surface of the earth. In the “Japan Integrated Velocity Structure Model (provisional version),” which is the currently available model, the surface of the engineering bedrock is set approximately at the layer with an S-wave velocity of 500–600 m/s. To evaluate a spectrum and waveform of an earthquake ground motion at short periods, the engineering bedrock must be set at shallower layers with a lower S-wave velocity than those of the present ones. Furthermore, earthquake ground motions estimated in many hybrid simulations with matching periods of 0.5–2 s between long- and short-period ground motions are likely to be affected by both the shallow and the deep sedimentary layers. Therefore, it is necessary to connect the shallow domain smoothly with the deep domain for a combined layer model without a velocity gap.

The shallow soil layers model was improved by using a large number of soil data, including boring data. The top layer of the engineering bedrock has an S-wave velocity of approximately 300 m/s in the created model, which has a horizontal resolution of several hundred meters. The combined model from the surface to the seismic basement consists of the advanced shallow soil layers model and the deep sedimentary layers model with considering their smooth connection. The goal of this combined model is evaluating a broadband ground motion in a period range of 0.1 to 10 s on the surface of the engineering bedrock (free engineering bedrock) at depths close to the surface of the earth using the hybrid method.

Figure 1-2 shows the detailed procedures for building the seismic velocity structure models. In Chapter 2, the modeling of the crustal structure, including the upper mantle, is introduced. The modeling of deep sedimentary layers that are deeper than the engineering bedrock is described in Chapter 3. In Chapter 4, the detailed procedure for developing a model of the shallow soil layers is explained. Finally, a “combined model of shallow and deep layers” is built for a usage to evaluate broadband ground motions in Chapter 5.

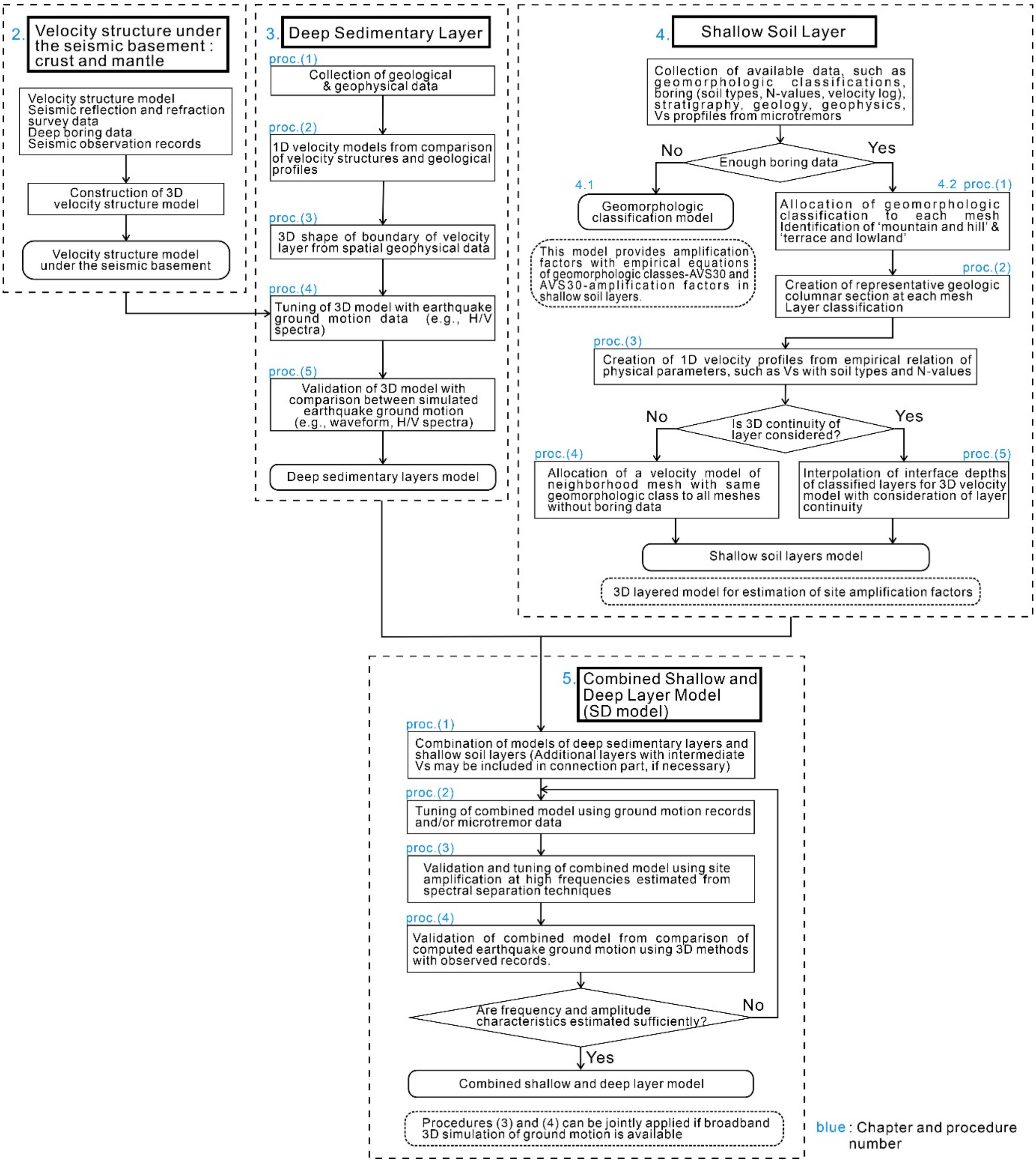

Figure 1-2. Procedure for seismic velocity structure model to evaluate broadband ground motions

2. “Crustal structure”

Seismic velocity models beneath the top surface of the seismic bedrock , including the upper mantle, can be constructed using the velocity structure models estimated with P-wave and S-wave travel times of earthquake records, results of deep boring surveys[A3] such as the MITI (current Ministry of Economy, Trade and Industry) Exploratory Test Wells, and physical property values obtained with seismic reflection and refraction surveys[A4] . Considering the characteristics of the seismic basement from the viewpoint of its physical properties, it is necessary to define the top-surface of the basement with a layer that has an S-wave velocity higher than 3 km/s, which can be found in a wide area. Firstly, a relationship between the basement depth and gravity anomaly values in the area of interest is determined. Then, a distribution of the basement depth is estimated using the relationship and the gravity anomaly map. The Conrad discontinuity (the boundary between the upper and lower parts of the crust) and the Mohorovičić discontinuity are modeled using the results of the seismic surveys. The shapes of these boundaries can be modeled with additional data from a regional gravity anomaly distribution.

As indirect information, one can use crust models used in analyses of hypocenter determinations and source inversions, three-dimensional seismic velocity structures (seismic tomography models), and so on. The S-wave velocities of these models are considered for interpolating the depths of the seismic basement and the velocity structures obtained from the original data, and a three-dimensional velocity structure model beneath the seismic basement are constructed based on the S-wave velocities. When a seismic velocity structure model in an ocean area is needed, the shape of an oceanic plate estimated from seismic surveys and seismic activity studies in the area is also considered. The use of a seismic tomography model can be effective for introducing complex velocity information, such as mantle wedges and subducting slabs, into the crustal and mantle structure model.

In the development of the “Japan Integrated Velocity Structure Model (provisional version),” the surface of the seismic basement was constrained by a distribution pattern of gravity anomaly values with data from boring and geophysical surveys. Furthermore, in modeling the depth to the plate surface in the building of a crustal model deeper than the seismic basement, the results of studies by Sato et al. (2005) and Baba et al. (2006) were incorporated, together with referencing other studies (e.g., Ryoki, 1999; Matsubara et al., 2008). In the crustal model published in J-SHIS, a seismic tomography model described by Matsubara et al. (2008; 2011) (released on the website of the National Research Institute for Earth Science and Disaster Resilience) was used. Furthermore, the crustal structure in the area of the Nansei Islands was modeled with the results obtained by Zhao et al. (1994) on the Conrad and the Mohorovičić discontinuities. Examples of seismic tomography models of the crust and the mantle below the Japanese Archipelago are summarized in the “Publications and Databases” on the website of the Earthquake Research Institute at The University of Tokyo, although the information is slightly old.

Measured gravity (anomaly) data for various regions of Japan were published by the Geological Survey of Japan, which is a part of the National Institute of Advanced Industrial Science and Technology (a DVD version of the Japan Gravity Database published in 2013 can be downloaded), and numerical data were released in a database by Kanazawa University (Honda et al., 2012). The Gravity Database (GALILEO) of the National Institute of Advanced Industrial Science and Technology enables users to specify and view generated plots.

3. “Deep sedimentary layers”

Procedure (1): Collection of geological information and various geophysical data

Existing information sources are collected. These include regional geological maps covering wide areas and various geological cross sections, information about soil profiles obtained by deep boring surveys (borehole observatory for crustal activity), including PS logging[A5], results from various geophysical surveys (seismic reflection and refraction surveys, microtremor surveys, gravity surveys, and electromagnetic surveys), and studies using earthquake ground motion records.

In the geophysical and deep boring surveys, information about the deep sedimentary layers in a large-scale area was also obtained in basic academic researches, such as for earthquake disaster prevention. These data as the fundamental materials for modeling deep sedimentary layers are available in databases containing subsurface data maintained by the National Research Institute for Earth Science and Disaster Resilience and the National Institute of Advanced Industrial Science and Technology. The results of basic geophysical surveys and information about the MITI Exploratory Test Wells of the Japan Oil, Gas, and Metals National Corporation are also available for public purposes, such as natural disaster prevention.

Procedure (2): Estimating one-dimensional structure models[4] by comparing geological profiles with velocity structures

Existing geological maps, geological columnar sections, boring data (particularly data from borehole observatory for crustal activity), and regional geological stratigraphic data are used for one-dimensional models (geological layer model) composed of multiple strata with individual geological classifications. A one-dimensional velocity structure model that corresponds to the above multiple strata is estimated by comparing physical property values, such as P-wave velocities, obtained in various surveys with the geological classifications. When the data are insufficient, or when only geological information is available, a geological layer model is estimated by the geological classifications from available geological data. Then, it is possible to estimate the velocity values from geological classifications. This is done by considering the relationships between the geological classifications and the physical property values established in previous studies, or with existing boring data in the other areas (for example, Suzuki, 1996).

To build a one-dimensional structure model that corresponds to the geological layer model, results such as S-wave velocities from PS loggings and microtremor surveys, densities from density loggings, and results of model analysis using earthquake ground motion records are used. They make it possible to determine the S-wave velocities, densities, and *Q*-values for individual layers considering their P-wave velocity structures. If only P-wave velocities are available, S-wave velocities, densities, and *Q*-values can be derived from empirical and/or theoretical equations with P-wave velocities.

The equation by Gassmann (1951) is an example of the equations available for addressing the relations between physical values. One can estimate an S-wave velocity and a density when a P-wave velocity and a void ratio are specified. Furthermore, empirical equations to convert a P-wave velocity (Vp) to a density (ρ) are also available, such as an equation for a velocity and a density by Ludwig et al. (1970) and an empirical equation of $\rho = 0.31 Vp^{0.25}$ by Gardner et al. (1974). When these theoretical equations and/or empirical equations are used, it is important to confirm their applicable ranges by referring to the original data used to generate the equations.

A simple assumption for the *Q*-values can be used at this stage, such as a value proportional to an S-wave velocity because there is an adjustment of the values as discussed later.

[4]This corresponds to the zero-th degree model (Fujiwara et al., 2006) in the strong ground motion prediction method for earthquakes with specified source faults (“Recipe”).

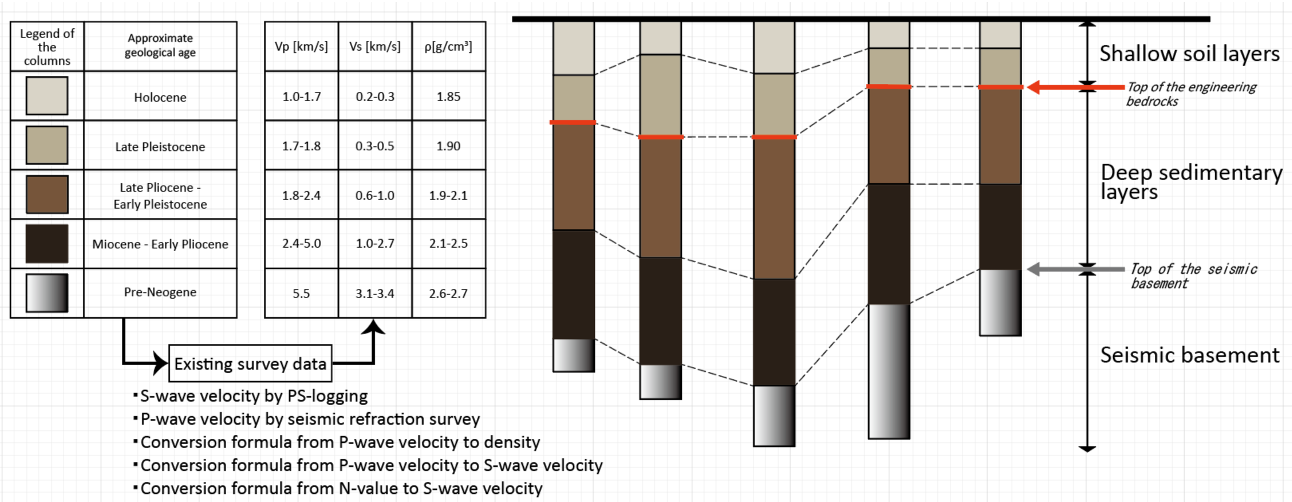

Figure 3-1. Building of one-dimensional structure model by comparing geological profile with velocity structure

Procedure (3): Development of three-dimensional model using one-dimensional profiles

To estimate a three-dimensional velocity structure model using the one-dimensional velocity structure models made in Procedure (2) for individual locations or areas, one categorizes layers with similar geological classifications into the same velocity layer and determine their velocity and thickness. For determining the spatial extent of each layer, spatial interpolation is performed. In this procedure, boundaries of layers with different velocities detected by seismic reflection and refraction surveys, density structures estimated from the gravity anomaly distribution filtered at wavelength components corresponding to the target depth of the structures, existing geological cross sections, geological contour maps, geological ages, and shapes of faults and folding are considered. Considering the three-dimensional distributions of individual geological boundaries, an initial model of the deep sedimentary layers from the top of the engineering bedrock to the top of the seismic basement is built. As the top of the engineering bedrock, a stratum is chosen to have an S-wave velocity used in the definition of the engineering bedrock. In an area where the top of the seismic basement is very shallow, weathering layers near the surface over the basement are also considered.

The final shape of each boundary can be refined through a forward analysis and/or an inversion of observed gravity anomaly data.

The relationship between the gravity anomaly and geologic structures was discussed in detail by Kimura (2002), and their usefulness as geological structure surveys has been mentioned in other works, such as those by Kono and Furuse (1989) and Yamamoto and Shichi (2004).

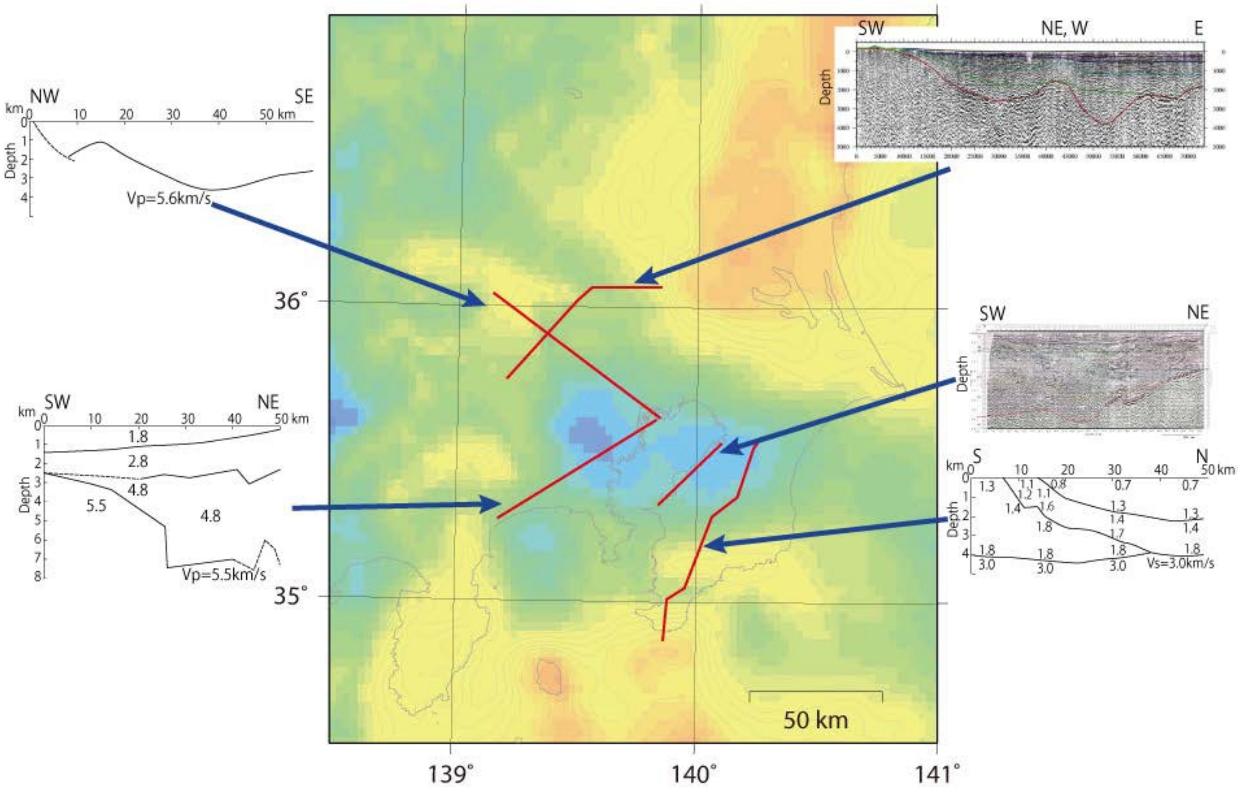

Figure 3-2. Example of an expansion of one-dimensional velocity structure models in horizontal directions using the seismic surveys and the gravity anomaly distribution. The red lines indicate surveying lines of seismic surveys for P-wave velocity images obtained by reflection surveys and boundary shapes obtained by refraction surveys. The color contours show the Bouguer anomaly from the Geological Survey of Japan (2013) with an assumed density of 2.0 g/cm^3. Layer boundaries are developed in the horizontal directions using this information as interpolation data.

Procedure (4): Confirmation of three-dimensional model[5] using earthquake ground motion records

One can estimate S-wave velocities and the depths to boundaries of the deep sedimentary layers using earthquake ground motion records, such as surface wave dispersion, horizontal-to-vertical spectral ratios, and receiver functions. One-dimensional profiles from these results are compared with the three-dimensional sedimentary layer structure model made in Procedure (3), and/or theoretical values calculated from the three-dimensional model are compared with these observed values to validate the three-dimensional model. If necessary, the model is adjusted.

The available methods for estimations of seismic velocity structures using earthquake records are the receiver function method (e.g., Langston, 1979) to detect velocity boundaries in a one-dimensional S-wave velocity structure below an observation station and a spectral ratio (H/V spectrum) of a horizontal component to a vertical component of Rayleigh wave (as the fundamental mode) to estimate a thickness and an S-wave velocity of each layer (e.g., Arai and Tokimatsu, 2004).

Earthquake ground motion data from strong earthquake observation networks densely placed in Japan, such as K-NET and KiK-net by the National Research Institute for Earth Science and Disaster Resilience, are easily obtained from the websites. Furthermore, data from the seismic intensity meters obtained by the Japan Meteorological Agency (JMA) are available to the public through its website and CD-ROMs.

[5]The adjusted model corresponds to the 0.5-th degree model (Fujiwara et al., 2009) in the strong ground motion prediction method for earthquakes with specified source faults (“Recipe”).

Procedure (5): Validation of velocity structure model with simulation of observed earthquake ground motions[6]

A simulation of earthquake ground motions observed at exiting strong motion stations is performed using the estimated three-dimensional structure model of the deep sedimentary layers. Synthetic seismograms calculated with analytical methods based on the elastic wave theory, such as the finite difference method, are compared with the observed ones to confirm whether the simulation reproduces observed amplitudes, appearance of distinct phases, amplification characteristics, and predominant periods. The model can be adjusted (model tuning) to enhance its ability to reproduce the ground motion characteristics. Adjusting the velocities and Q-values through an inversion scheme is recommended.

It is necessary for ground motion simulation to evaluate various characteristics in observed waveforms, such as amplitudes, predominant periods, arrival times of distinct phases, and time-variant characteristics, with the three-dimensional model. In this procedure, it is also important to set a proper Q-value of each layer, which controls the attenuation features of seismic waves. To establish a high-accuracy Q-value model, one must refer information related with the regionality (i.e., geological classification) of the physical properties for a target area[A7]. Although conducting of inversion analyses, or parameter tuning, by modeling of observed waveforms to obtain the proper values of those physical properties would be effective, it is not always possible because of the limitation of data and computing resources. Without tuning the physical properties such as velocities and Q-values, the ability of the velocity model to reproduce the observed waveforms is limited.

It is necessary to complete the modeling of the velocity structure using Procedure (5) for a ground motion prediction considering only the effects of the deep sedimentary layers. However, when one combines the modelds of the shallow soil layers and deep sedimentary layers, it is desirable to conduct the model tuning and the verification with earthquake records after the combination has been done.

4. “Shallow soil layers”

An amplification of earthquake ground motion at short periods (mainly periods less than 2 s) is significantly affected by S-wave velocity structures in the shallow soil layers from the top of the engineering bedrock to the surface of the earth. The principal procedure for modeling shallow soil layers is to build one-dimensional multi-layered velocity structural models to calculate a ground response by collecting surface geological data and boring data from soil surveys. However, a large number of the boring data are required to develop a model with a significant local lateral variation of the shallow soil, which is not rare in actual conditions. Furthermore, it is recommended, in the building of a three-dimensional model by connecting one-dimensional structures from the boring data, not to apply a simple mathematical interpolation. Instead, the continuity of the surface geological condition should be considered, and tuning should be performed by considering S-wave velocity profiles from geophysical surveys, such as microtremor survey. However, the boring data are insufficient to build three-dimensional model in many areas. In this case, one needs to extrapolate information and could get a spatially smooth three-dimensional model. One needs to judge the model appropriateness for applying his frequency range of the seismic waves to be treated and computer resources.

Here, we explain a method using geomorphologic classification model and a method using the boring data for modeling shallow soil layers. Two procedures are introduced for the latter method. One is an interpolation method using geomorphologic classification for an area without the sufficient data, and the other is a detailed method that emphasizes the three-dimensional continuity of the surface geological conditions which is used for the combined model of the shallow and deep layer (hereinafter referred to as “SD model”).

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[6]The adjusted model corresponds to the first-degree model[A6] in the strong ground motion prediction method for earthquakes with specified source faults (“Recipe”).

4.1 Method for building of the geomorphologic classification model

Geomorphologic classification model

The region of interest is discretized into appropriately sized meshes, considering the scales of existing maps, such as terrain maps and soil classification maps. When a mesh contains multiple kinds of the geomorphologic units, we choose a geomorphologic unit that occupies the largest area within the mesh or a geomorphologic unit at the center of the mesh to represent its classification. The representative topographical and geomorphologic units in each mesh are recategorized with the given criteria. For the categorized meshes, the site amplification characteristics are empirically estimated with explanatory variables of an altitude, a slope angle, and a distance from mountains or hills formed in old geological ages.

An AVS30 (the mean S-wave velocity in the top 30 m from the surface), which has a high correlation with the site amplification factors of the shallow soil layers, is estimated using an empirical equation based on PS logging data[A8]. Moreover, the amplification factor is calculated for each geomorphologic classification from the relationships of the AVS30 with the site amplification factor of the peak ground velocity, and so on. This approach can be used to evaluate the site amplification characteristics throughout Japan, including areas with insufficient soil data.

The “site amplification capability map based on the 7.5-arc-second Japan Engineering Geomorphologic Classification Map” (Matsuoka and Wakamatsu, 2008) is a geomorphologic classification model. In this model, an AVS30 is estimated using an empirical equation (Matsuoka et al., 2005) with the geomorphologic classification in the “7.5-arc-second Japan Engineering Geomorphologic Classification Map” (Wakamatsu and Matsuoka, 2003). Then, a site amplification factor is calculated from the AVS30 using an empirical equation of the site amplification factors with the mean S-wave velocities of the shallow soil layers (Fujimoto and Midorikawa, 2006). The “7.5-arc-second Japan Engineering Geomorphologic Classification Map based on the uniform national standards” (Figure 4-1) (Wakamatsu and Matsuoka, 2013), which was made by reconsidering the geomorphologic classifications based on new geomorphological data, is also used in the modeling.

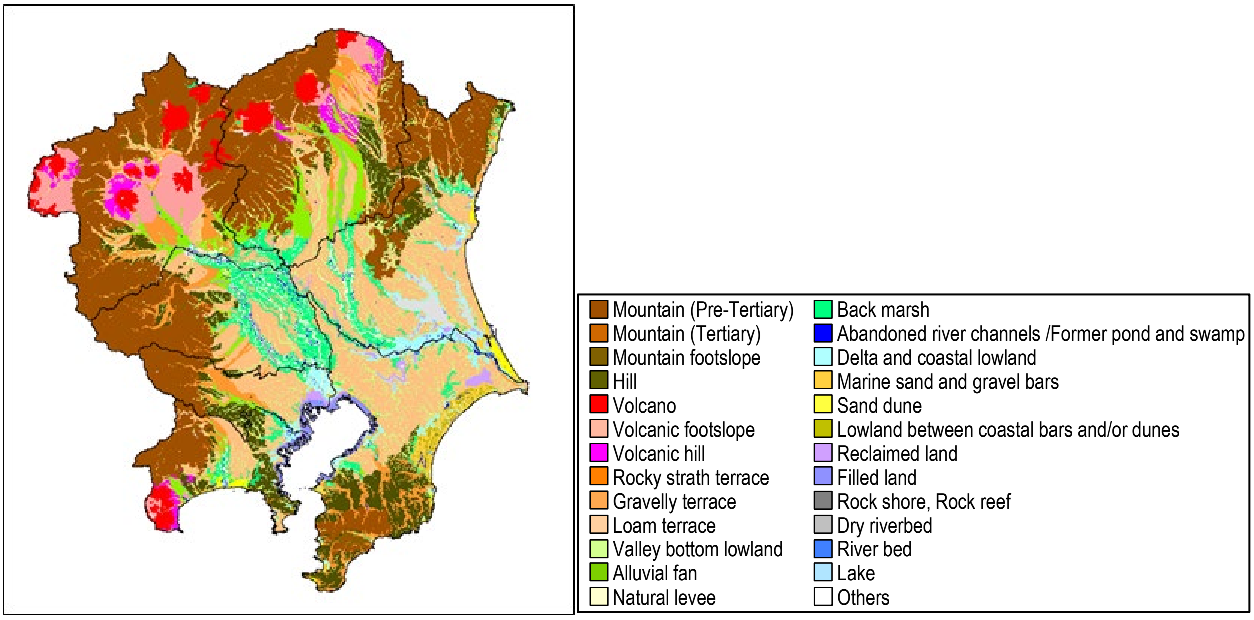

Figure 4-1. Geomorphologic classification map in World Geodetic System with reconsidered geomorphologic classification (Wakamatsu and Matsuoka, 2013)

4.2 Method for building of soil model using boring data

Procedure (1): Assignment of various collected data to each mesh and classification of "mountain/hill" and "plateau/lowland" based on geomorphologic classification data

After a target area is divided into meshes, one marks the positions of available boring data, and assigns attributes, such as the availability of PS logging data, the number of boreholes with their drilling depths, and the geomorphologic classifications to each mesh. One also notes availability of geophysical surveys, such as seismic and microtremor surveys without any boreholes in meshes along surveying lines.

A classification criterion (Wakamatsu et al., 2004) was made by considering geomorphologic terrain classification standards for engineering uses to evaluate shallow soil layer characteristics. The criterion is used to classify the meshes into the classification of "mountain/hill" corresponding to "mountain, a mountain footslope, a hill, a volcano, a volcanic foots-lope, or a volcanic hill", and the classification of "plateau/lowland" defined as the geomorphologic units other than "mountain/hill."

Some local governments and some institutions have attempted to release borehole information to the public. Examples include Kunijiban by the Public Works Research Institute, Geo Station from the National Research Institute for Earth Science and Disaster Resilience, the Research Information Database from the National Institute of Advanced Industrial Science and Technology, and the Nation-wide Electronic Geotechnical Database Systems by the Japanese Geotechnical Society.

To build the shallow soil layers model, the following data are often used: the Digital Japan Basic Map and Fundamental Geospatial Data (provided online by the Geospatial Information Authority of Japan), geology information that can be confirmed using the 1:200,000 Seamless Digital Geological Map of Japan (multiple pieces of geological information are provided online at Geomap Navi from the National Institute of Advanced Industrial Science and Technology), and the "7.5-arc-second Japan Engineering Geomorphologic Classification Map based on the uniform national standards" (Wakamatsu and Matsuoka, 2013), in addition to the information used in the deep sedimentary layers model.

Procedure (2): Estimation of representative columnar section of each mesh and layer classification

A borehole columnar section is estimated to represent each mesh. When a mesh contains multiple boring data, the data with the deepest borehole depth or boring data with PS logging are chosen for "representative columnar section" of the mesh. Alternatively, the representative columnar section can be determined from soil types and the mean of *N*-values[7] at each depth of the boring data in a mesh, after removing low-quality boring data. For this representative columnar section, layers are classified considering the geologic stratigraphy, soil classification, and *N*-values available in the literature.

In a mesh classified as "mountain/hill," it is necessary to set weathering layers and covering layers at a depth of several meters from the surface, because of the low S-wave velocities near the surface resulting from the weathering and stress release in the shallow part of the bedrock and an existence of loam layers. When it is possible to estimate the representative columnar section, the classifications for the weathering layers and the covering layers are determined considering the depth variation of the *N*-value distribution.

The soil type, thickness, and *N*-value vary in horizontal directions, even within a mesh, because of the positions of the available boring data. In some cases, the geomorphologic unit and geologic stratigraphy may be also different in a mesh. Such variation in the soil types and the *N*-values is caused by their spatial extent within a mesh, and one can develop the representative columnar section from the averages of these values (Yasuda et al., 2009).

[7]This value is used as an index of ground strength, and it is defined as the number of drops of a hammer required to make a Standard Penetration Test sampler penetrate to a distance of 300 mm. It is obtained with in-situ test to determine engineering characteristics using a soil sample (Standard Penetration Test).

Furthermore, when the geomorphologic unit, geologic stratigraphy, and layer classification in boreholes within a mesh are different or when layer thicknesses vary significantly in boreholes within a mesh, one may select only highly reliable boring data as representative, or boring data whose geomorphologic unit or geologic stratigraphy occupies the largest area in the mesh. The layers belonging to the weathering classification, including the weathering layers, are classified in the SD model with *N*-values from boring data obtained in "mountain/hill" regions of the Kanto district and nationwide PS logging data (Figure 4-2). In a mesh having the representative columnar section that belongs to the "mountain/hill" classification, three layers are prepared: "covering layer/strong weathering part (*N*-values less than 10)," "weak weathering part (*N*-values between 10 and 50)," and "fresh part (*N*-values of 50 or higher)." If there are no boring data, the layers are classified considering their spatial continuity.

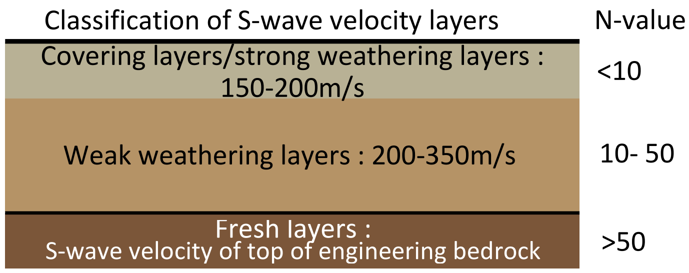

Figure 4-2. Examples of shallow soil classifications of mountains/hills.

Procedure (3): Building of one-dimensional velocity structure model using correlation of physical property values with *N*-values and soil classification

P-wave and S-wave velocities obtained by PS logging are assigned to the layer classifications made in Procedure (2). When no PS logging data are available in a mesh, A velocity value is estimated to each layer using an empirical equation for *N*-value and physical values (mainly S-wave velocity) for each soil type and each geological age, and thereby a one-dimensional velocity structure model is built for each mesh.

Many regression formulas for S-wave velocities from various types of soil data have been proposed in previous investigations. These include regression formulas with explanatory variables of *N*-values and soil types (Imai and Tonouchi, 1982) and *N*-value, soil types, geological ages, and depths (Ohta and Goto, 1976; Masaki, 1984; Fukuwa et al., 1999).

One can build a velocity structure model by using an averaged velocity for each classification based on the representative columnar section without estimating different velocity structures from *N*-values and soil types for each mesh. In the SD model, an S-wave velocity for each layer classification is assigned referring a regression formula of N-values, soil types, and geological ages by the Central Disaster Prevention Council (2001) when the representative columnar section is not based on PS logging data. For the weathering classification of the "mountain/hill" part, S-wave velocities of 150–200 and 200–350 m/s are used for the "covering layer/strong weathering part" and "weak weathering part," respectively, as shown in Figure 4-2. The S-wave velocity of the "fresh part" is set to the same value as the surface of the engineering bedrock. In the method by the Central Disaster Prevention Council (2001), the weathering layer with an S-velocity of 300 m/s is set with a thickness of 10 m for Quaternary volcanoes and Tertiary sedimentary layers and 5 m for the other layers.

Procedure (4): Modeling for meshes without boring data (with weak emphasis of layer continuity on building a three-dimensional model)

For a mesh without boring data, one assigns a one-dimensional velocity structure model of the representative columnar section of one of the neighboring meshes that has the same geomorphologic classification as the geomorphologic features of the largest area in the mesh. When the mesh is surrounded by multiple meshes belonging to the same geomorphologic classification in "plateau/lowland" part, a velocity model of the closest mesh is used for that mesh.

For the mesh belonging to the "mountain/hill" part, one also uses a velocity model of a mesh with the same geomorphologic classification. However, the surface geological condition can be also considered, because the thickness of the weathering layers varies depending on the surface geology.

In a region without any boring data, the same one-dimensional model may spread widely. However, the resultant three-dimensional model becomes close to the one-dimensional multi-layered model because the layer structure models are different for the geomorphologic classifications of the meshes. Although the accuracy of the three-dimensional model depends on the number of the boring data, this approach is widely used because of the easy modeling work (the left panel of Figure 4-3).

Procedure (5): Modeling for meshes without boring data (with strong emphasis on layer continuity for building a three-dimensional model)

The depths of each layer boundary of the one-dimensional velocity structure models made in Procedure (3) are interpolated for meshes without any boring data using the information of neighboring meshes with boring data. In this step, the spatial continuity of the layers is considered referring to the topographical and geological characteristics.

Because an important boundary of the physical properties can be identified using data from geophysical surveys for the shallow soil layers, it is important to perform additional microtremor observations and geophysical surveys at locations without boring data. Microtremor observations can be used to determine an S-wave velocity structure to tune the layer thicknesses. The data from the geophysical surveys can provide spatial information to interpolate the shape of the layer boundaries of the one-dimensional velocity structure models into the horizontal directions (to develop a three-dimensional velocity model). Moreover, for an interpolation of the one-dimensional velocity structures, one can calculate interpolated values in the entire target area with a kriging method, an inverse distance weighting interpolation method, and a spline function method as a surface model, using altitude values of the layer boundaries that have been set in the representative columnar section for each mesh. It is necessary to consider sufficiently the spatial distribution ranges of the layer interfaces and their regional boundaries. For example, the distribution of the alluvium layers is limited within the lowland regions, and the distribution of the loam layers is limited within the regions belonging to the plateaus. Therefore, a significant irregularity in the top-surface of the engineering bedrock may be generated in the regional boundary of the areas between “mountain/hill” and “plateau/lowland” because of the geological differences. It is necessary to express the shape of the connecting part of these areas with a consideration of an accuracy corresponding to the adopted mesh size.

Two approaches are available to interpolate a velocity value for each layer classification in meshes without boring data. One is a method in which the velocities are obtained directly by an interpolation of the velocity values of the corresponding layer classifications in the representative columnar sections of the neighboring meshes. In the other method, an S-wave velocity is estimated from an empirical formula between a soil classification and a *N*-value which is interpolated from a soil types and *N*-values at the neighboring meshes (Kimura et al., 2014).

Because the SD model is established to reproduce an observed broadband ground motion, the shallow soil layers model is built using this advanced three-dimensional approach (the right panel of Figure 4-3). Therefore, a large number of the boring data were collected, and many observations of microtremors were also conducted to obtain the local variation of the layer boundary shapes accurately.

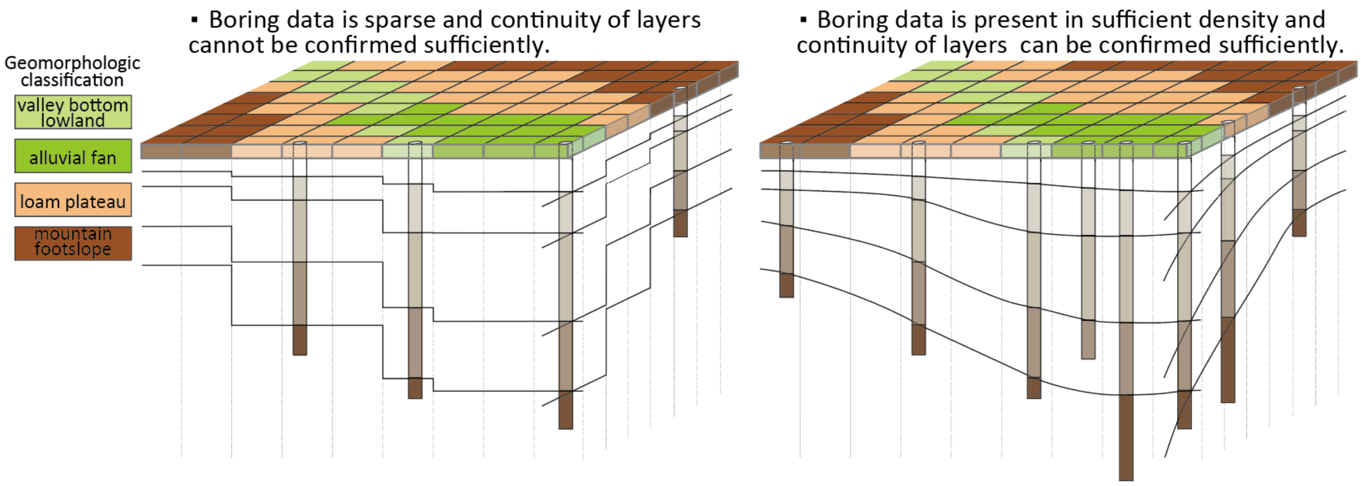

Figure 4-3. Differences in approaches for shallow modeling in a mesh with and without boring data: approach with weak emphasis of layer continuity on building a three-dimensional model (left), which generates a block-shaped model having constant depths to layer boundaries in meshes belonging to same geomorphologic classification, and approach with strong emphasis of layer continuity on building a three-dimensional model (right), in which the depths to boundaries are modeled with consideration of the spatial information for smooth connection of the layer classifications of neighboring meshes without boring data.

5. Building of "SD model"

A SD model from a combination of the shallow and the deep layers is built for evaluating broadband ground motion using the shallow soil layers model and the deep sedimentary layers model. The effects of the nonlinearity amplification in the shallow soil layers are not considered in the present ground motion prediction using the SD model. The shallow part of the SD model is used to calculate the linear amplification. The evaluation of the site amplification characteristics with methods including the nonlinear soil effects is necessary to consider the variation of earthquake ground motion features caused by the nonlinear behavior of the soil.

When the shallow soil layers model is built using data in boring that penetrates, in general, to a depth of the stratum with an *N*-value of 50, one can set the top surface of the engineering bedrock with an *N*-value of 50 and an S-wave velocity of 300 to 400 m/s as the bottom layer of the shallow soil layers model, referring to the *N*-values. However, the top of the deep sedimentary layers model is often set to be near a stratum with an S-wave velocity of 500 to 700 m/s considering various types of information. Here, the procedure to build the SD model is explained. By this procedure the two models explained in Chapters 3 and 4 are connected without an artificial discontinuity between them, and the combined model is improved with the results of earthquake ground motion observations and microtremor surveys for the SD model.

Procedure (1): Connection of the shallow soil layers model and the deep sedimentary layers model and its adjustment

The shallow soil layers model is connected to the deep sedimentary layers model directly when the difference of the S-wave velocities (or the impedance contrast) is small between the bottom of the shallow soil layers model and the top of the deep sedimentary layers model. When the difference is large, intermediate layers having intermediate S-wave velocities of 400 to 500 m/s are added between the two models to prevent an artificial discontinuity as a result of the connection. The thicknesses and the velocities of the additional intermediate layers are set by referring to existing data, such as PS logging data from deep boring surveys. An artificial discontinuity should not be also generated three-dimensionally with an adjustment of the thicknesses of the additional layers considering the regional tendency of the depths to the deep sedimentary layers and the top of the seismic basement in a wide region including a basin and surrounding mountain areas.

The intermediate layers are set with a careful consideration of the three-dimensional shapes of the interfaces and thicknesses of the connecting part between the shallow soil layers model and the deep sedimentary layers model (Figure 5-1).

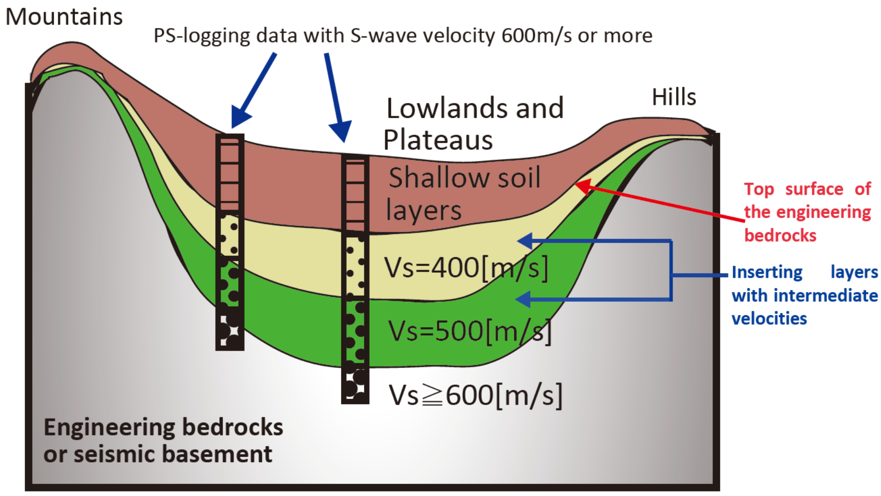

Figure 5-1. Image of setting additional layers with intermediate velocities.
The three-dimensional shapes of the top surfaces of the engineering bedrock and the seismic basement are considered in setting the thicknesses and the velocities of the additional layers with intermediate S-wave velocities by referring to PS logging data from deep boring surveys.

Procedure (2): Adjustment of the SD model using earthquake records and microtremor data

Earthquake ground motion records and microtremor data are collected to adjust the SD model made in Procedure (1). The SD model is tuned using information on seismic velocity structures beneath the observation points extracted from the earthquake records and microtremor data. If there is difficulty in tuning the model, one must collect additional data and perform microtremor observations.

The thicknesses and the velocities of the layers in the SD model are tuned, including the additional intermediate layers applied in Procedure (1). One can reconsider the modeling of the connecting part if necessary.

To extract information on seismic velocity structures from earthquake records and microtremor observation data, various analysis methods are available, such as H/V spectrum, which is the Fourier spectrum ratio of horizontal motion to vertical motion of earthquake records (called the “R/V spectrum” when applied to the Rayleigh wave part), H/V spectrum of microtremor data, spectral ratio of a seismic record on the surface to a borehole record in a vertical array , and surface wave phase velocity from a microtremor array survey. For example, one can determine an S-wave velocity and layer thickness from comparison of the peak period and shape of the observed H/V spectrum of microtremor data at a single point with the theoretical ellipticity of Rayleigh waves with an assumption of a homogeneous layered velocity structure. It is also often applied to determine an S-wave velocity and layer thickness with an inverse analysis of surface-wave phase velocity obtained from microtremor array records. A joint inversion analysis in which multiple observed data are simultaneously analyzed is also an effective method for the model tuning.

Procedure (3): Validation and adjustment of the SD model with short-period empirical site effect

After estimating site effects at short periods (for example, periods of less than 2 s) by means of an empirical method using ground motion records from moderate to small earthquakes, the estimated site effects are compared with the calculated ones using a theoretical method to validate the SD model adjusted in Procedure (2). When there is difficulty in reproducing the site effects, it is necessary to return to Procedure (2) for readjustment.

Spectral separation inversion (for example, Iwata and Irikura, 1986) can be used as an evaluation method for the empirical site effects at short periods. *Q*-values for the soil layers and the propagation path can also be validated (for example, Fukushima and Midorikawa, 1994; Yamanaka et al., 2009). The one-dimensional elastic wave propagation theory is mainly used for the one-dimensional theoretical evaluation of the site effects.

Procedure (4): Comparison with reproduction of observed earthquake ground motion using a three-dimensional calculation method

The validated or adjusted SD model in Procedure (3) is used to calculate earthquake ground motions for moderate to small earthquakes by means of a theoretical method based on the elastic wave theory, such as the finite difference or finite element methods, considering the influence of the three-dimensional seismic velocity structure. Then, the overall characteristics of the observed and calculated waveforms, such as P-S travel times, amplitudes, peak periods, spectral shapes, time-variant characteristics, and durations, are compared. If there is a difficulty in the reproducibility, one must return to Procedure (2) to adjust the SD model again.

Depending on the purpose of ground motion simulation, a comparison of ground motions on the surface of the earth and the top-surface of the engineering bedrock is performed. For the comparison of the motions on the top-surface of the engineering bedrock, the shallow soil layers are deleted from the SD model established in Procedure (3), and the modified model is used in the theoretical calculations. Besides, earthquake ground motion on the surface of the engineering bedrock is estimated from the observed waveforms using correction factors calculated from the one-dimensional soil amplification of the shallow soil layers model that has been removed in the model used in the three-dimensional simulation.

It may be possible to perform the validations simultaneously in Procedures (3) and (4) to compare the broadband ground motion calculated by hybrid methods.

Appendices

1. Previous developments in building of seismic velocity structure models

The Headquarters for Earthquake Research Promotion summarized the procedures for building a seismic velocity structure model by referring to Koketsu et al. (2009), Fujiwara et al. (2009), and so on. These procedures were published in the strong ground motion prediction method for earthquakes with specified source faults ("Recipe"). The sedimentary layer model for the wide area made with the "Recipe" was published in J-SHIS by the National Research Institute for Earth Science and Disaster Resilience in 2010. Furthermore, the "Japan Integrated Velocity Structure Model (provisional version)" and its background idea for the model building for long-period ground motion predictions were released in "Long-period ground motion hazard map" (prototype version in 2012).

2. Engineering bedrock

This is defined as a firm soil layer that is used as the position for setting predicted earthquake ground motion in building design in construction engineering fields, such as building engineering and civil engineering. Its S-wave velocity varies depending on the kind of man-made structures and soil conditions. However, it is within a range of 300 to 700 m/s in many cases (Architectural Institute of Japan, 2009). Furthermore, the stratum with an *N*-value of more than 50 is often considered as the top of the deep sedimentary layers. Careful attention must be paid to determine how deep the surface of the engineering bedrock should be set, because a stratum with an *N*-value of less than 50 may appear below the above-defined engineering bedrock.

3. Seismic reflection and refraction surveys

The seismic survey methods are used to explore seismic velocity structures from surface observation of ground vibration generated by a controlled seismic source (or an artificial seismic source). Physical phenomena of elastic seismic wave propagating to the boundary of geological layers with different physical properties, such as refraction and reflection are utilized in the methods. There are two survey methods. A seismic refraction survey captures the wave propagation velocities and attenuation factors mainly by using refracted waves, whereas a seismic reflection survey captures the distribution and shapes of reflection interfaces using reflected waves.

4. Deep boring surveys

MITI exploratory test wells were conducted to discover oil and gas fields on land. There are also examples of deep boring surveys down to 3000 m in the Kashiwazaki deep ground motion observation project. In sea areas, boring surveys have been conducted with the research vessel "Chikyu" (which drilled down to approximately 2200 m in the Nankai Trough) as an example.

5. PS logging

Velocity logging is a survey method in which a velocity structure is deduced by utilizing a borehole to measure the elastic waves propagating in soil. The elastic wave velocities that can be obtained include those for P-waves and S-waves. When both velocities are obtained, it is called "PS logging."

6. First-degree model

This is a seismic velocity structure model for an assumed Tokai earthquake and Tonankai earthquake ("Long-period ground motion hazard map," Headquarters for Earthquake Research Promotion, 2009); "Japan Integrated Velocity Structure Model (provisional version)"; ("Long- period ground motion hazard map," Headquarters for Earthquake Research Promotion, 2012; Koketsu et al., 2008, 2012), which can be found on the website of the Headquarters for Earthquake Research Promotion (https://www.jishin.go.jp/evaluation/seismic_hazard_map/lpshm/).

7. Important notice about ground motion simulations for moderate to small earthquakes

Even if one uses a velocity model revised by repeated verification through the reproductions of earthquake ground motions of moderate to small earthquakes, discrepancies between the observed motions and the calculated ones may be found for an earthquake that was not used for the verification. In such cases, one must be careful with a consideration of non-neglectable effects due to the hypocenter parameters, the crustal structures and anisotropy of the propagation path from the hypocenter of each earthquake to an observation point as factors that are not related with the characteristics of the shallow soil layers and the deep sedimentary layers.

8. Empirical equations for AVS30 (mean S-wave velocity from the surface of the earth to a depth of 30 m)

The followings are examples of the empirical equations for an AVS30 and a site amplification factor.

- Matsuoka and Midorikawa (1994): A mean S-wave velocity of soil layers was empirically obtained from Digital National Land Information data which include the topographical classifications and altitudes in the Kanto region. The empirical equation is mainly applicable to the Kanto region.
- Midorikawa and Matsuoka (1995): The relationship between an AVS30 and an amplification factor for the peak ground velocities of strong earthquake records was obtained. Then, an AVS30 was generated from the empirical equation with the topography, altitude and distance from a river on the basis of the topographic information, soil data and so on.
- Matsuoka et al. (2005): An empirical method for the AVS30s was proposed with a consideration of altitudes, slope angles, and distances from mountains and hills formed in the old geological ages, considering the significant differences of the AVS30s in each geomorphologic classification caused by the soil formation processes and sedimentary environments. The empirical equation was applied for the 7.5-arc-second Japan Engineering Geomorphologic Classification Map.

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