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SUBSURFACE VELOCITY STRUCTURE MODELS IN TOKAI RESION, JAPAN, FOR BROADBAND STRONG GROUND MOTION EVALUATION

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Abstract

For sophistication of strong ground motion evaluation in terms of disaster mitigation, one of the principal issues is to model subsurface velocity structures in sedimentary layers on the seismic bedrock with S-wave velocity of about 3.0 km/s so that characteristics of earthquake ground motions can be reproduced in the broadband range 0.1 Hz to 10 Hz. Above all, it is dispensable to comprehensively model shallow and deep velocity structures which have been separately modeled before. In recent years, subsurface velocity structures have been comprehensively modeled in sedimentary layers for a few regions of Japan, in a national project. These models were constructed in accordance with the subsurface velocity structure modeling scheme [1].

The modeling procedure can be briefly described as follows. To begin with, initial velocity structure models were constructed based on a great number of existing bore-hole data, geological information and models constructed in the past investigations, etc. Next, they were improved based on results of microtremor explorations which had been conducted with spatial density and homogeneity in the national project and which had been performed in the past investigations. At the same time, they were also improved based on records of earthquake ground motions obtained at seismic stations in the region.

As a whole, it was found that the improved models had more or less different velocity structures and amplification factors in some areas, in comparison to the conventional models. In particular, for reducing uncertainty in wide-area modeling, it can be essential to obtain array microtremor data at the measurement points with spatial dense and uniformity. Also, for earthquake disaster mitigation, it is important to consider not only but amplification factors also period characteristics. Furthermore, with respect to modeling shallow velocity structures, it was suggested that array microtremor data were effective in addition to borehole ones to evaluate the engineering basement more accurately.

This paper will report on subsurface velocity structures modeled from the seismic bedrock to the ground surface for the Tokai region, central Japan. It is concerned that this region will be suffered from serious damage due to a Nankai Trough megathrust earthquake in the future [2]. It is expected that the subsurface velocity structures can be used as a basic information in a damage estimation due to a mega earthquake of the national and a local government.

Keywords: subsurface velocity structure, shallow-deep integrated model, Tokai region, strong ground motion

1. Introduction

For enhancement of strong ground motion evaluation in terms of earthquake disaster mitigation, it is one of the important issues to model subsurface velocity structures in sedimentary layers on the seismic bedrock with hardness compared to S-wave velocity of around 3.0 km/s so that earthquake ground motions can be accurately evaluated in the broadband range 0.1 s to 10 s. Therefore, it is indispensable to comprehensively model shallow velocity structures and deep ones in sedimentary layers so that earthquake observation records can be reproduced in the target range. Here, shallow structures can indicate sedimentary layers from the engineering basement with hardness compared to S-wave velocity from 300 to 700 m/s to the ground surface, and deep structures can indicate sedimentary layers from the seismic bedrock to the engineering basement.

In recent years, subsurface velocity structure models have been constructed from the seismic bedrock to the ground surface for the Kanto region [3][4], which will be suffered from severe damage due to a Tokyo inland earthquake, for the Tokai region [4][5], which will have severe damage due to a Nankai Trough mega earthquake, and for the Kumamoto region [6], southwestern Japan, which had severe damage due to the 2016 Kumamoto Earthquake, in a national project of Japan. These were constructed according to the subsurface velocity structure modeling scheme published by a government agency, the Headquarters for Earthquake Research Promotion [1].

As a whole, it was found that there were some differences between the improved models and the conventional models or J-SHIS ver.2 [7] in terms of velocity structures and amplification factors. Especially, to remove spatial uncertainty as much as possible in modeling of the wide area, it can be meaningful to obtain array microtremor exploration data at the measurement points with spatial dense and homogeneity. Also, for earthquake disaster mitigation, it is essential to take into consideration not only amplification factors but also period characteristics with respect to the ground-motion characteristics. Furthermore, for shallow velocity structures, it is suggested that it can be effective to use array microtremor exploration data in addition to bore-hole data, P-S logging ones and so on for more appropriate evaluation of the depth of the engineering basement.

In this paper, from a qualitative standpoint, characteristics of subsurface velocity structure models will be principally reported about the Tokai region, which have been constructed in the national project. To begin with, overview of subsurface velocity structure modelling scheme will be described. In the next, characteristics of improved models in the Tokai region will be described with respect to the depth of typical velocity layers and ground-motion characteristics and so on.

2. Subsurface velocity structure modeling scheme

The subsurface velocity structures were modeled for the Tokai region based on the modeling scheme [1] as follows (See Fig. 1). The modeling procedure focuses on sedimentary layers from the seismic bedrock to the ground surface. In the national project, these models were constructed in 7.5-arc-second grid, or around 250-meter one.

To begin with, initial deep S-wave velocity structures were modeled based on the existing velocity structures modeled in the past national investigations, results of previous array microtremor explorations and those of deep boring surveys and P-S loggings, which had ever been collected from kinds of organizations. Meanwhile, initial shallow S-wave velocity structures were modeled based on topographic informaiton, surface geological information, a great number of bore-hole data and P-S logging ones, which had ever been collected from kinds of organizations. Then, through integrating initial deep structures and initial shallow ones in the engineering basement, initial S-wave velocity structure models were constructed from the top surface of seismic bedrock to the ground surface.

At the same time, a lot of ground-motion records were obtained through spatially dense and homogeneous array microtremor measurements in the plains and earthquake observations at seismic stations in the target region. Based on ground-motion characteristics such as disperse curves and H/V or R/V spectral

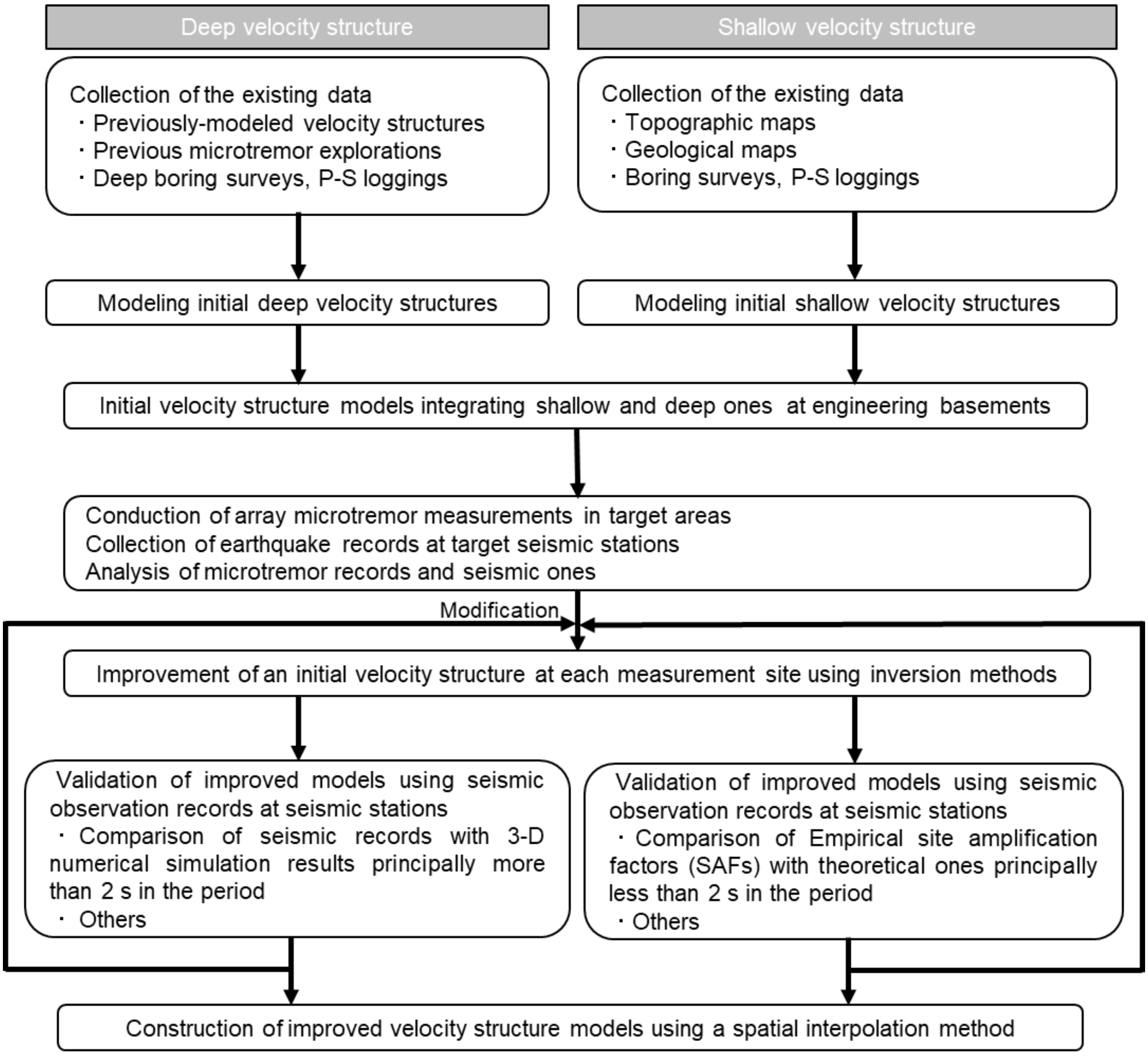

Fig. 1 – The subsurface velocity structure modeling procedure for the Tokai region [1]

ratios obtained from microtremor or seismic records, each initial one-dimensional S-wave velocity structure has been improved at each measurement point using inversion methods. By importing these results into the initial S-wave velocity structure models, they have been improved with a spatial interpolation method from the top surface of seismic bedrock to the ground surface in the region.

In the end, subsurface velocity structures modeled by the procedure mentioned above were validated using earthquake observation records at seismic stations. In this study, empirical site amplification factors were compared with theoretical ones based on the improved velocity structures by means of one-dimensional multiple reflection theory in the range shorter than 2.0 s for shallow velocity structures. And, a spectral ratio of the ground surface records to the bore-hole ones observed at KiK-net stations were compared with theoretical amplification factors based on the improved velocity structures in the range kind of longer than 2.0 s. Also, earthquake observation records will be compared with results of three-dimensional numerical simulation based on the improved velocity structures in the range longer than 2.0 s for deep velocity structures. If there are crucial errors, it is necessary to check the details and modify such velocity structures through the inversion analyses.

3. Validation of the improved velocity structure models

For validation of the improved velocity structures modeled based on the subsurface velocity structure modeling scheme, in this paper, the theoretical amplification factors based on the improved models were compared with the spectral ratios of the ground surface records to the bore-hole ones observed at some KiK-net stations. By the way, we can see validation using empirical site amplification factors based on the observation records at the seismic stations in the reference [5].

Earthquake observation records were collected under the condition of medium and small scale earthquakes which occurred in these twenty years, that of the Japan seismic intensity scale of more than 2.0 for removing records with a poor S/N ratio and that of the peak ground acceleration of less than 100 cm/s^2 for removing records with nonlinear behavior in the surface soil. Meanwhile, the theoretical amplification factors were obtained based on the improved velocity structures by means of 1-dimentinal multiple reflection theory.

Fig. 2 indicates location of KiK-net stations in the Tokai region. The target stations were basically selected in terraces and lowlands because the improved models were constructed for plains. And Fig. 3 indicates comparison of observed and theoretical amplification factors with respect to time periods for the target KiK-net stations. It can be seen that a theoretical amplification factor based on the improved model (a red line) is generally consistent with that based on the PS logging (a black line) at each station. Also, with respect to the first-order and the second-order peak period, it can be seen that theoretical amplification factor based on the improved model (a red line) is generally consistent with the spectral ratio of the ground surface to the bottom of a borehole with respect to records observed at each station (a blue line). According to velocity structures of KiK-net stations, it seems that the bottom of a borehole each target station exists in the layer deeper than the engineering bedrock and shallower than the seismic bedrock. Therefore, it is suggested that the improved models can be appropriate to some extent in the period range sort of longer than 2.0 s although there are few target stations.

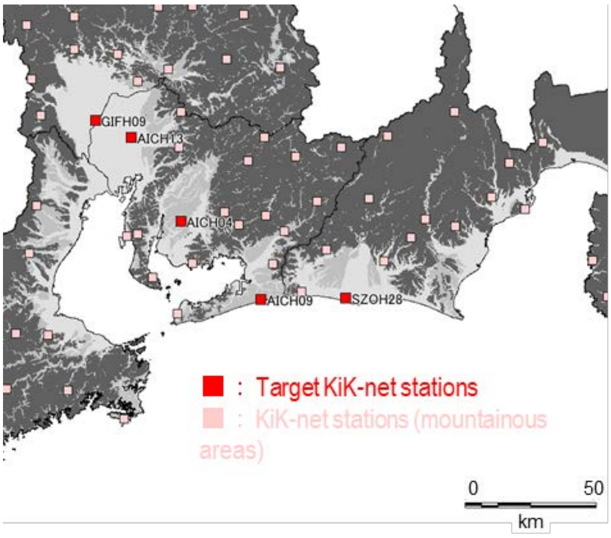

Fig. 2 – KiK-net stations in the Tokai region. A red square shows a target station for validation. A pale pink square shows a station in a mountainous area.

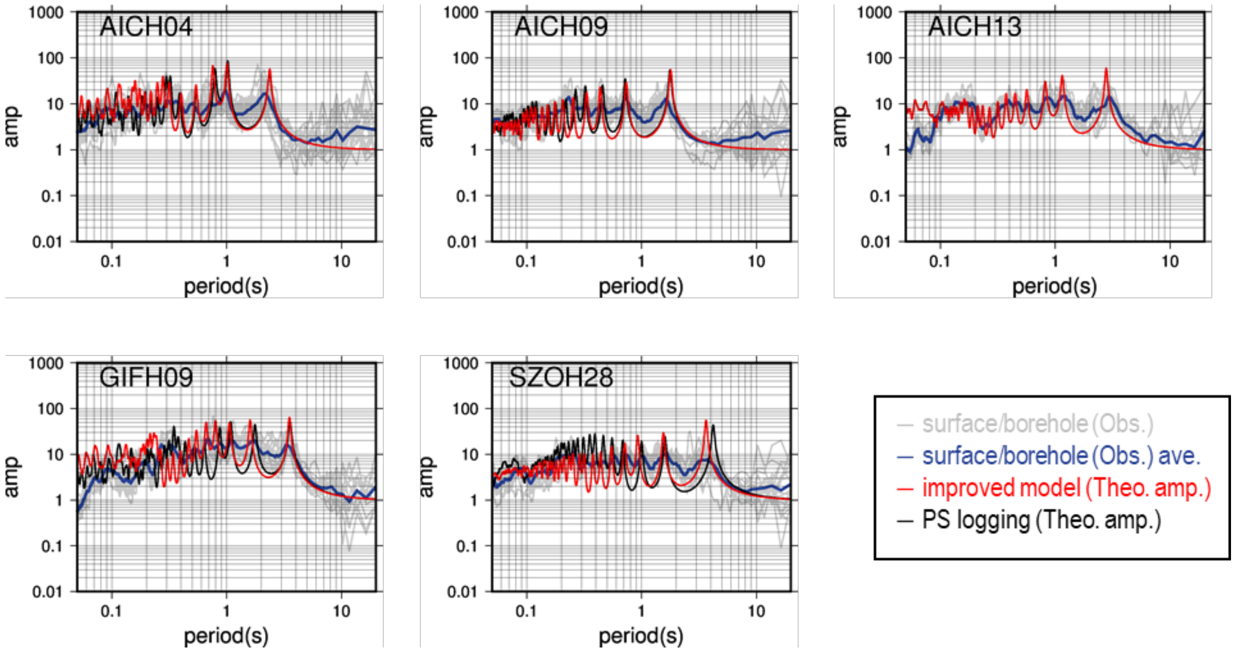

Fig. 3 – Comparison of amplification factors with respect to time periods for target KiK-net stations. Gray solid lines show observed spectral ratios of the surface ground to the bottom of borehole. A blue line shows observed average one. A red line shows theoretical amplification factor from the bottom of borehole to the ground surface based on the improved S-wave velocity structure. A black line shows theoretical one using S-wave velocity structure based on the PS logging.

4. Characteristics of the improved velocity structure models

Fig. 4 shows the Japan engineering geomorphologic classification map [8] in the Tokai region. The Tokai region, central Japan, has one of the major metropolitan areas and one of the major plains in Japan. It is the Nobi plain with some major rivers in the west of the Tokai region. Also, there are some medium and small-scale plains with major rivers, and there are vast mountainous, volcanic and hill areas.

4.1 Shallow velocity structure models

Fig .5 shows distribution maps on the depth of the top surface of the engineering basement, which indicates the Vs350 m/s layer here, in the Nobi plain. On the initial model, the engineering basement generally appears to be deeper toward the west and to have small change in the north-south direction. Meanwhile, on the improved model, the engineering basement appears to be deeper toward the southwest direction where the three or four major rivers run. It can be considered that the difference reflects the effect of a spatial interpolation on the initial model because borehole points and PS logging ones are sparse in the northern area of the Nobi plain while they are dense in the southern area.

Fig .6 shows cross-section views along the north-south survey line in the Nobi plain as shown in Fig. 5. On the improved model, the top surface of the Vs350 m/s layer seems to be deeper toward the south direction corresponding to Fig. 5, unlike the initial model. By the way, the red solid line in the altitude range of -20m to -50m represents the bottom surface of alluvial deposits (Holocene).

Fig. 7 shows distribution maps on theoretical amplification factors of the ground surface to the Vs400 m/s layer based on the improved velocity structures at some typical time periods. A theoretical amplification factor was evaluated by one-dimensional multiple reflection method. It is found that the areas with amplification factors more than two make a difference depending on each time period. At the period of 0.5 s, the areas with amplification factors more than two can be seen even in the medium and small-scale plains besides the surrounding area of the Nobi plain. Meanwhile, at the period of 1.0 s, larger amplification factors

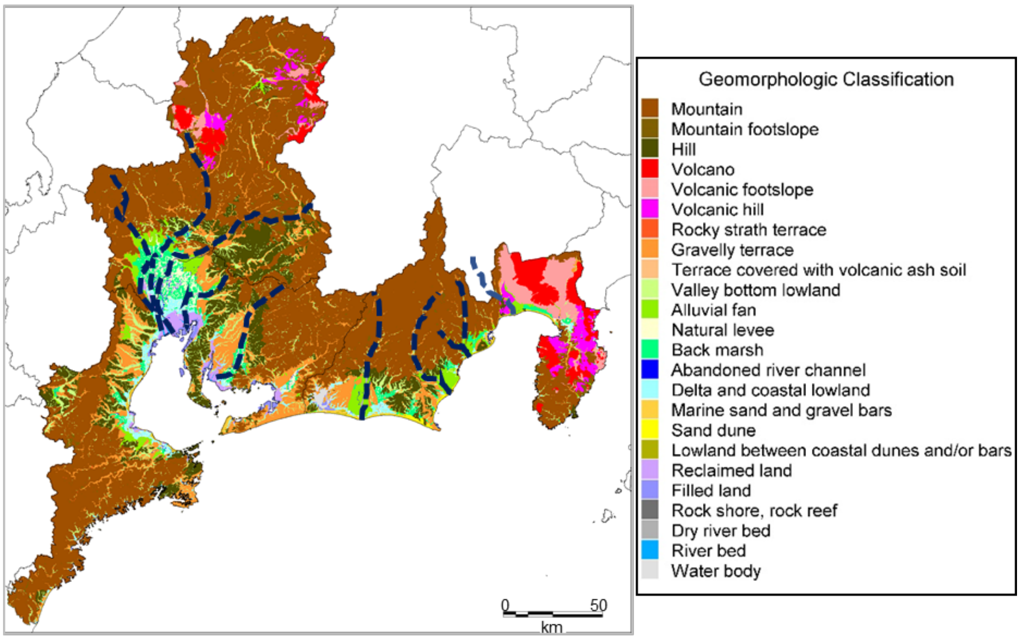

Fig. 4 – The Japan engineering geomorphologic classification map [8] in the Tokai region. A navy dashed line represents a major river running in each typical plain

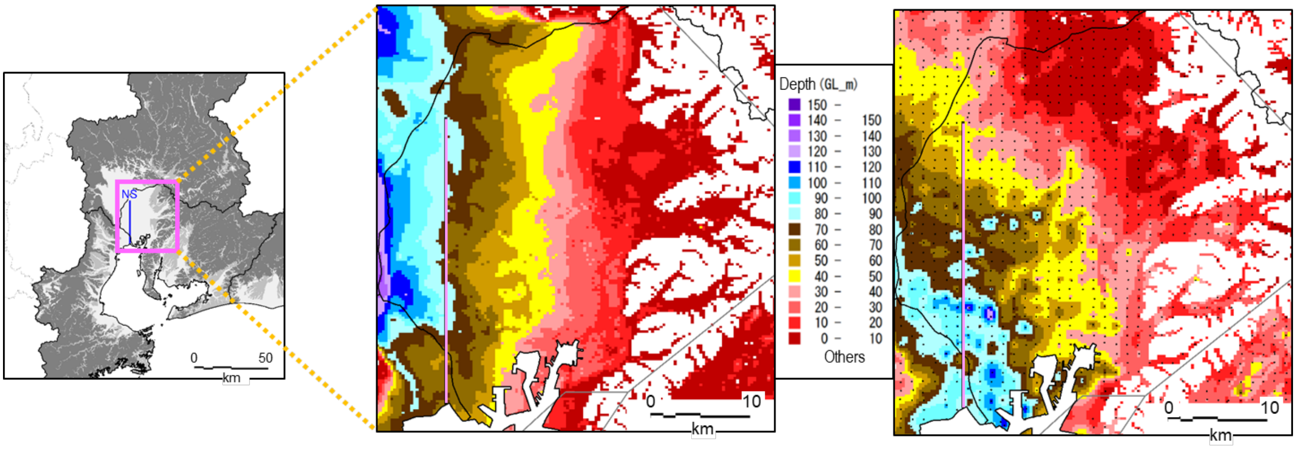

Fig. 5 – Distribution maps on the depth of the top surface of the engineering basement (here, the Vs350 m/s layer) in the Nobi plain. The left one shows the initial velocity structure model and the right one shows the improved one.

appear to spread to the wider area in the Nobi plain. Strong motion around this period can have an influence on damage for houses and low-rise buildings. This result suggests that it can be very essential to evaluate ground-motion characteristics considering the period characteristics.

4.2 Deep velocity structure models

Fig. 8 shows a distribution map on the depth of the top surface of the seismic bedrock or the Vs3.0 km/s layer in the right and location of the survey lines for cross-section views shown in Fig. 9 in the left in the

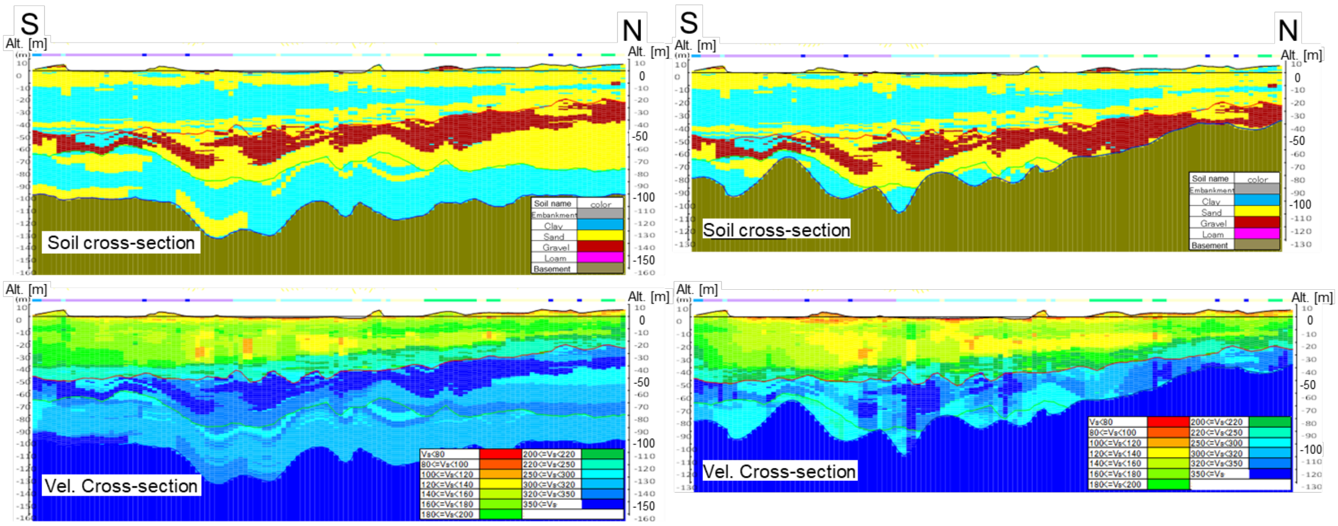

Fig. 6 –Cross-section views along the north-south survey line (see Fig. 5) in the Nobi plain. The left shows the initial model and the rigth shows the improved one. The top shows the soil classification and the bottom shows S-wave velocity structures. With respect to the S-wave velocity, while a warmer color indicates smaller velocity (a red part in the legend means less than Vs80 m/s), a colder color indicates larger velocity (a blue part in the legend means more than Vs350 m/s).

Tokai region. As seen in the right figure, the Nobi plain has the depth of around 2.0 km. In addition, there are some areas with the depth of around 3.5 km in the eastern areas of the Tokai region.

Fig 9 shows cross-section views along the three survey lines drawn in the left of Fig. 8. Comparing the initial model with the improved model, when there is small change in the velocity structures as the cross-section view along the line-1, the initial model could be built with a lot of geological and geophysical data. Meanwhile, when there is large change in the velocity structures as the cross-section view along the line-3, the initial model could be built with few geological and geophysical data. Also, as shown in cross-section views along the line-1 and line-2, an S-wave velocity contrast appears to be so large at the top surface of the seismic bedrock in the Nobi plain. In concrete terms, there exists the Vs1.3 km/s to Vs1.5 km/s layer or the Vs1.1 km/s to Vs1.2 km/s layer on the seismic bedrock. This suggests that an earthquake ground motion can be very large in a certain time period range.

Fig. 10 shows distribution maps on theoretical amplification factors of the ground surface to the Vs3.2 km/s layer based on the improved velocity structures at some typical time periods. A theoretical amplification factor was evaluated by one-dimensional multiple reflection method. It is found that the areas with larger amplification factors make a difference depending on each time period. At the period of 2.0 s, there exists many areas with amplification factors more than three even in the medium and small-scale plains. The areas with larger amplification factors appear to decrease as the period becomes longer. With respect to the Nobi plain, especially in the southern area, there exists the areas with larger amplification factors in the broad period range. As seen in Fig. 9, it can be considered that this is because these areas have a larger impedance contrast of sedimentary layers to the seismic bedrock in comparion to other areas. Strong ground motion around these period can have significant influence on damage for mid and high-rise buildings, skiscraperes and engineering structures. This result suggests that it can be very essential to evaluate earthquake ground-motion characteristics considering the period characteristics.

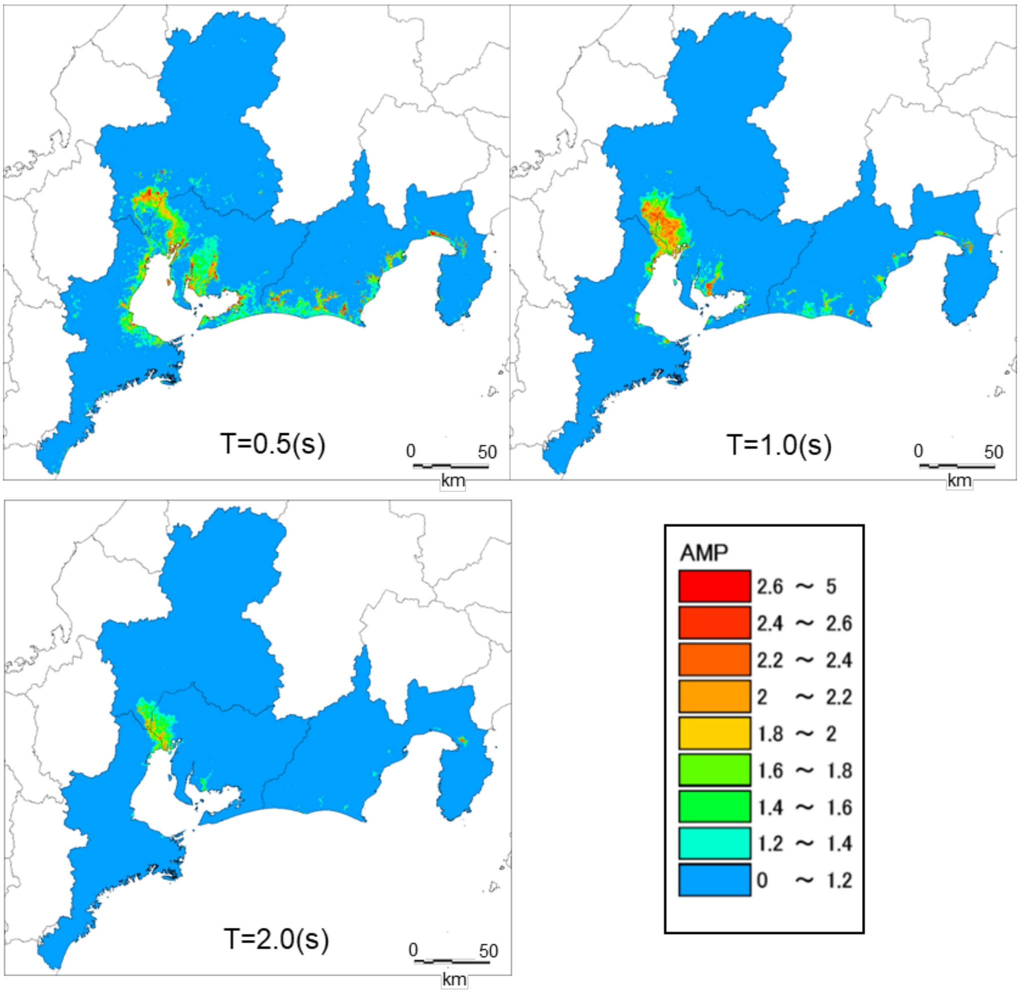

Fig. 7 – Distribution maps on theoritical amplification factors of the ground surface to the Vs400 m/s layer based on the improved model at some typical time periods. The top left shows the one at 0.5 s, the top right shows the one at 1.0 s and the bottom left shows the one at 2.0 s.

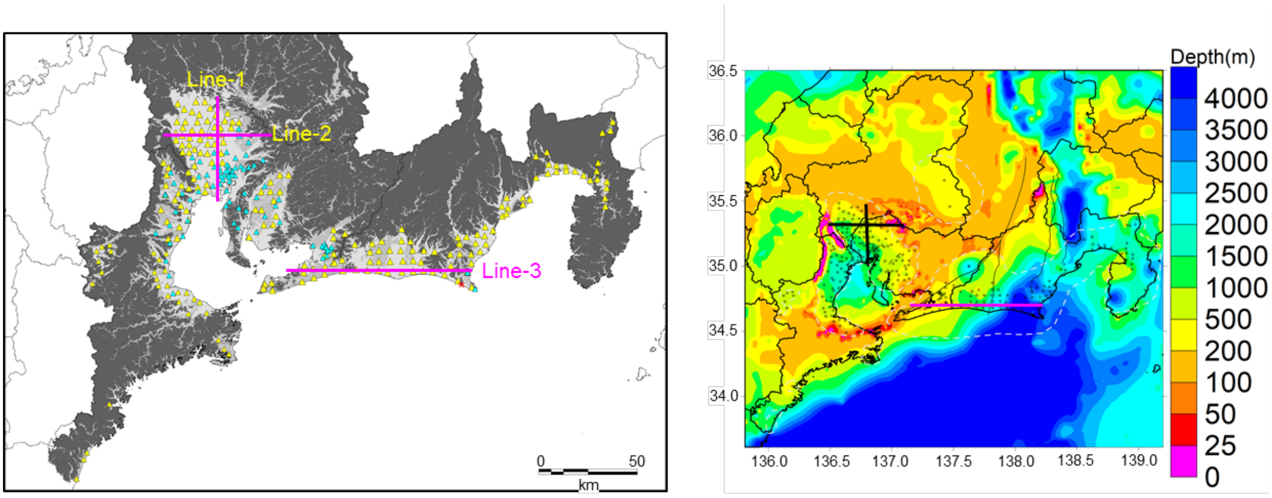

Fig. 8 – The right one: the distribution map on the depth of the top surface of the seismic bedrock (around the Vs3.0 km/s layer) in the Tokai region, the left one: location of survey lines for cross-section views shown

in Fig. 9. The yellow and aqua blue triangles show the array microtremor measurement points for modeling deep velocity structures.

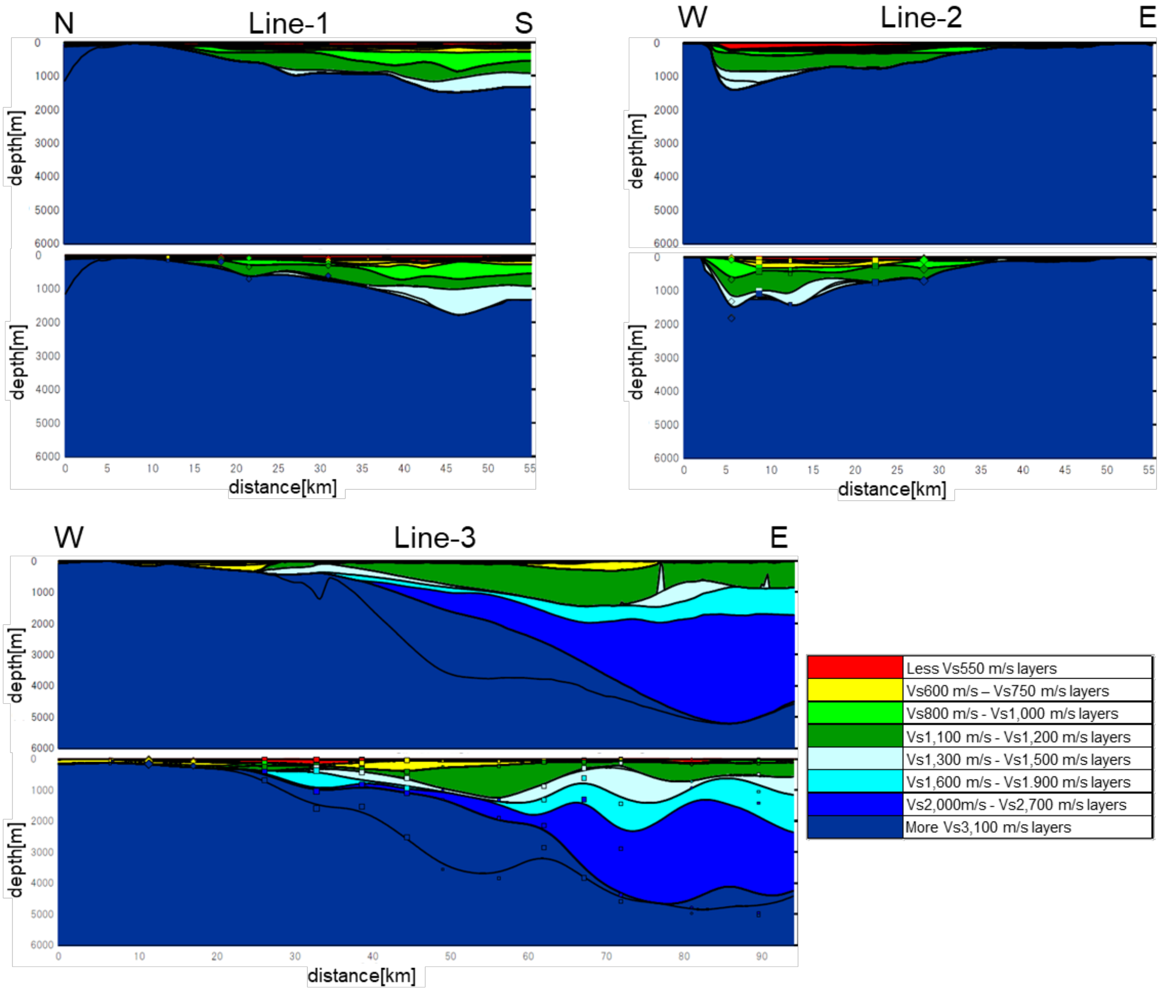

Fig. 9 – Cross-section views along the three survey lines drawn in the left of Fig. 8. The upper left ones indicate cross sections along the line-1, the upper right ones indicate those along the line-2 and the lower ones indicate those along line-3. In the cross-section views along each line, the upper one shows the initial model and the lower one shows the improved model.

5. Conclusion

In recent years, subsurface velocity structures have been modeled from the seismic bedrock to the ground surface for the Kanto, Tokai and Kumamoto regions in the national project of Japan. In this paper, we focused on the Tokai region and reported on the modeled subsurface velocity structures and those ground-motion characteristics. As a result, it is suggested that it can be valid to model subsurface velocity structures by a combination of borehole and array microtremor data for shallow structures, by conducting array microtremor measurements with spatial homogeneity and density. Furthermore, it is essential that period characteristics are taken into consideration in addition to amplification factors.

In the near future, a three-dimensional numerical simulation will be performed as validation principally for deep velocity structures. Also, it is expected that a nationwide subsurface velocity structures can be modeled, by means of state-of-the-art technology as of this moment, based on the modeling scheme.

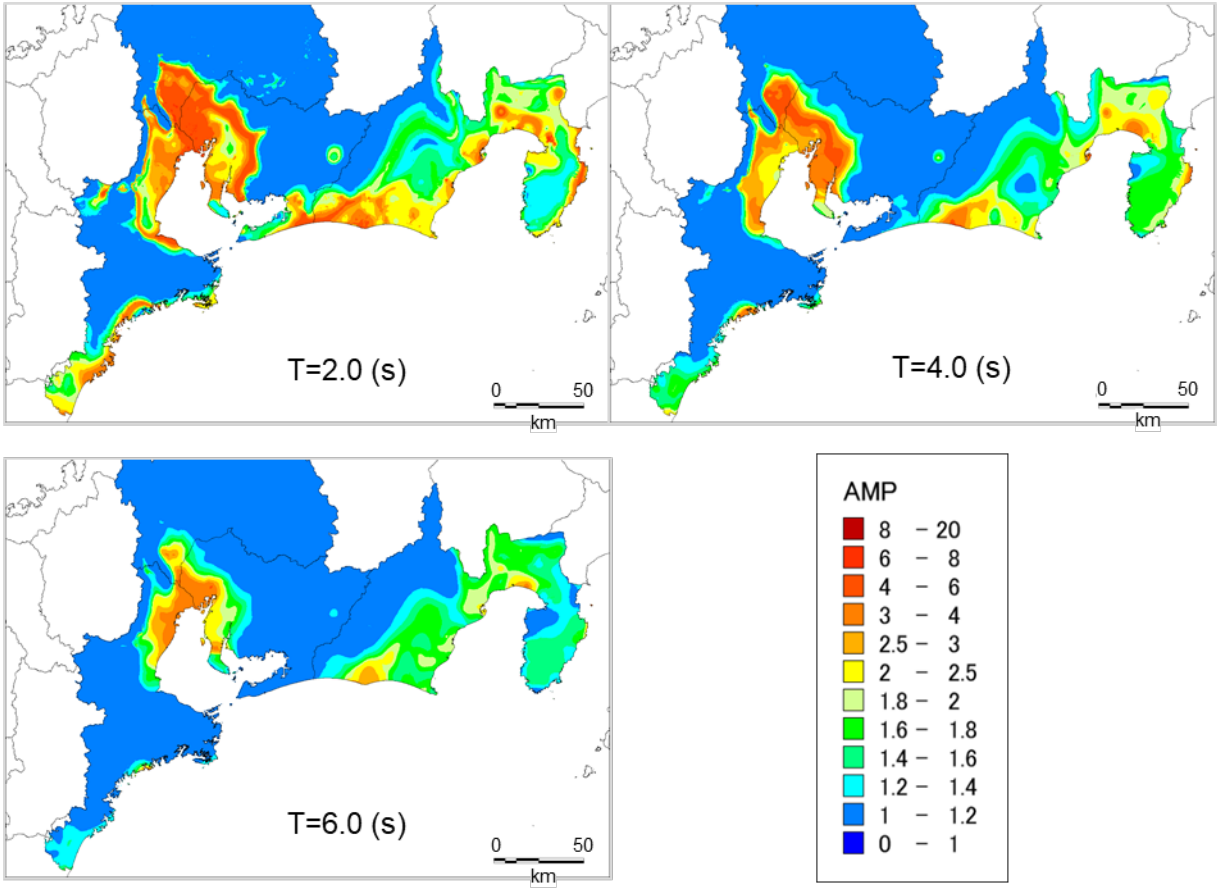

Fig. 10 – Distribution maps on theoritical amplification factors of the ground surface to the Vs3.2 km/s layer based on the improved model at some typical time periods. The top left shows the one at 2.0 s, the top right shows the one at 4.0 s and the bottom left shows the one at 6.0 s.

And then, it is expected that the sophisticated subsurface velocity structure models could contribute to an earthquake ground motion prediction and a damage estimation with higher resolution and accuracy.

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References

[1] The Headquarters for Earthquake Research Promotion (2017): Modeling concept of subsurface structures from seismic bedrock to ground surface, https://www.jishin.go.jp/evaluation/seismic hazard map/ underground model/ (in Japanese).

[2] Cabinet office, Government of Japan (2012): Damage estimate on Nankai Trough megathrust earthquake (the initial report), http://www.bousai.go.jp/jishin/nankai/taisaku/pdf/20120829 higai.pdf (in Japanese) [accessed June 18, 2019].

[3] Senna S, Wakai A, Jin K, Yatagai A, Matsuyama H, Suzuki H, Fujiwara H (2019): Modeling of the subsurface structure from the seismic bedrock to the ground surface for a broadband strong motion evaluation in Japan. *7th International Conference of Earthquake Geotechnical Engineering Proc*, Rome, Italy.

[4] Wakai A, Senna S, Jin K, Yatagai A, Suzuki H, Inagaki Y, Matsuyama H, Maeda T, Fujiwara H (2019): Subsurface velocity structure models from seismic bedrock to ground surface for Kanto region and Tokai one, Japan, for broadband strong ground motion prediction. *7th International Conference of Earthquake Geotechnical Engineering Proc*, Rome, Italy.

[5] Wakai A, Senna S, Jin K, Yatagai A, Suzuki H, Inagaki Y, Matsuyama H, Fujiwara H (2019): Modeling of subsurface velocity structures from seismic bedrock to ground surface in the Tokai region, Japan, for broadband strong ground motion prediction, *J., Disaster Research*, Vol.14, No.9, 1140-1153.

[6] Senna S, Wakai A, Suzuki H, Yatagai A, Matsuyama H, Fujiwara H (2018): Modeling of the subsurface structure from the seismic bedrock to the ground surface for a broadband strong motion evaluation in Kumamoto plain, *J., Disaster Research*, Vol.13, No.5, 917-927.

[7] Fujiwara H., et al (2009): A study on national seismic hazard maps for Japan. *Technical note of the NIED*, No.336 (in Japanese).

[8] Wakamatsu K, Matsuoka M (2013): Nationwide 7.5-arc-second Japan engineering geomorphologic classification map and Vs30 zoning. *J., Disaster Research*, Vol.8, No.5, 904-911.