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NUMERICAL SIMULATION OF STRONG GROUND MOTION ON ADAPAZARI BASIN DURING THE 1999 KOCAELI, TURKEY, EARTHQUAKE

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SUMMARY

The 1999 Kocaeli Earthquake brought serious damage to the downtown of Adapazari, Turkey. This implies that a deep ground structure may affect the distribution of strong ground motions. Several surveys have been performed to obtain the information of subsurface structure beneath the Adapazari basin. We proposed a model of 3D subsurface structure of the basin based on the survey results, which are refraction/reflection survey, gravity survey, microseism observations and aftershock records. The strong ground motions during the main shock are simulated by 3D finite-difference methods. The results of this simulation show that the ground motions at the downtown of Adapazari are significantly amplified by the basin-edge effect in comparison with the region between the downtown and the source fault.

INTRODUCTION

The Kocaeli Earthquake (*Mw*=7.4) took place in the western part of Turkey on August 17, 1999. This earthquake killed more than 5,000 persons, and collapsed and heavily damaged about 120,000 buildings. The downtown of Adapazari, the central city of Sakarya, was one of the most damaged areas. The damaged area is located 8-10 km away from the fault, whereas the damage was moderate or even light between the downtown and the source fault.

A tradition says that the downtown of Adapazari consisted of swamps, ponds and lakes around a market on a central island more than 150 years ago, which is imagined from the fact, 'ada' means 'island' and 'pazari' means 'market'. As the swamps around Adapazari have decreased by floods of Sakarya River again and again, it is considered that the downtown of Adapazari is located on soft and thick layer. In addition, Adapazari is surrounded with hills and mountains. This implies that the deep ground structure may affect the distribution of strong ground motions, which we have already observed on 1995 Hyogoken-nanbu (Kobe) Earthquake, Japan.

Several surveys have been performed to obtain the information of subsurface structure beneath the Adapazari basin, e.g. Komazawa *et al.* [1], Kudo *et al.* [2]. The shape of bedrock has been reported based on a gravity survey (hereafter Komazawa model) and the results of the array and single-site observation of microseisms (Komazawa *et al.* [1]). They revealed that; (1) the basin consists of three narrow depressions of the basement, E-W and NE-SW trending; (2) the bedrock subsides stepwise at the edge of

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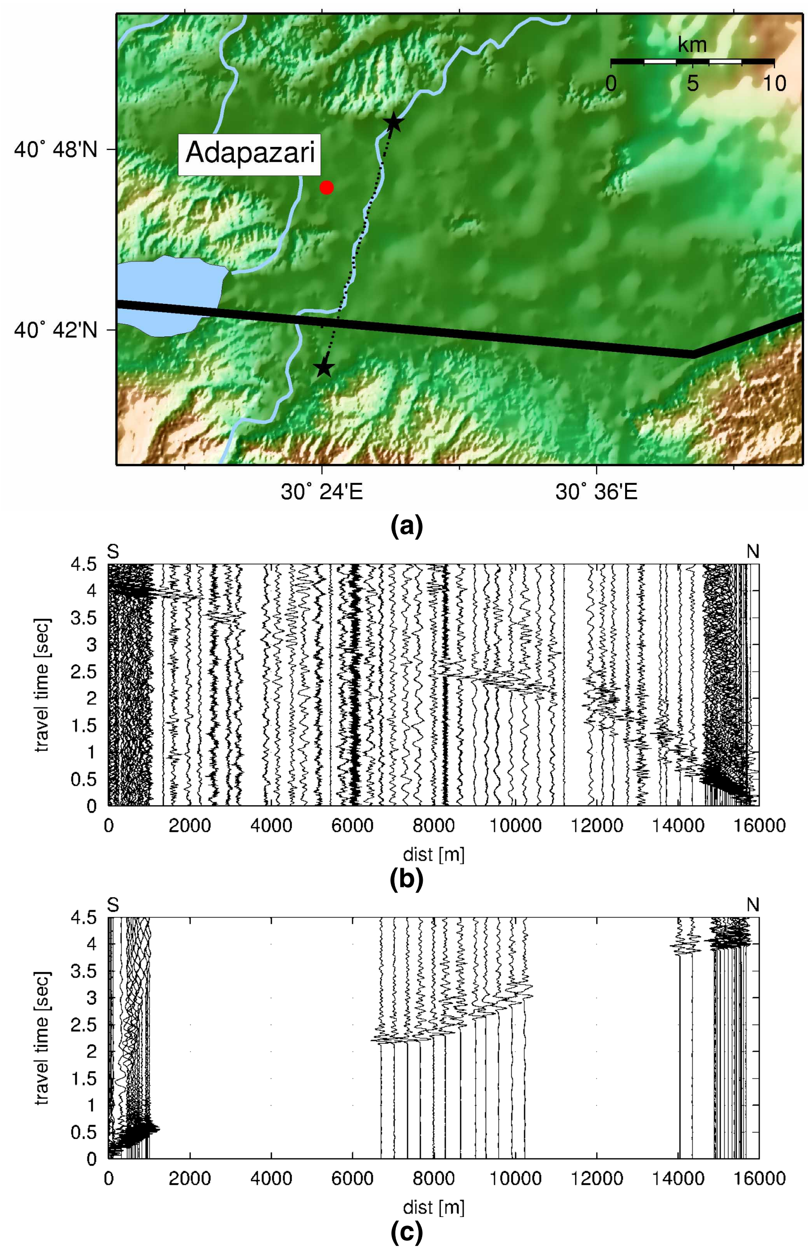
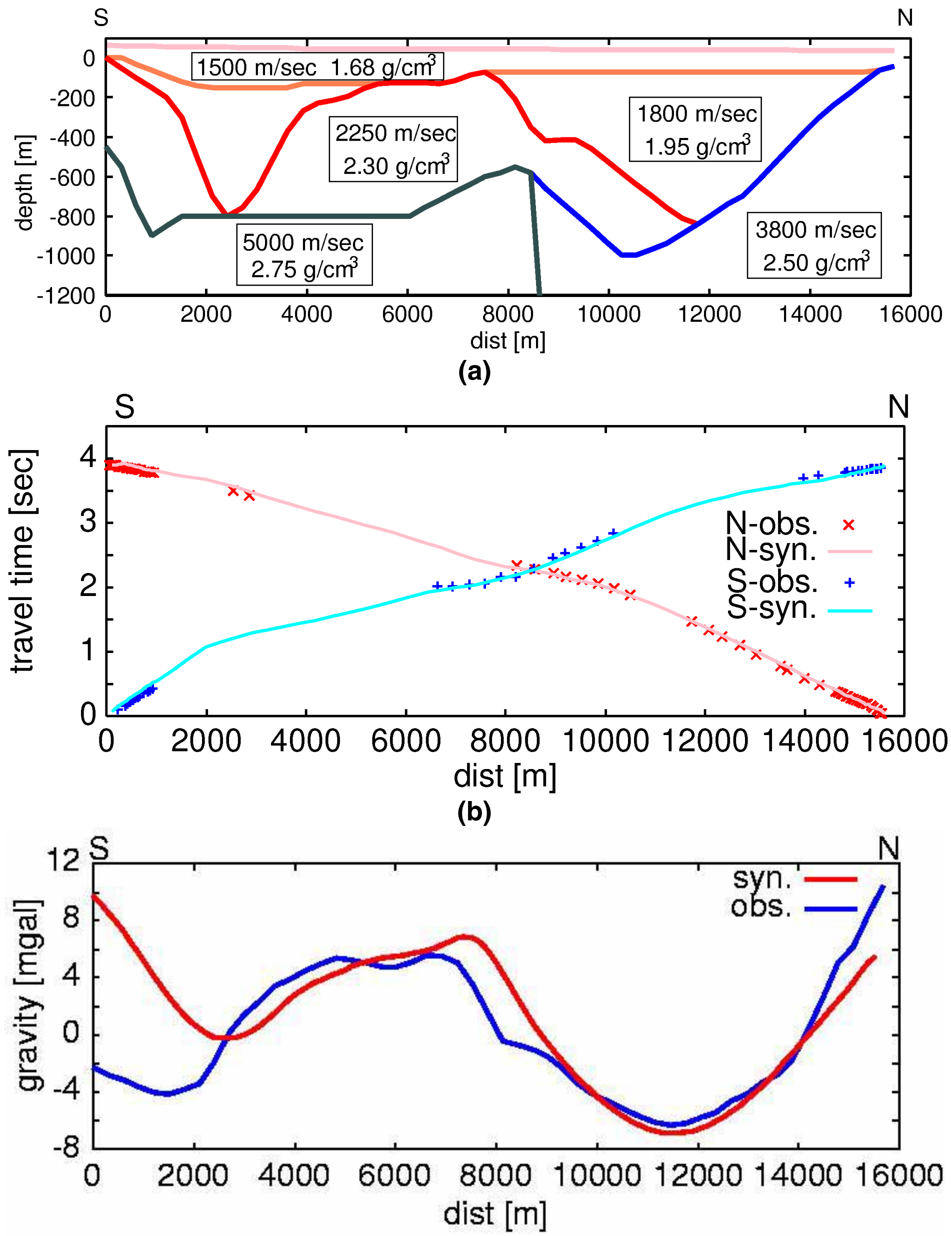


Figure 1: The seismic refraction and reflection survey, (a) location of blasts (★) and receivers (•), (b) the records for the northern blast, (c) the records for southern blast.

depressions; (3) the depth to bedrock reaches 1000-1500 m. We, however, do not know the detailed velocity structures which are necessary to simulate the strong ground motions in the area. Goto *et al.* [3] carried out the seismic refraction/reflection survey to get the information of velocity structure of the basin.

The outline of our study is as follows. A detail of the refraction and reflection survey is introduced. The velocity structure under the survey line has been estimated, based on the observed refraction and reflection waves and verified by the gravity data. 3D model of Adapazari basin is proposed using a cubic B-spline function for representing its shape considering the result of gravity survey, array and single-site observation of microseisms as the constraints in addition to the refraction and reflection survey. Several aftershocks of Kocaeli earthquake are simulated by using the proposed 3D model. Finally, the strong



(c)

Figure 2: The proposed 2D model under the survey line, Goto *et al.* [3], (a) proposed 2D model (P-wave velocity [m/sec] and density [g/cm^3]), (b) calculated first travel times for both blasts, (c) observed gravity anomaly except a trend component and calculated one.

ground motions during the main shock on Adapazari basin are simulated numerically up to 0.4 Hz using the 3D finite-difference methods.

3D MODEL ON THE ADAPAZARI BASIN

Refraction/reflection survey and 2D model [3]

Table 1: Physical parameters and information considered for estimating the depth of upper boundary.

	Vp (m/sec)	Vs (m/sec)	Density (g/cm^3)	Information considered	Number of data
1st soil layer	1500	200	1.68	topography	-
2nd soil layer	1800	500	1.95	array observations of microseisms 2D model	5 53
3rd soil layer	2250	1000	2.30	array observations of microseisms 2D model Komazawa model	5 53 29445
Upper rock layer	3800	2190	2.50	array observations of microseisms single-site observations of microseisms 2D model	5 48 53
Lower rock layer	5000	2890	2.75	array observations of microseisms single-site observations of microseisms 2D model	5 48 53

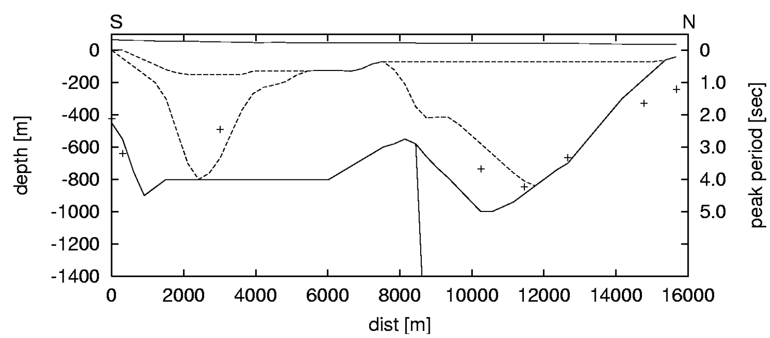


Figure 3: Comparison between predominant periods (+) and depth of bedrock along the refraction/reflection survey line.

A seismic refraction/reflection survey was performed in order to obtain the subsurface geometry of soft sedimentary layers and their seismic properties overlying the bedrock beneath the Adapazari basin. Two blasts were carried out at northern and southern edges of the Adapazari basin on June 15 and 17, 2002. The survey line was set up approximately N-S direction as shown in Figure 1 (a). Bore holes to 50 m depth were prepared and 100 kg of dynamite was used for each seismic blasts. The location of two seismic blasts were 40.8148° N, 30.4521° E for the northern blast and 40.6790° N, 30.4012° E for the southern blast. Seismic refraction waveforms recorded with respect to the northern blast and the southern blast are shown in Figure 1 (b) and (c), respectively.

Goto *et al.* [3] have proposed a 2D model under the survey line as shown in Figure 2 (a). As the recorders at 8280-10200 m from southern blasting point succeed in observing the both shots, subsurface structure at the region can be calculated using the stripping method. The P-wave velocity at this region is obtained as 3800 m/sec, but the average velocity between the northern and southern shots is about 4000 m/sec. Then the disagreement of bedrock structure around 8000 m from southern blasting point is assumed, as shown in Figure 2 (a). In addition, the array observations of microseisms (Komazawa *et al.* [1]) showed that at least three soil layers over the bedrock should be considered. Based on those result, the 2D velocity structure model under the survey line has been proposed, which consist of three soil layers and two rock mediums. This model has been verified by the first arrival travel-times and gravity data, as shown in Figure 2 (b), (c), and both data are calculated well for this model.

3D model based on the survey results

The 2D model reveals some physical parameters of subsurface structure such as density and velocity, whereas 3D shape of each layer is not known. Then, we estimate a 3D model of subsurface structure in the Adapazari basin adding some survey results to constraints.

Komazawa model based on a gravity survey should represent the upper boundary of third soil layer, which has been concluded from the discussion that the density between the second and third soil layer is changed a lot. Then, we add Komazawa model to the constraints of third soil layer for estimation of 3D model. The array observations of microseisms were carried out at two sites near the blasting points (Komazawa *et al.* [1]), and at three sites around the Adapazari city (Kudo *et al.* [2]). 1D structures of layered grounds under the array sites were estimated by these results, which have information of the depth and S-wave velocity of soil layers. The predominant periods was also obtained from the peak of Horizontal/Vertical spectrum of microseisms (Komazawa *et al.* [1]). It is expected that predominant periods correlate with the depth of bedrock. Figure 3 shows the comparison of predominant periods and the depth of bedrock on 2D model. This result shows a strong correlation as $z=-200T$ approximately, where z is depth of bedrock (m) and T is predominant period (sec). We add this information to the constraints of bedrock in the analysis. The information of layers of 2D model is also added to the constraints. The upper boundary of lower rock layer is assumed to exist under 1400 m depth in the northern area from 40°45'30" N, where the bedrock velocity change from 5000 m/sec to 3800 m/sec in the 2D model. The region higher than 200 m of altitude are assumed to be outcrops of bedrock. Table 1 shows the constraints to estimate each shape of layer.

The shape of each layer is represented by a cubic B-spline function. This technique was introduced by Koketsu and Higashi [4] into these objectives. Depth of each layer $z(x,y)$ is written as

$$z(x,y)=\sum_{i=I-1}^{I+2}\sum_{j=J-1}^{J+2} c_{ij} B_{3+I-i}\left(\frac{x-x_I}{w_x}\right) B_{3+J-j}\left(\frac{y-y_J}{w_y}\right) \qquad \left(x_I \le x \le x_{I+1}, y_J \le y \le y_{J+1}\right)$$

$$\begin{aligned} B_1(r) &= \frac{r^3}{6} \\ B_2(r) &= \frac{-3r^3+3r^2+3r+1}{6} \\ B_3(r) &= \frac{3r^3-6r^2+4}{6} \\ B_4(r) &= \frac{-r^3+3r^2-3r+1}{6} \quad , \end{aligned} \tag{1}$$

where x_I, y_J are locations of control points, w_x, w_y are the grid spacing between control points and c_{ij} is the coefficients of control points. c_{ij} are determined by weighted least-square method based on the constraints of each layer listed in Table 1. The weight of least-square method is determined from the number of data set which belongs to the categories of information shown in Table 1. For example, as the number of data set of array observation is 5 for each layer, the weight is set to be 1/5.

Figure 4 (a) shows the "3D model" of the Adapazari basin proposed. This model has three soil layers and two rock mediums which changes at 40°45'30" N. The thickness of the soil layer under the downtown of Adapazari is about 1000 m. Figure 4 (b) shows the profiles of the model along A-A' lines, which passes through SKR and the downtown of Adapazari. The main shock is recorded at SKR during Kocaeli earthquake, as described later for detail. The figure shows that SKR is located on a thinner soil layer than the downtown of Adapazari. These soil layers around SKR and the downtown of Adapazari are separated by the bedrock.

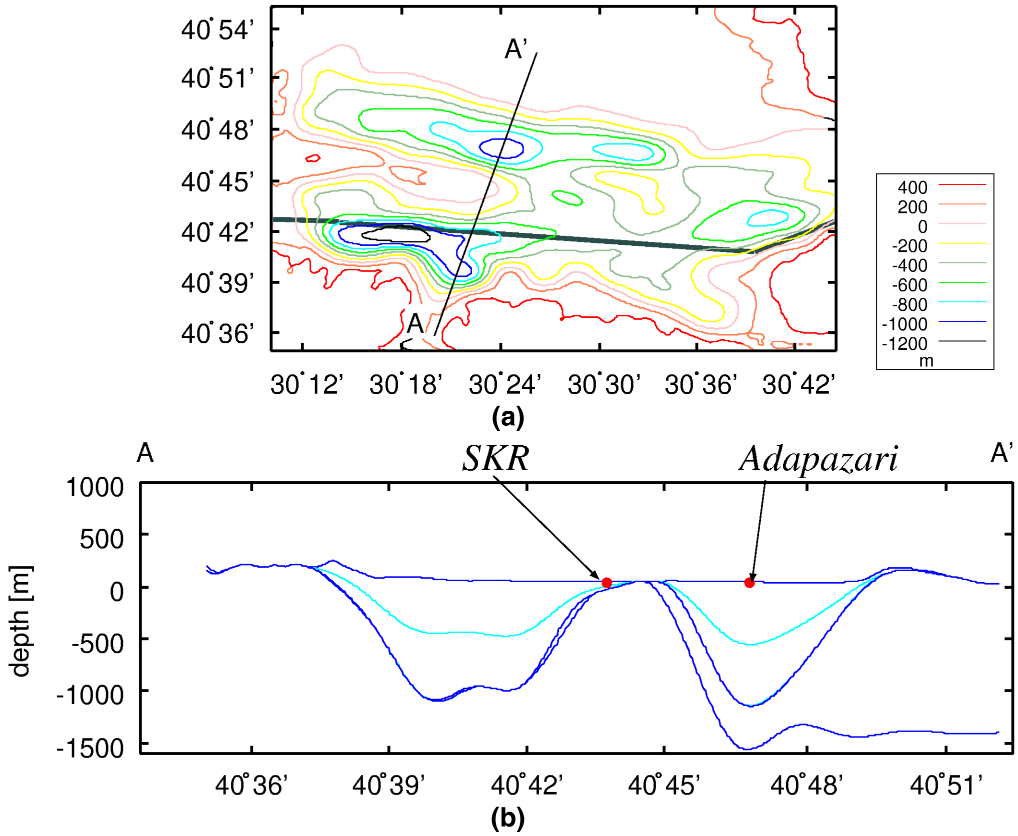


Figure 4: The profile of 3D model, (a) Location of the cross sections, (b) Profile included Adapazari and SKR (A-A').

Verification of 3D model by the aftershock records

There are several aftershock records of Kocaeli earthquake observed on Adapazari basin. We verify whether the simulated waveforms of aftershocks using the 3D model agree well with the observed ones.

In the simulation, we use a staggered-grid finite-difference method (FDM) (Graves [5], Pitarka [6]) with forth order approximation for space and second order approximation for time. The model for the simulation consists of an area of 49.4 km (E-W) × 37.4 km (N-S) and its south-west corner is located at 40°34'43" N and 30°09'55" E. 100 m of grid spacing and 0.0079 sec of time step are adopted whose values make the effective frequency range up to 0.4 Hz. Anelastic attenuation is considered using Graves method (Graves [5]) assumed as $Q=V_S/15$, where V_S is S-wave velocity and its unit is m/sec. 6 CPUs are used for parallel computing of FDM separating the calculation area into 6 by the N-S section.

Aftershock events are chosen by the criteria that their epicenters and observed sites are located in the simulated area. Table 2 shows the aftershock events used, Table 3 lists the site where the aftershocks are observed. They are also shown in Figure 5. The observed records and the site locations are referred to USGS OFDA PROJECT website [7]. The information of source parameter is reported by Örgülü and Aktar [8].

The ground motions during aftershock events are simulated using the 3D model mentioned before. A low-path filter of 0.4 Hz is applied to the simulated waveforms and the observed waveforms. Figure 6 shows the comparison of the simulated results with the observed waveforms, whose time axes are moved in order to match their predominant phases well because the time records of the observed are sometimes

Table 2: Aftershock events and its source parameter, Örgülü and Aktar[8].

Date	Time	Latitude	Longitude	Mw	Azimuth	Dip	Rake	Depth
Nov. 07, 1999	16:54	40.65° N	30.69° E	4.5	282°	64°	166°	7.0 km
Nov. 11, 1999	14:41	40.78° N	30.29° E	5.5	307°	66°	179°	22.0 km

Table 3: Stations for aftershock records.

Station Code	Latitude	Longitude	Nov. 07	Nov. 11	Data sources
c0362	40.6698° N	30.6655° E	O	O	LDEO-USA*
c1060	40.7773° N	30.6128° E	O	O	LDEO-USA*
TYR	40.737° N	30.380° E	O	—	USGS-GOLDEN-USA**

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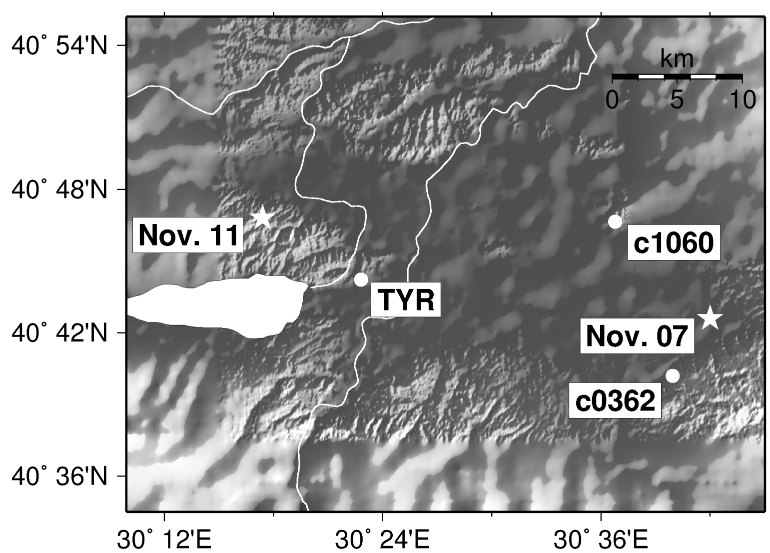

Figure 5: Epicenter of aftershock (Nov. 07, and Nov. 11) and observed station (TYR, c1060, and c0362).

incorrect. It is considered that it is difficult to simulate the waveforms at c0362 site during Nov. 7, 1999 aftershock because they are located near the basin edge where none of surveys have been performed. The observed records may be affected by the detailed location of the source and the site relative to the basin edge. The significant phases of simulation waveforms at c1060 represent well the observed one. S-wave radiation pattern of this aftershock implies that amplitude of NS component at TYR station is larger than the other components, which is recognized by the simulation results. Source parameter of the aftershock is determined from all of the observed data as well as Adapazari region. There is no information to modify the source parameter to simulate the waveform at TYR well. The surface waves at c0362 station

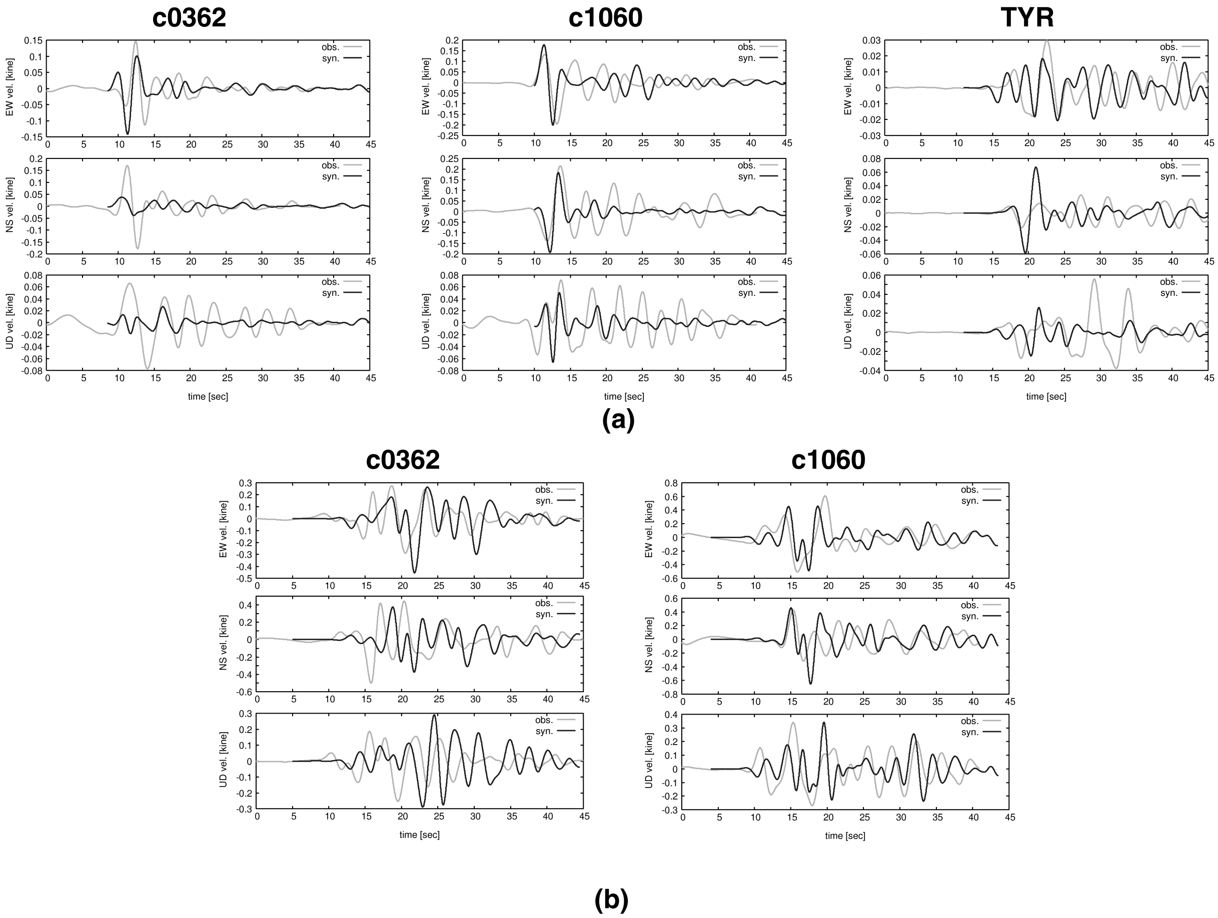

Figure 6: Observed waveforms of aftershock and simulation waveforms using 3D model, (a) Nov. 07, 1999 aftershock, (b) Nov. 11, 1999 aftershock.

may be simulated as similar as the observed one during Nov. 11, 1999 aftershock, in spite of difficulties due to the site location. The simulated waveforms at c1060 during Nov. 11 1999 aftershock look similar to the observed ones up to about 15 seconds.

NUMERICAL SIMULATION OF KOCAELI EARTHQUAKE

The ground motions during the main shock of Kocaeli earthquake have been recorded only at SKR (Sakarya) site (40°44'13" N 30°23'02" E) on the Adapazari basin. SKR is located in the region where moderate damage occurred in comparison with the downtown of Adapazari (Figure 7). It is obvious that the observed record at SKR does not represent strong ground motions at the downtown of Adapazari. Then, we try to reveal how the strong motions at the downtown of Adapazari were affected by 3D subsurface structure by the simulation on the Adapazari basin. The method for the simulation mentioned in previous section is also used.

Rupture model during the main shock proposed by Sekiguchi and Iwata [9] is adapted as the source model for this simulation. Their model is constructed along 100 km length of the fault which consists of 4 rectangle segments. We use only a part of their model included in the simulation area. It is confirmed by comparing the calculated waveform at SKR from all rupture process and the part of rupture process used for the simulation. Figure 8 shows these displacement waveforms calculated by the representation

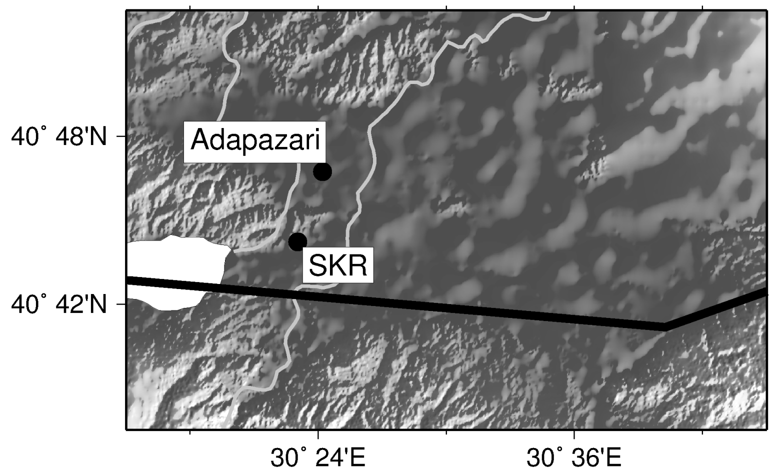

Figure 7: Location of SKR and the downtown of Adapazari.

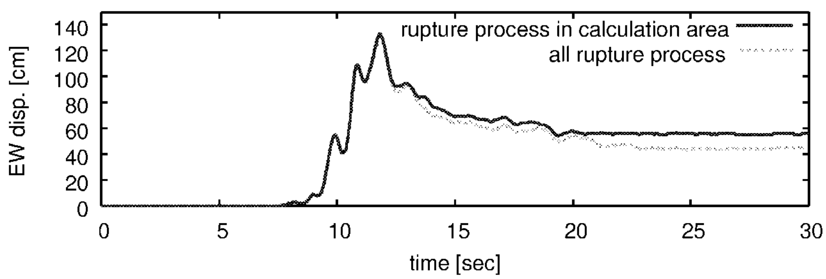

Figure 8: SKR waveform calculated representation theorem, pale line waveform come from all rupture process and deep line waveform come from limited rupture process in calculation area.

theorem using a homogeneous medium. It is concluded that the limited source model in the calculation area can estimate the waveforms on Adapazari basin.

The proposed 3D model is used for the simulation. We add horizontal layers for deep structure under the 3D model, as shown in Table 4, which is used for the analysis of rupture process (Sekiguchi and Iwata [9]). The ground surface of simulation area is assumed to be horizontal because FDM with irregular free surface has a tight stability condition. Simulation area is surrounded with the absorbing boundary by Cerjan *et al.* [10].

Figure 9 (a) shows the observed and simulated waveforms at SKR, where N-S component was not observed unfortunately. A low-pass filter of 0.4 Hz is used for the observed and simulated waveforms because effective frequency range for the simulation is up to 0.4 Hz. The first motion of the simulated waveforms agrees well with the observed, that show a validity of the numerical simulation. The waveforms at the downtown of Adapazari (40°46'44" N and 30°24'12" E) shown in Figure 9 (b) is larger than those at SKR for each component.

In order to know why the large amplification is obtained at the downtown of Adapazari, we conduct another simulation using 1D model. 1D model is assumed to have horizontal layered ground which has the same physical parameters and thickness as the 3D model just under the downtown of Adapazari. Note that the boundaries of each layer are discretized into every 100 m because of the same discretization is done for the finite-difference model. SH-wave propagation up to ground surface is calculated by Haskell Matrix method (Haskell [11]). The incident wave for 1D simulation is calculated on the upper interface of

Table 4: Physical parameter of 3D model.

	Vp (m/sec)	Vs (m/sec)	Density (g/cm^3)	Top Depth (m)
1st soil layer	1500	200	1.68	-
2nd soil layer	1800	500	1.95	-
3rd soil layer	2250	1000	2.30	-
1st rock layer	3800	2190	2.50	-
2nd rock layer	5000	2890	2.75	-
3rd rock layer	5150	2970	2.75	2000
4th rock layer	5380	3110	2.75	4000
5th rock layer	5640	3250	2.75	5000
6th rock layer	5870	3390	2.75	7000
7th rock layer	6060	3500	2.75	9000
8th rock layer	6170	3560	2.75	11000
9th rock layer	6230	3600	2.77	13000

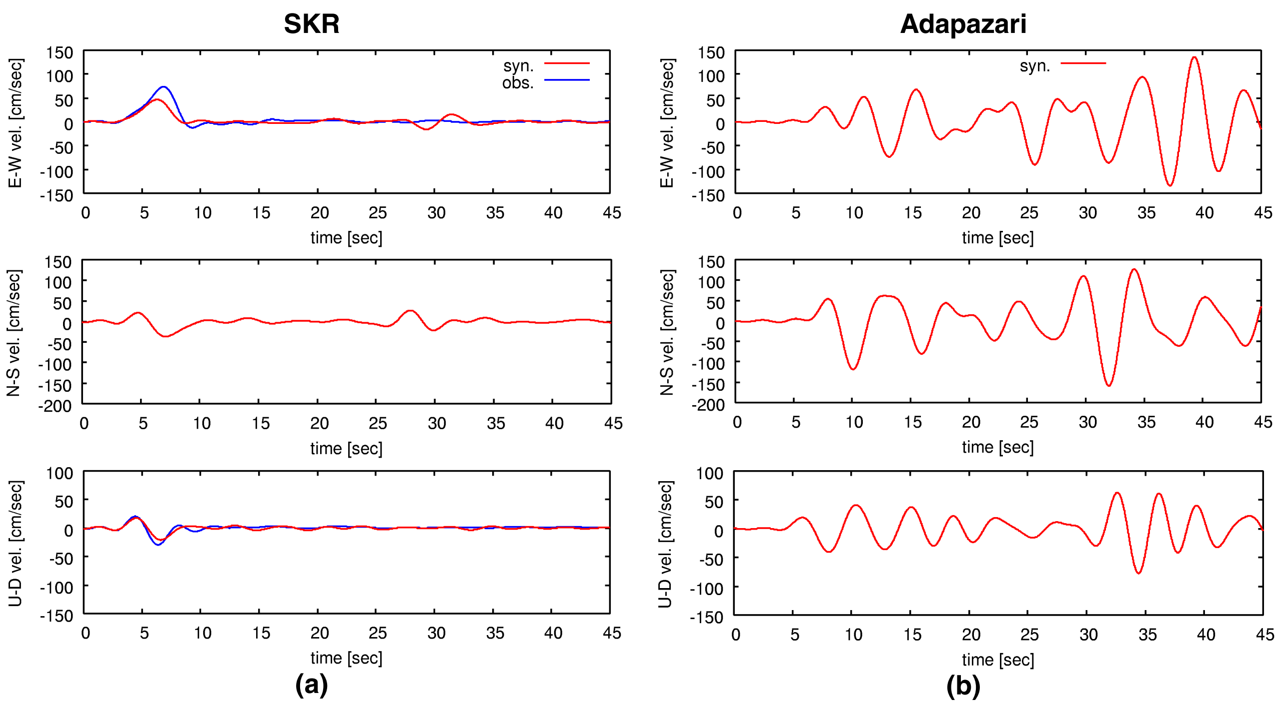

Figure 9: Simulated waveform using 3D model and observed ones, (a) E-W, N-S, U-D waveforms at SKR, (b) E-W, N-S, U-D waveforms at downtown of Adapazari.

lower rock layer of the 3D model by finite-difference method. Figure 10 shows the comparison of waveforms at the downtown of Adapazari obtained from 1D model and 3D model. The peak velocity of E-W component for 1D model is less than that for 3D model. This result shows that the reason of amplification at the downtown of Adapazari can not be explained by one-dimensional horizontal soil layers.

Figure 11 shows the distribution of peak velocity on the Adapazari basin obtained by 3D simulation. It is indicated that the region with the large peak velocity is distributed around the seismic fault, a part of the North Anatolian faults. It is also shown that the ground motions are greater at the downtown of Adapazari in comparison with the region around SKR. This implies that the numerical simulation of strong ground motions using 3D model explains the distribution of damaged area during the earthquake.

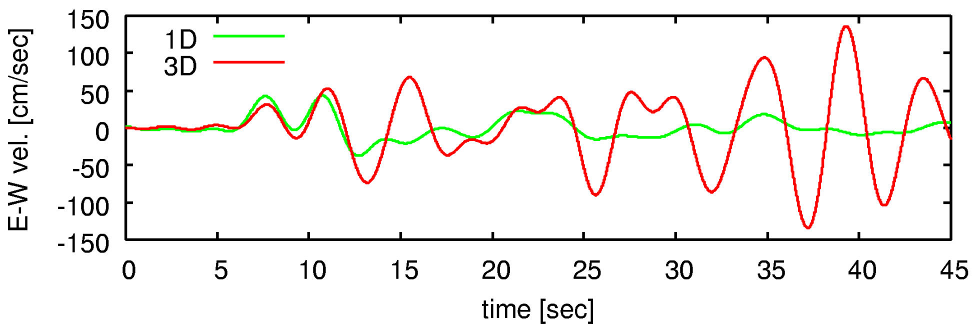

Figure 10: Comparison between simulated waveform (E-W) by 3D and 1D model.

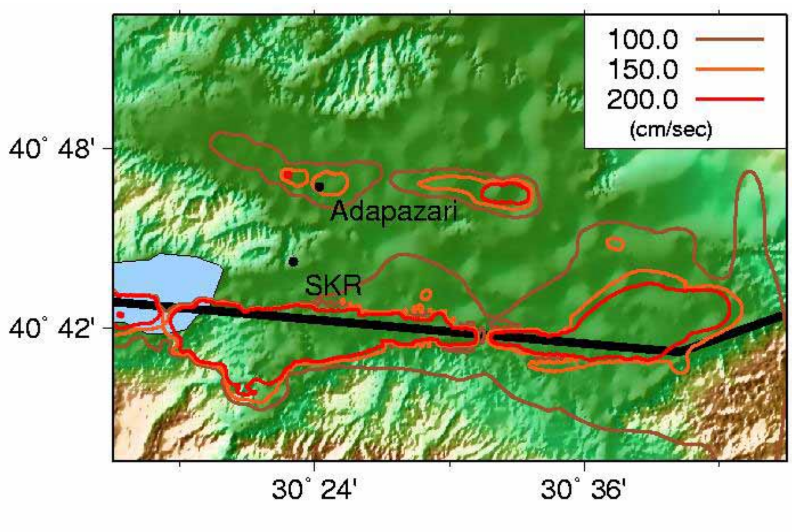

Figure 11: Simulated distribution of peak velocity on Adapazari basin.

CONCLUSION

3D velocity structure of Adapazari basin, which consists of three soil and two rock mediums, is proposed on the basis of the refraction and reflection survey, array and single-site observations of microseisms and gravity survey. The gravity basement from Komazawa model is used for the upper boundary of third soil layer, because the gravity basement is not considered to represent the bedrock. The proposed 3D model is verified using aftershock records. The strong ground motions on the Adapazari basin during the Kocaeli earthquake are numerically simulated using the proposed 3D model. The results of simulation showed that 3D subsurface structure of Adapazari basin amplified the ground motions at the downtown of Adapazari in comparison with the region between the downtown and the seismic fault.

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