

EFFECTS OF Q_s-MODEL ON THREE-DIMENSIONAL SIMULATION OF SEISMIC MOTION

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SUMMARY

In this paper we examined the effects of Q_s model on three-dimensional simulation of long-period ground motions in the northwestern part of Chiba prefecture, Japan. Q_s model of deep sedimentary layers was estimated from spectral ratio of borehole array records using genetic algorithm. The simulations of longperiod ground motions were carried out by pseudo-spectral method (PSM) / finite difference method (FDM) hybrid parallel scheme. Two different Qs models for the simulated region, taken from inverted Q_s and commonly used Q_s (=V_s/15), were applied to the simulation. The inverted Q_s model well explained the initial phases and amplitudes of the observation waveforms. The commonly used Q_s model overestimated the amplitudes of the observations for all stations.

INTRODUCTION

Estimation of decay rate for S-waves (Q_s) in the sedimentary basin is one of the important subjects in earthquake engineering because an amplitude level of seismic motion is directly influenced by Q_s . It is well understood that Q_s is composed by intrinsic attenuation derived from friction and scattering attenuation derived from inhomogeneity of subsurface structure [e.g. Richards and Menke [1]]. In general, there are two popular methods in estimation of Q_s for engineering purpose. The one is laboratory test of boring core sample and the other one is inversion of spectral ratio calculated from borehole array records of seismic motion. Laboratory test, however, isn't able to estimate both intrinsic attenuation and scattering attenuation but is able to estimate only intrinsic attenuation. Therefore, inversion method gives us more reliable Q_s model for simulation of seismic motion than laboratory test. In numerical simulation of longperiod seismic motion, it remains as a difficult problem for us to know Q_s model in deep sedimentary basin, because of the lack of deep borehole array observatory. Therefore, commonly used Q_s model (e.g. $Q_s=V_s/15$, where V_s is the S-wave velocity (m/s)) or assumed Q_s model are used for numerical simulation of long-period seismic motion in large basins [e.g. Sato *et al.* [2]; Yamada and Yamanaka [3]]. If the deep

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borehole array observation has been deployed in the simulated region, the inverted Q_s model is seen to be of value to three-dimensional simulation of deep sedimentary layers. In this research, we would like to examine difference between inverted and commonly used Q_s models for deep sedimentary basin and its influence on three-dimensional simulation of long-period seismic motion. First, we model threedimensional subsurface structure in the northwestern part of Chiba prefecture, Japan, based on the result of geophysical survey conducted by Chiba prefectural government. Q_s models are estimated by genetic inversion of spectral ratio derived from deep borehole array observatory down to the depth of 2300 m in this region [Kinoshita, [4]]. Then, we carry out three-dimensional ground motion simulation of the earthquake with the magnitude 4.9 and the focal depth of 78km, by using inverted and commonly used Q_s models. Finally, the better Qs model for three-dimensional simulation in this region is discussed.

DATA

Earthquake observation

The investigated region is the northwestern part of Chiba prefecture where is adjacent to Tokyo metropolitan region as shown in Fig. 1. Earthquake array observation is deployed by Chiba prefectural government. The array, called KKNET Chiba, consists of 13 stations and installed accelerometers in this region. The locations of stations are displayed as solid squares in Fig. 1. We are also installed 3 accelerometers in this region. The locations of our observatories are shown as open squares in Fig. 1. Furthermore, in this region, there is a deep borehole array down to the depth of 2300 m installed by Natural Research Institute of Earth Science and Disaster Prevention [Kinoshita [4]]. The location of the borehole array (SHM) is shown as solid circle in Fig. 1. Two accelerometers are installed at depths of 0 m and 2300 m. The bottom of borehole array is about 800 m below the upper border of the pre-Tertiary basement.

Fig. 2. shows an example of observed velocity wave traces in EW component from the earthquake with magnitude 4.9 and focal depth of 78 km occurring on November 8, 1998. All the traces in the figure are filtered in a period range of 1 to 10 sec. In the Kanto basin including the investigated region, long period surface waves were often clearly detected in the records by band-path filtering processes [e.g. Zama [5]]. Since this region is far away from basin edge where long period surface waves are induced and the focal depth of the earthquake is deep, significant surface waves can't be seen in all the traces. However, reflected wave from the pre-Tertiary basement is clearly seen about 5 to 7 sec after initial S-wave arrival in all the traces. The differences of the arrival time residuals between the initial S-wave and the reflected wave imply that S-wave structure of sedimentary basin is varied in this region. The maximum amplitudes of wave traces differ from one another, which were affected by subsurface structural models of S-wave and Q_s .

Subsurface model

The pre-Tertiary basement of Kanto basin is covered with Quaternary and Tertiary sediments. In the investigated region, the deep seismic reflection surveys were conducted by Chiba prefectural government. The migrated profile from ABI to FUN (A-A' line) is displayed in Fig. 3. It is interpreted that the sediments consist of three major geophysical formations in this region. As shown in Fig. 3, the upper layer of the pre-Tertiary basement corresponds to Miura group. The layer distributed on Miura group corresponds to Kazusa group. The top layer of the sediments corresponds to Shimohsa group of Quaternary sediment. Fig. 4 shows three-dimensional boundary surface model of sedimentary layers in the northwestern part of Chiba prefecture produced by Chiba prefectural government. This model is mainly constructed by reflection and gravity surveys. The top surface in Fig. 4 is the border of Shimohsa and Kazusa groups, and the second one is the border of Kazusa and Miura groups. The distribution of pre-Tertiary basement depth existing the border of Miura group and the basement in this region is expressed by the third surface in the figure. As can be seen in Figs. 3 and 4, the basement depth is gradually

increased from northeast to southwest, and Miura group is thinner in the north. In contrast, the boundary shape between Shimohsa and Kazusa groups is almost flat in this region.

INVERSION

In Kanto basin, estimation of Q_s based on deep borehole records has been already performed by Kinoshita [4], [6]. He determined frequency dependent Qs in a period range of 0.25 to 5 sec by using borehole records at SHM. As has well known, since scattering attenuation has frequency dependent characteristics [e.g. Sato [7]; Sato and Kawase [8]], total Q_s should be also estimated as a function of frequency by the inversion method. However, it is difficult to deal with frequency dependent Q_s in a numerical simulation of time domain. For this reason, we estimated frequency-independent Q_s model of deep sedimentary layers in this region by genetic inversion of spectral ratio using borehole records at SHM.

In this study, we applied an inversion method using genetic algorithms proposed by Yamanaka and Ishida [9]. In the inversion, Q_s models were searched by minimizing the misfit that is defined L2-norm of residuals between observed and theoretical spectral ratios. Theoretical spectral ratio was calculated by one-dimensional wave propagation theory [Haskell [10]]. Unknown parameter Q_s in the inversion assumed to be represented as the function of S-wave velocity V_s/n . Since the other parameters were fixed, n was only unknown parameter in the inversion of this study. The search limit of n and the other physical parameters are represented in Table.1.

As an inversion result, we estimated Q_s model of deep sedimentary layers in this region as $V_s/42$. Fig. 5 shows the comparison between the observed spectral ratio and the theoretical one using inverted Q_s . The observed spectral ratio is the average of NS and EW components. As shown in Fig. 5, the theoretical one using commonly used Q_s (=Vs/15) is also depicted. The theoretical spectral ratio using inverted Q_s well explains the observed one than that using commonly used Q_s . The comparison of observed ground motion at SHM with those simulated from inverted and commonly used Q_s models are shown in Fig. 6. In the simulation, one-dimensional wave propagation theory was used, and the bottom record of borehole array at SHM was used as the input motion. While the theoretical spectral ratio using commonly used Q_s model fails to explain the observed one, both models almost match the amplitude and phase of the observed ground motion. It is interpreted that the difference of Q_s models has little effect on the waveform of long-period ground motion by one-dimensional wave propagation theory. Fig. 7 shows the comparison of estimated Q_s models in this region between this study and Kinoshita [4]. We see from Fig. 7 that Q_s of Kinoshita [4] is nearly as much as the average of overall Q_s in sediments derived from this study.

NUMERICAL SIMULATION

The three-dimensional simulations of seismic motions were conducted by pseudo-spectral method (PSM) / finite difference method (FDM) hybrid parallel simulation [Furumura *et al.* [11]]. In this hybrid method, PSM is used to calculate spatial derivatives in the horizontal direction, and FDM is used to calculate spatial derivatives in the vertical direction. The simulated region in this study is shown in Fig. 1. The model is 23.84 km long, 29.28 km wide, and 80 km deep. The subsurface model is divided into four parts in the vertical direction. The grid spacing in the horizontal direction is 160 m, while that in the vertical direction is 80, 80, 160, and 320 m in each subdomain. In order to calculate vertical differentiation using FDM, data is exchange between the adjoining subdomains by using MPI (message passing interface) library. The frequency resolution limit is 1.25 Hz and the time increment is 0.005 sec.

In the subsurface model, P-wave velocities in sediments are 1700, 2200, and 2900 m/s, respectively. S-wave velocities in sediments are 450, 900, 1500 m/s, respectively. The pre-Tertiary basement is P-wave

velocity of 5700 m/s and S-wave velocity of 3000 m/s. The deeper subsurface model beneath the pre-Tertiary basement was modeled following Sato *et al.* [2]. Physical parameters of the subsurface model in this study appear in Table. 2.

The epicenter (35.6N, 140.05E) of simulated earthquake is shown in Fig. 1. The earthquake is magnitude of 4.9 and focal depth of 78 km. This information was derived from Japan Meteorological Agency. In this study, seismic moment of 2.90×10^{16} Nm was estimated by trial and error using the observed record at SHM of GL-2300 m. A comparison of the observed record at SHM of GL-2300 m with the simulated waveform obtained using estimated seismic moment is shown in Fig. 8. Both the record and the synthetic have been filtered at 1.0 to 10 sec. Since the synthetic waveform well explains the observed one, it is interpreted that estimated seismic moment of the earthquake is reasonable. The earthquake source was represented using a point source with the source mechanism determined by F-NET from Natural Research Institute of Earth Science and Disaster Prevention. The Herrmann's pseudo-delta function with a time width of 1.0 sec was used as the source time function (moment rate function).

RESULTS

Comparisons of ground velocities observed at selected stations with those simulated from the inverted Q_s model is shown in Fig. 9 and the case of commonly used Q_s model is shown in Fig. 10. Both the observed and synthetic waveforms are bandpass filtered from 1.0 to 10.0 sec. Here, inverted Q_s model is $V_s/42$ and commonly used Q_s model is $V_s/15$ in the sediments. As for the treatment of Q_s model in this simulation, we used the technique of Graves [12]. In this approach, Q_s has linear dependence on frequency, which is correspond with the frequency independent Q model at a specified reference frequency. The reference frequency was set at 0.2Hz following Sato *et al.* [2] in this simulation.

Stations Kashiwa (KAS) and Shonan (SHO) are located in the northern part of simulated region. At these stations, both Q_s models well explain observed initial and later phases of S-wave, although both Q_s models overestimate the amplitudes of the observed initial phases. For stations Shimohsa (SHM) and Kamagaya (KMY) located in the central part of simulated region, while inverted Q_s model matches well the initial phases and amplitudes of the observations, commonly used Q_s model overestimate the amplitudes of the observations. Furthermore, at these stations, the later phases of the synthetics mismatch the one of the observations for each Q_s model. At Funabashi (FUN) and Narashino (NRS) located in the southern part of simulated region, inverted Q_s model matches well the initial phases and the amplitudes of observations, although the phase arrival time of initial S-wave is estimated later. In case of commonly used Q_s model, the amplitudes of initial phases are estimated twice as much as the amplitudes of the observations, inverted Q_s model matches well the observed waveforms compared with commonly used Q_s model. Therefore, it is interpreted that inverted Q_s model is more reasonable than commonly used Q_s model when long-period ground motion is simulated based on three-dimensional subsurface model.

As for the phase arrival time of initial S-wave, the synthetics in the northern and central stations show good agreement with the observation whereas the ones in the southern stations are later than the observation. In the simulated region, for the thickness of sediments, there is large difference between the northeastern part and the southwestern part, especially for Kazusa group as shown in Fig. 4. In the northern and central part, the thickness is more than twice as much as the one in the southern part. Therefore, it seems reasonable to suppose that the later arrival times in the southern stations are due to insufficient subsurface modeling of Kazusa group.

CONCLUSIONS

In this study, we carried out three-dimensional simulation of seismic motion to examine the effect of Q_s models on long-period seismic motion. Q_s model of the sedimentary layers in the simulated region was estimated by genetic inversion of spectral ratio derived from deep borehole array records. Inverted Q_s model was, then, applied to three-dimensional simulation of long-period ground motion. The synthetic waveforms were compared with the ones simulated by using inverted Q_s (=Vs/15) model and the observed one. From the comparison, we showed that inverted Q_s model well explained the amplitudes of observed record relative to commonly used Q_s model. Therefore, it is concluded that inverted Q_s model was more reasonable than commonly used Q_s model for the simulation of long-period ground motion based on three-dimensional subsurface model in the northwestern part of Chiba prefecture.

As for the accuracy of the subsurface model, it was found that the synthetics in the northern and central stations in the simulated region are good agreements with the observations for the phase arrival times of initial S-wave, while the phase arrival times of synthetics in the southern stations are later than the observation. Therefore, the future direction of the subsurface model tuning will be mainly in the southwestern part of the simulated region.

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Fig. 1 Map of simulation model area, with strong motion stations (squares and circle) and seismic reflection survey (lines)



Fig. 2 Observed ground velocities in the NS component with bandpass filtered at 1.0 to 10.0 sec.



Fig. 3 Seismic reflection profile along the A-A' line (Chiba prefectural government, 2000)



Fig. 4 Three-dimensional boundary surface shapes in the northwestern part of Chiba prefecture.

Table 1 Search limit in genetic inversion of spectral ratio and other fixed parameters.

Layer	Vs(m/s)	Thickness(m)	Density(<i>t</i> m ³)	n	
Shimohsa	450	436.9	1.8	1.0 ~ 100.0	
Kazusa	900	789.6	2		
Miura	1500	257.7	2.3		
Basement	3000	846.3	2.5	20	
	3000	∞	2.5		



Fig. 5 Comparison of the observed spectral ratio with the theoretical ones at SHM.



Fig. 6 Comparison of one-dimensional synthetics (NS componet) with the observed ground motion (thin) at SHM (surface).



Fig. 7 Comparison of inverted Qs model with the previous study at SHM (Kinoshita [4]).

Layer	P-wave velocity (m/s)	S-wave velocity (m/s)	Depth to the top of layer (km)	Density (t/m ³)	Qs
1	1700	450	0	1.8	
2	2200	900		2	V _s /42
3	2900	1500	Variavle	2.1	
4	5700	3000		2.5	150
5	5700	3330	3	2.6	150
6	6600	3710	12	2.8	250
7	6700	3740	20	2.8	250
8	7000	3930	25	3	250
9	7900	4440	34	3.2	500

Table 2 Velocity structure model used for three-dimensional simulation.



Fig. 8 Comparison of three-dimensional synthetics (bold) with the observed borehole record (thin) at SHM (GL-2300m). The top, middle and bottom pairs of traces are the NS, EW, and UD component respectively.



Fig. 9 Observed (thin) and synthetic (bold) ground velocities for inverted Qs model. The top, middle and bottom pairs of traces are the NS, EW, and UD component respectively.



Fig. 10 Observed (thin) and synthetic (bold) ground velocities for commonly used Qs model. The top, middle and bottom pairs of traces are the NS, EW, and UD component respectively.