Finite Difference Method Simulation of Long-Period Ground Motion at the Northern Kanto Region, Japan, Using the Earth Simulator

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To conduct precise three-dimensional finite difference method (FDM) simulations of long-period ground motion in the Kanto basin, Japan, we investigate the characteristics of the *S*-wave velocity in the Kanto Basin and construct a realistic sedimentary structure model. The *S*-wave velocities derived from the vertical seismic profiling measurements in the Kanto Basin show smooth depth gradients rather than step-like increases and can be successfully modeled by an exponential asymptotically bounded velocity function. We conduct large-scale FDM simulation of long-period ground motion using constructed high-resolution sediment structure in the Kanto region. Our simulation using the modified Japan integrated velocity structure model by incorporating a sedimentary layer with *S*-wave velocity-depth gradients well reproduces the excitation and dispersion of the observed surface waves at northern Kanto. This result indicates that a realistic modeling of the impedance contrast at the sediment-bedrock interface is indispensable for the precise evaluation of surface wave excitation at the basin edge.

Keywords: long-period ground motion, surface wave excitation, sedimentary basin, Kanto Basin

1. Introduction

Long-period ground motion is generated by shallow moderate-to-large earthquakes and its dominant period is ranging from several to ten seconds. It often causes significant resonance and severe damage to large-scale man-made structures, such as high-rise buildings, oil-storage tanks, and suspension bridges, which are often located in large-scale sedimentary basins. Therefore, it is very important for the disaster mitigation of future large earthquakes to investigate characteristics of long-period ground motion in large complex basins.

In Kanto region, Japan, long-period ground motions are frequently observed for shallow local moderate-to-large earthquakes (e.g., Yamanaka et al., 1989 [1]; Kinoshita et al., 1992 [2]; Sato et al., 1999 [3]; Koketsu and Kikuchi, 2000 [4]). Such strong long-period ground motions are often caused by the surface wave excited at the edge of basin. The excitation of long-period surface waves at a sedimentary basin edge owing to the incidence of *S*-waves has been reported by many researchers (e.g., Kawase and Aki, 1989 [5]; Hatayama et al., 1995[6]). Furumura and Hayakawa (2007)[7] visualized that the surface waves excited at the northern edge of the Kanto Basin by the 2004 Niigata-ken Chuetsu earthquake (M_W 6.6) propagated toward the southern part of the basin and caused large long-period ground motions with a predominant period of approximately 7 s in Tokyo. This observation indicates that the study of surface wave excitation at the basin edge is important for the precise evaluation and prediction of the long-period ground motion and disaster mitigation in the Tokyo metropolitan area.

To precisely expect long-period ground motion for disaster mitigation from future large earthquakes, the study of the basin structure is necessary for gaining a better understanding of the observed phenomenon. However, the heavily urbanized state of the Tokyo metropolitan area and the complex shape of the bedrock (seismic basement) resulting from the active tectonics in the Kanto region have prevented the rapid advance of the related studies. Using extensive geophysical datasets from refraction/reflection experiments, gravity surveys, microtremor surveys, etc., Koketsu et al. (2008)[8] proposed the Japan integrated velocity structure model (JIVSM) as a regional three-dimensional (3-D) velocity structure model of Japan, including the complex Kanto Basin structure. Although the JIVSM is one of the latest and most widely used structure models for the evaluation of strong and long-period ground motions of local and/or regional earthquakes, this model has scope for improvement, especially in the deterministic evaluation of the surface waves observed in the Kanto Basin.

In this report, we discuss the significant structural properties that control the surface wave excitation at a basin edge on the basis of a 3-D finite-difference method (FDM) simulation. In this process, we first investigate the characteristics of the *S*-wave velocity in the Kanto Basin and find that the *S*-wave velocity in the sediment shows a smooth depth gradient rather than a step-like increase assumed in a conventional layered structure modeling. Our analysis indicates that the *S*-wave velocity-depth gradient is well represented by an exponential asymptotically bounded velocity function (Ravve and Koren, 2006 [9]). Adopting this function, we modify the JIVSM and propose a 3-D structure model. By using the Earth Simulator, we demonstrate that the simulation of long-period ground motion using our model accurately reproduces the amplitudes and dispersions of the surface waves observed in the northern edge of the Kanto Basin.

2. Realistic velocity structure model of the Kanto Basin

The Kanto Basin spreads over an area of approximately 10000 km^2 in central Japan, with a sediment-bedrock interface locally deeper than 4 km (Fig. 1a). The characteristics of seismic wave propagation in the sediment in this basin have been investigated at the seismological observation wells of the National Research Institute for Earth Science and Disaster Prevention (NIED) by use of the vertical seismic profiling (VSP) method (e.g., Yamamizu, 1996 [10]; Yamamizu 2004 [11]). Fig. 1b shows the one-way travel time of *S*-waves from the surface to a certain depth (depth-time curve) obtained at 14 wells of the NIED. The slopes of the depth-time curves correspond to the reciprocals of *S*-wave velocity. Despite the local variation in the depth-time curves, this figure shows that the curves are smooth enough to suggest a continuous increase in *S*-wave velocity with depth at all sites. This observation indicates that the conventional layered structure modeling of *S*-wave velocity is not appropriate for the Kanto Basin.

In this report, we adopt a simple analytical velocity function, the exponential asymptotically bounded velocity function (Ravve and Koren, 2006)[9], for the expression of *S*-wave velocity in the Kanto Basin. This function assumes that the *S*-wave velocity $V(z)$ at a depth z is given by the equation

$$V(z) = V_0 + \Delta V\left[1 - \exp\left(-\alpha z / \Delta V\right)\right] , \qquad (1)$$

where V_0 is the *S*-wave velocity at $z = 0$, ΔV is the increment of the *S*-wave velocity at infinite depth, and α is the positive constant for adjusting the velocity-depth gradient. The velocity-depth gradient, which is controlled by the nonlinear exponential term in this equation, gradually decreases with increasing depth. For this function, the one-way travel time of *S*-waves $t(z)$ from $z = 0$ to a certain depth z is analytically calculated by the following equation:

$$t(z) = \frac{\Delta V}{\alpha\left(V_0 + \Delta V\right)} \ln \frac{\left(V_0 + \Delta V\right)\exp\left(\alpha z / \Delta V\right) - \Delta V}{V_0} . \qquad (2)$$

Equation (2) can be directly applied to the results of the VSP measurements in the *S*-wave velocity structure modeling. Because the *S*-wave velocity in the sediment approaches the value in the bedrock as depth increases, we assumed ΔV = 3.2 km s^{-1} by referring to the JIVSM in our least-squares regression analysis. Figure 1c shows the best-fitting functions for the three wells close to the northern edge of the Kanto Basin. The result well explains the observed depth-time curves, except for the very shallow part of the Isesaki well. Similar results obtained at other wells (shown in Fig. 1d) confirm that the exponential asymptotically bounded velocity function is practically useful for modeling the *S*-wave velocity structure of the sedimentary basin. Figure 1e shows the depth variations of *S*-wave velocities at all wells analyzed in this study. Nonlinearity in the *S*-wave velocity increase with depth can be clearly seen in this figure.

Based on the above findings, we construct an *S*-wave velocity model in the Kanto Basin. We adopt a linear interpolation method to estimate sedimentary *S*-wave velocities over the target area. Figures 2a and 2b respectively show the local variation in V_0 and α estimated for the northern edge of the Kanto Basin. The values in the area are characterized mainly by the VSP observations at the Isesaki, Iwatsuki, and Mohka wells. An artificial boundary seen at southwestern part of Fig. 2b are due to the coarse distribution of VSP observation wells and may not affect our discussions in this report.

To construct a velocity structure model for 3-D FDM simulations, we modify the JIVSM by discarding three sedimentary layers and incorporating a sedimentary layer with the *S*-wave velocity-depth gradients estimated above. *P*-wave velocity and the density of the sediment are estimated by using empirical relations given by the Ministry of Education, Sports, Culture, Science and Technology (MEXT) (2007)[12] and Shiomi et al. (1997)[13], respectively. Anelastic attenuation Q-values of the sediment are taken from the JIVSM as it is, allowing depth dependent anelastic attenuation. Other structures beneath the sediment, including the bedrock, subducted oceanic plates, and mantle, are also taken from the JIVSM. We hereafter refer to the velocity structure model constructed in this study as the modified JIVSM.

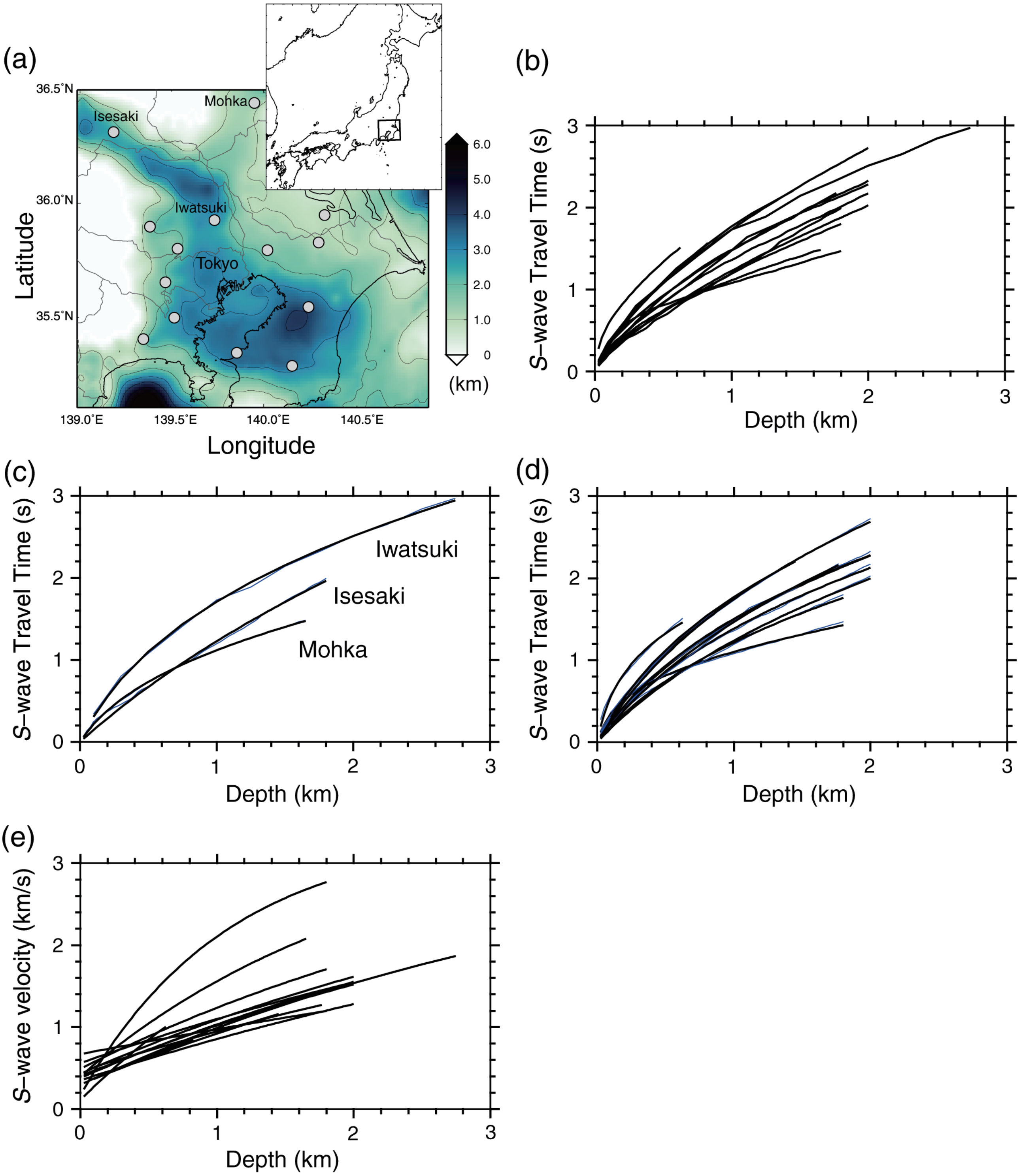

Fig. 1 (a) Map showing Kanto Basin and the locations of 14 seismic observation wells (gray circles), where VSP measurements were carried out. Local variation of sediment-bedrock interface depths from the JIVSM [8] is shown by color gradations. (b) One-way travel time of S-waves from the surface to certain depths obtained by VSP measurement at 14 wells (Yamamizu, 1996 [10]; Yamamizu, 2004 [11]). (c) Best-fitting exponential asymptotically bounded velocity functions (black lines) to the VSP observations at the Isesaki, Iwatsuki, and Mohka wells (blue lines). (d) Best-fitting exponential asymptotically bounded velocity functions (black lines) to the VSP observations at other wells (blue lines). (e) Depth variations of S-wave velocities at 14 wells evaluated by the best-fitting exponential asymptotically bounded velocity functions.

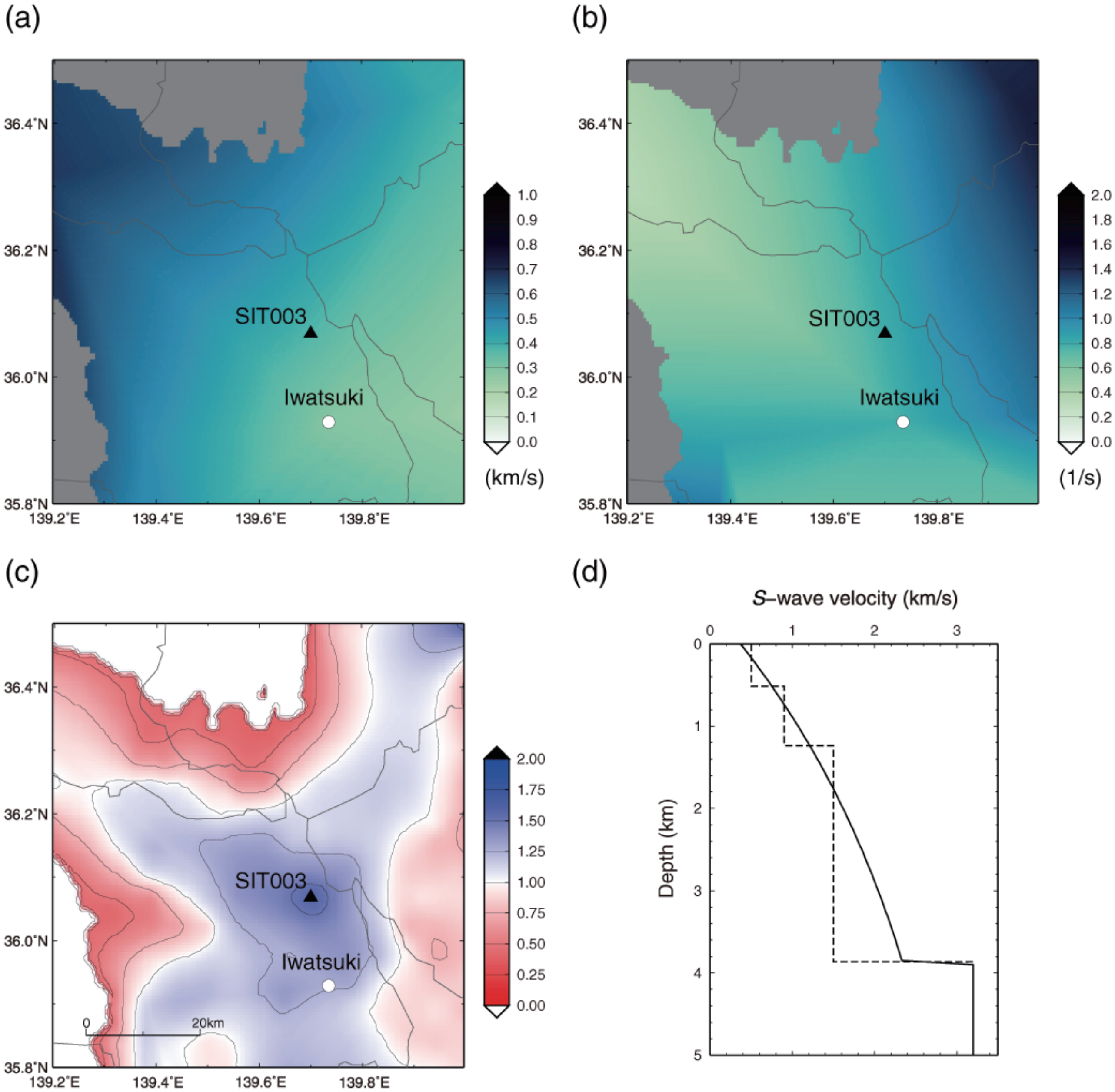

Fig. 2 (a) Local variations in V_0 estimated around the northern edge of the Kanto Basin. (b) Local variations in α. (c) Local variations in ratio of sedimentary *S*-wave velocity just above the bedrock of the modified JIVSM to that of the JIVSM. (d) *S*-wave velocity structure models beneath SIT003 from the JIVSM (broken line) and modified JIVSM (solid line).

3. 3-D FDM simulation of long-period ground motion around the northern Kanto

Using the velocity structure model constructed in the previous section, we conduct 3-D FDM simulation of long-period ground motion to examine the influence of the sedimentary velocity structure on the surface wave excitation at the basin edge. To conduct precise simulation of long-period ground motion in model with smooth velocity gradient, the computations were conducted on the Earth Simulator at the Japan Agency for Marine-Earth Science and Technology.

The model of the 3-D simulation covers an area of 320 km × 220 km in horizontal directions and 64 km in depth, which is discretized by a grid interval of 0.1 km in the horizontal directions and 0.05 km in the vertical direction. To perform an effective simulation, we employ a parallel 3-D FDM simulation code based on a domain-partitioning procedure that utilizes a large number of processors with the message passing interface (MPI) (e.g., Furumura and Chen, 2004 [14]; Maeda and Furumura, 2013 [15]).

The seismic source at the northern Tochigi Prefecture, corresponding to the seismic activity that occurred on February 25, 2013, at a depth of 8 km, is used in this simulation. A focal mechanism of strike/dip/rake = 168/86/-10° and moment magnitude of M_W = 5.8 are assumed by referring to the centroid moment tensor (CMT) solution of F-net. A source time function represented by the asymmetric cosine function (Ji et al., 2003 [16]) with t_s = 0.3 and t_e = 2.7 is adopted for a point seismic source. After the calculation, the value of seismic moment is adjusted to 77% of CMT estimation to explain the observed waveform amplitude of a rock site (TCG011 shown in Fig. 3c).

Figure 3 shows record sections of transverse (T) component seismograms derived from simulations and dense-array observation. A band-pass filter with a pass-band of 0.125–0.25 Hz is applied to extract surface waves with a predominant period of approximately 7 s, and each trace is multiplied by the hypocenter distance to enlarge seismogram amplitudes at far stations. Because of the strong *SH*-wave source radiation in the direction of the Kanto Basin, large-amplitude *SH* waves are expected in the T component.

At hypocenter distances of less than 60 km, simulation results from the JIVSM and the modified JIVSM well reproduce waveforms observed by the KiK-net and K-NET of the NIED. This ability indicates that the modeling of the source and the velocity structure of the crust and uppermost mantle are appropriate for calculating the seismic wave propagation in this frequency range. As the hypocenter distances exceed 70 km, source-radiated body waves enter the Kanto Basin, and excitation of surface waves (Love waves) occurs at the edge of the basin. The simulated and observed seismic waves show strong amplification by the low-velocity sediment as they propagate toward the inner part of the Kanto Basin.

The amplitude of the Love waves derived from the simulation using the JIVSM (Fig. 3a) is much larger than that from observation (Fig. 3c). The JIVSM predicts strong excitation and development of the Love waves, and an unrealistically large wave packet appears at SIT010. Meanwhile, the amplitude of the Love waves derived from the simulation using the modified JIVSM (Fig. 3b) is much closer to that from observation, though it is still far from perfect fitting.

Figure 4 shows a comparison of horizontal-component waveforms at SIT003 as obtained from simulations and observations. SIT003 is located in the Kanto Basin and at 30 km from the basin edge. It is clear that a dominant wave packet of Love waves in the T component appears significantly earlier in the simulation using the JIVSM than in the observation. The simulation result using the modified JIVSM (Fig. 4b) drastically minimizes this inconsistency. Moreover, the amplitude and dispersion of the surface waves in both the T and the radial (R) components are well reproduced.

To examine the effect of velocity gradient model on the level of long-period ground motion in the Kanto basin, we calculated peak ground velocity (PGV) for frequency of 0.125–0.25 Hz using two horizontal component seismograms. Figure 5 shows PGV distributions derived from simulation results and observations. PGV from original JIVSM (Fig. 5a) was overestimated around the deeper basement region, such as southern Saitama, eastern Tokyo and Chiba. By introducing a velocity gradient model (Fig. 5b), the gap of PGV between simulations and observations became smaller. Thus, we conclude that the impedance contrast at the sediment-bedrock boundary in modified JIVSM may be more suitable compared to original JIVSM.

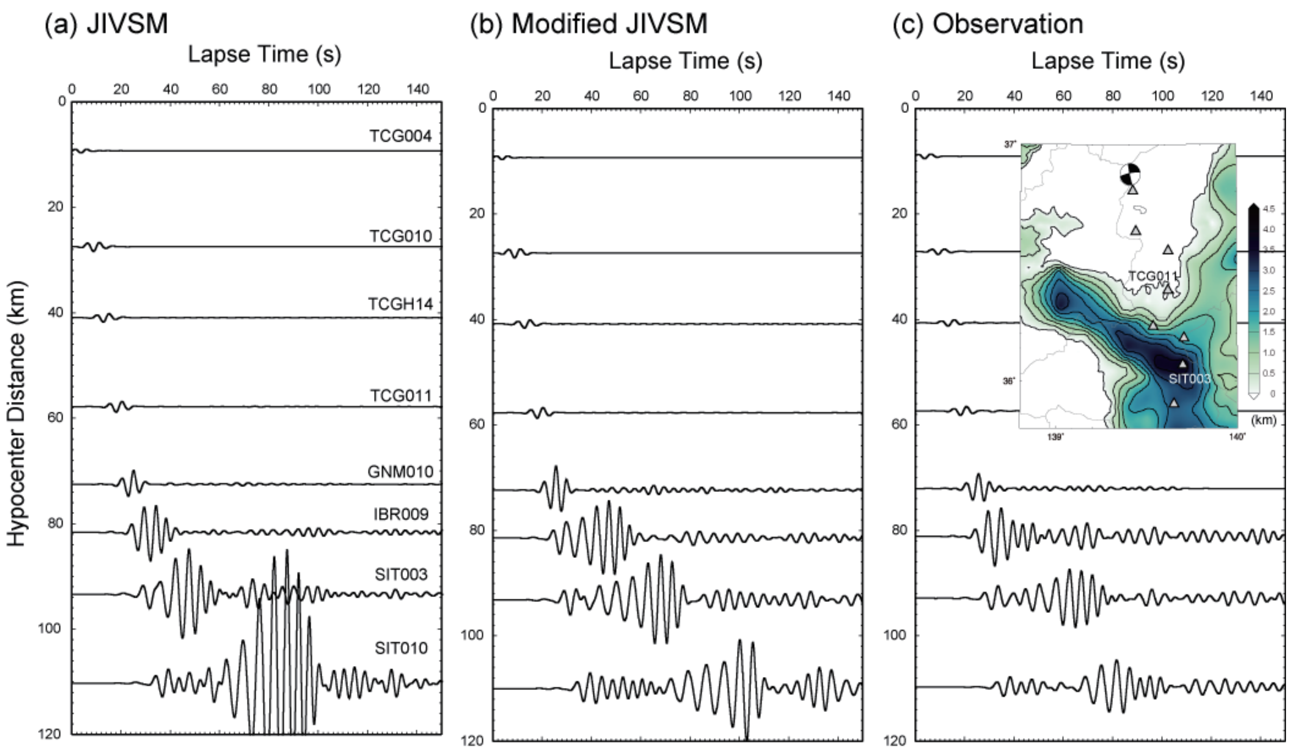

Fig. 3 Comparison between simulated and observed velocity seismograms of transverse component: (a) JIVSM, (b) modified JIVSM, and (c) observations. A band-pass filter with a pass-band of 0.125–0.25 is applied. Each trace is magnified by a factor proportional to the hypocenter distance to enlarge seismogram amplitudes at far stations. An inset map in (c) shows the locations of the epicenter and the observation stations, and the local variation of sediment-bedrock interface depths from the JIVSM.

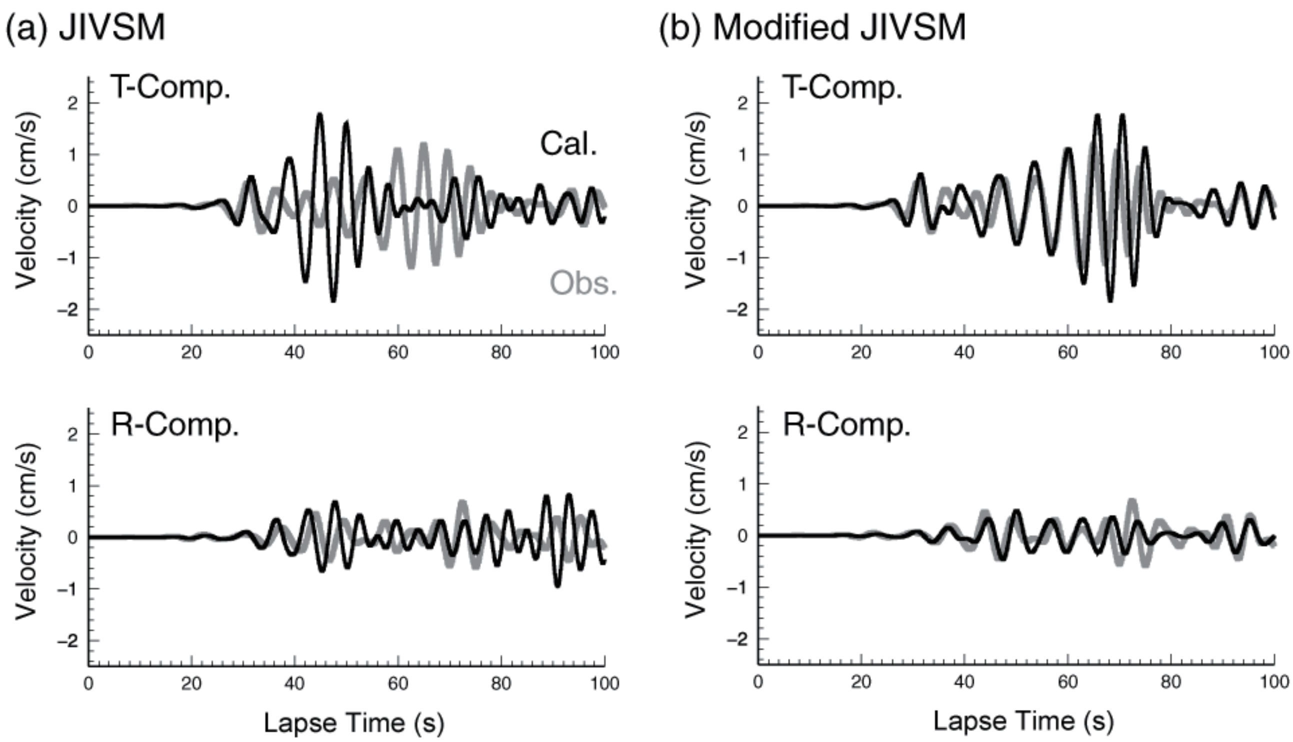

Fig. 4 Comparison of horizontal seismograms recorded at SIT003 between simulations and observation: (a) JIVSM and (b) modified JIVSM. The black and gray lines represent the simulation results and observations, respectively.

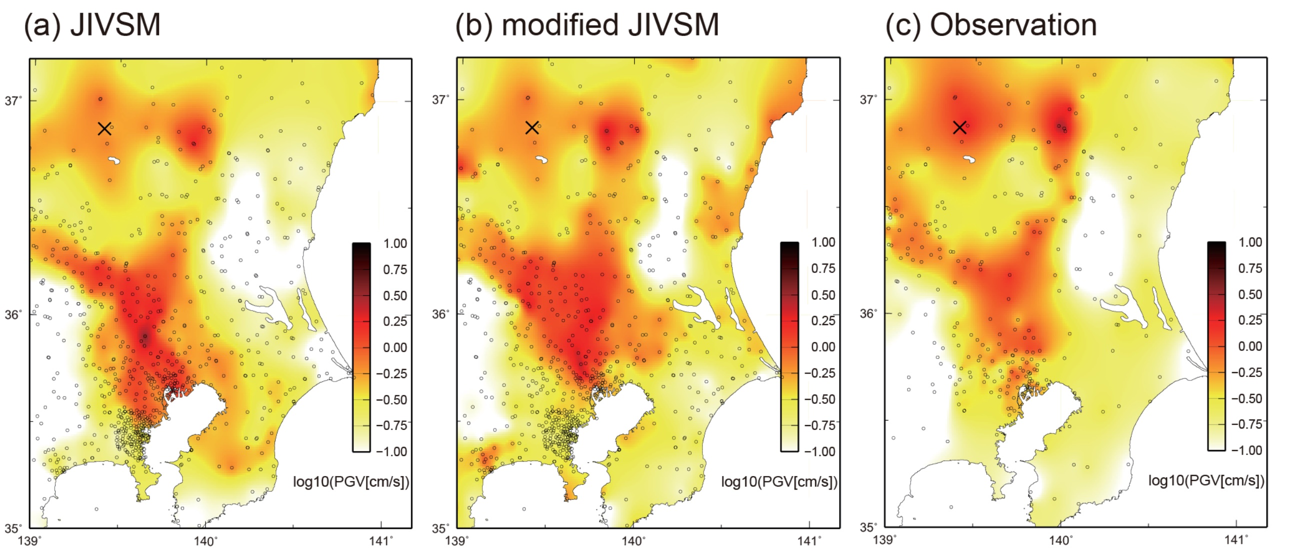

Fig. 5 Peak ground velocity (PGV) distributions derived from horizontal seismograms for 0.125-0.25 Hz: (a) JIVSM, (b) modified JIVSM, and (c) observation.

4. Discussion and Conclusion

Our 3-D FDM simulation using the modified JIVSM well reproduced the characteristics of the surface waves observed at the northern edge of the Kanto Basin in the frequency range of 0.125–0.25 Hz. In particular, the appearance of the dominant wave packet of Love waves was satisfactorily reproduced by introducing the velocity gradient of sediment into the JIVSM. Because the depth of the bedrock, which is supposed to be well constrained in the refraction/reflection experiments (e.g., Hamada et al., 1990)[17], was not modified in our simulations, the improvement in the reproducibility can be attributed solely to the modeling of the sedimentary structure.

The dominant wave packet of Love waves recorded at SIT003 shows clear normal dispersion, indicating the propagation of this packet over a certain distance where arrival-time differences of 40 s can be expected between the direct *S*-waves and the Love waves. However, the simulated Love wave packet at SIT003 using the JIVSM precedes the corresponding wave packet in the observation by 20 s and shows very weak dispersion, implying Love wave excitation close to this station. Because the surface wave is excited by the trapping of the body-wave energy in a low-velocity surface structure, the abovementioned discrepancy is most probably the result of inexact modeling of the impedance contrast at the sediment-bedrock interface. Figure 2c shows the local variation in the ratio of the sedimentary *S*-wave velocity just above the bedrock of the modified JIVSM to that of the JIVSM. This ratio is relatively small at the extreme edge of the basin (within 15 km of the border), where the bedrock is not deeper than approximately 2 km; the ratio is conversely large in the inner part of the basin, where SIT003 is located. This observation indicates that the modified JIVSM has a higher potential to excite Love waves at the extreme edge of the basin than does the JIVSM. Figures 3b and 4b show that the dominant wave packets of the observed Love waves are well explained by the simulation using the modified JIVSM. This result strongly suggests that the Love waves are excited at the extreme edge of the basin, and propagate toward the inner part of the basin with a group velocity of approximately 1 km/s.

To investigate the influence of the velocity gradient in the sediment on the surface wave propagation, we conducted additional 3-D FDM simulations using simple 1-D velocity structure models from the SIT003 site of the JIVSM and the modified JIVSM (Fig. 2d). Although the figures are not shown here owing to space constraints, they confirm that no apparent difference exists between the two models in terms of the group velocity and the dispersion of the Love waves in the frequency range of 0.125–0.25 Hz. This result implies that the incorporation of the velocity gradient affects the surface wave excitation much more strongly than it affects the surface wave propagation at the basin edge in the analyzed frequency range.

The results of this study indicate that a realistic velocity structure model is required to explain the excitation and propagation of the surface wave in the sedimentary basin. Our results also strongly suggest that the dominant wave packet of Love waves is excited at the extreme edge of the Kanto Basin and propagates toward the inner part of the basin. This finding indicates that the study of the surface wave excitation at the extreme edge of the basin, including dense-array observations, is quite important for the precise evaluation and prediction of the long-period ground motion in the Tokyo metropolitan area.

We showed a case study in which the realistic modeling of the sedimentary velocity structure improves the geophysical reproducibility of the surface wave excitation at basin edge, but the highly accurate modeling of the phase and amplitude of excited surface waves remains as a matter to be studied further. It is obvious that the number of the VSP measurements used in this study is insufficient to construct an accurate sedimentary structure model of the Kanto Basin. Concerning this matter, we should determine the local variation of the model parameter of the sedimentary structure (e.g, V_0 and α of the *S*-wave velocity) using geophysical analyses such as phase and group velocity analysis, spectral analysis and a waveform inversion of surface waves of local and/or regional earthquake. For the fully accurate modeling of the sedimentary structure, an additional consideration how to specify the relation among the structural parameters, including anelastic parameter, may be required.

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地球シミュレータによる関東平野北部で励起した長周期地震動のシミュレーション

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より高精度な長周期地震動のシミュレーションを行うために、中深層の観測井による VSP 調査の結果から堆積層内の S 波速度構造の特徴を調査した。その結果、既往のモデルで用いられているような 3 層構造ではなく、深さに対してゆるやかに速度が増大するような構造により VSP 調査の結果を正確に表現できることを明らかにした。鉛直速度勾配を含んだ堆積層の速度構造を用いて栃木県北部の地震（Mw 5.8）の地震動シミュレーションを行った結果、関東平野北部における長周期地震動の励起・伝播を再現することに成功した。これらの結果から、地震基盤におけるインピーダンスコントラストを正確に表現することが長周期地震動を再現する上で重要であることが示唆された。

キーワード: 地震, 表面波, 長周期地震動, 不均質構造, 堆積盆地構造