

ESTIMATION OF STRONG GROUND MOTION AT DAMAGED AREAS (ADAPAZARI, GOLCUK) DURING THE KOCAELI, TURKEY EARTHQUAKES OF AUGUST 17, 1999

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SUMMARY

The estimation of strong ground motions at downtown Adapazari and Golcuk, where heavy damage was observed, is inevitable to understand the relation between ground motion severity and damage to buildings. For this purpose, we adopted the empirical Green's function method for ground motion synthesis using observed aftershock recordings. First, we estimated the bedrock motion and then convolved the effects of surface sediments taking into account of nonlinear behaviors of soil by the equivalent linear method. We selected five large asperities from the heterogeneous source model determined by Sekiguchi and Iwata (2002) for synthesizing the ground motion from the mainshock. The validity of this simulation was confirmed by the comparison of the strong motion records and the synthetics at several stations near the fault.

INTRODUCTION

Major damage to buildings and loss of life during the Kocaeli (Izmit), Turkey earthquake, were concentrated near the surface earthquake fault, therefore, the primary reasons for the damage are attributed to near earthquake source effects, leaving aside the quality of buildings. The strong motion records from the Kocaeli earthquake near the fault were successfully recovered by the Earthquake Research Department, and the Kandilli Observatory. However, because of a sparse network in Turkey (Celebi [1]), no strong motion record was obtained at severely damaged areas, except Duzce (DZC). The strong contrast of damage ratios between the strong motion observation site, Sakarya (SKR) and downtown Adapazari, and the wide variation of the damage ratios even in the relatively small area of Golcuk (Architectural Institute of Japan Reconnaissance Team [2]) are also similar issues. It is our concerns to estimate the severity of the ground motions at damaged areas.

The shallow and intermediate-depth S-wave velocity structures in Adapazari and Golcuk areas were determined by the array observation of microtremors (Kudo [3]). In addition, we also conducted temporal array observations of aftershocks to understand the relative differences of site effects on strong motion or damage in and around Golcuk, near the surface fault. It is our concerns to estimate the strong ground

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motions at the severely damaged areas, especially at downtown Adapazari and Golcuk. In case of Adapazari, the ground motion at SKR is able to use as an input motion to sediment sites, or bedrock motion, for roughly estimating the ground motions in downtown Adapazari (e.g. Kudo [3]; Bakir [4]), since the S-wave velocity near the surface at SKR is approximately 1,000 m/sec or higher and the distance between SKR and downtown sites is not large. However, there still exist uncertainties, which are the NS motion, near source radiation effects, nonlinear effects of surface soils, and so on. The case of Golcuk is much difficult task, because we have no record near by the sites and the damaged areas in Golcuk, where surface soils are very soft, was very close to the surface earthquake fault.

Nevertheless very limited data and these difficulties, this paper is an attempt to estimate strong ground motions at damaged areas using the empirical Green's function method with regards for source complexities (asperities) and nonlinear amplification of seismic waves in sedimentary basins.

SITE CHARACTERISTICS OF STUDIED AREA

Studied areas that we made temporal aftershock observations and array observations of microtremors are shown in Figure 1, with permanent strong motion observation sites SKR, YPT, and IZT and the surface earthquake fault (e.g. Barka [5]). A temporary aftershock observation, which was very short period (three days), was conducted at GLS, GLA, GLF, GLJ, and GLN in the Izmit bay area including YPT (Figure.1). The array observations of microtremors were carried out at SKR, ADC, ADU, YPT, GLF, and GLN and the S-wave velocity structures of sedimentary layers are estimated. The estimated S-wave velocity structures are shown in Table 1, which are mostly reproduced from Table 3 in Kudo [3] with slight modifications. Underground structures at GLA and GLJ, where only aftershock observations were carried out, were estimated using the following procedures.

- 1. Compute the ratios of the aftershock motions at GLA and GLJ to those at GLF.
- 2. Computation the site amplifications at GLF based on the 1-D propagation theory using the Swave velocity structure obtained by the array observation of microtremors. The density of each layer is estimated by using the empirical relation (Ludwig at al., 1970).
- 3. Estimate the site amplifications at GLA and GLJ convoluting the spectral ratios computed in STEP 1 and the theoretical site effects at GLF (STEP 2).
- 4. The S-wave velocity structures at GLA and GLJ are inverted from the site amplifications computed in STEP 3 by the genetic algorithm (GA) (e.g., Yamanaka [6]).



Figure 1. Studied area showing the locations of epicenters of the mainshock, the aftershocks, and observation sites.

Figure 2 shows the comparison of the theoretical site amplifications with the convoluted ones. We assume further that common seismic basements (bedrock) among sites in Golcuk and Adapazari are the layers of which S-wave velocities are 950 m/sec and 1,500 m/sec, respectively. It is also assumed that the seismic basement of similar S-wave velocity outcrops at GLS and IZT. The studied areas are very close to the surface earthquake fault, especially the observation sites GLN, GLJ, and GLF are located within a distance of a few hundreds meters from the fault. While the distance of ADC and ADU in Adapazari area from the fault are 6 km and 10 km, respectively.



Figure 2. The comparison of the theoretical site amplifications by the genetic algorithm with that of the convoluted ones

SKR		ADC			ADU	YPT	
Vs	Thickness	Vs	Thickness	Vs	Thickness	Vs	Thickness
1050	72	234	38	166	44	344	42
1500		441	97	331	88	445	94
		728	242	500	281	591	90
		1500		878	63	727	290
				1050	100	950	
				1500			
GLN		GLF		GLA		GLJ	
Vs	Thickness	Vs	Thickness	Vs	Thickness	Vs	Thickness
283	19	150	14	71	5	299	49
512	52	259	70	168	12	392	80
694	97	531	270	297	64	629	239
752	61	950		597	297	950	
950				950			

 Table 1. The S-wave velocity structure model estimated by the array observations of microtremors (Kudo [3]) and the inversion analysis of spectral ratios of the aftershock records using the GA.

unit Vs: m/sec; Thickness: m, ---: infinity

ESTIMATION BY THE EQUIVALENT LINEAR METHOD FOR SOIL RESPONSE

We estimated the strong ground motions during the mainshock in the Adapazari sites similarly to Kudo [3], but taking into account for nonlinearity of soils. First, we estimated the incident wave at ADC and

ADU by deconvolving the responses of the surface layers estimated by microtremors at SKR from the mainshock record based on the equivalent linear method (Schnabel [7]), while the computer code developed by Yoshida [8] was used. Next, the estimated input motion is convolved with the response due to the velocity structure models at ADC and ADU, assuming a common seismic bedrock of which S-wave velocity is 1,500 m/sec. Distances form the surface earthquake fault to SKR, ADC, and ADU are 3.4 km, 6.4 km, and 9.6 km, respectively, therefore, a distance correction would be necessary, when we use the ground motion at SKR for input motions to ADC and ADU. As mentioned before, we assumed that the contribution of source to strong ground motion were only five large asperities as shown in Figure 6 (discuss later). We evaluated the distances of those sites using the method of equivalent hypocentral distance (Ohno [9]) by only taking into account the number 3 asperity (see Figure 6), which was closest to the Adapazari area.

Since we have not enough data on soil properties at those sites, we used the representative dynamic model of soil property $(G/G_0-\gamma, h-\gamma)$ proposed by Osaki [10] for equivalent linear analyses. While, we used the effective strain proposed by Sugito [11], for taking into account damping factors, in which the strain of each layer depends on frequency as equation (1).

$$\gamma_{\rm eff}(\omega) = \alpha \gamma_{\rm max} F(\omega) / F_{\rm max}$$
⁽¹⁾

where ω is angular frequency, $\gamma_{eff}(\omega)$ and $F(\omega)$ effective strain and Fourier spectra of ground motion strain at ω , respectively. γ_{max} and F_{max} are the maximum strain and the maximum value of their spectra, respectively. α is the coefficient (0.65) for the equivalent linear method. In addition, we assumed that the soft layers of which S-wave velocity is lower than 400 m/sec were taken as sand, because of less information of soil properties. An analysis was made for only EW component because of lack of record of NS motion at SKR during the mainshock and the frequency ranges between 0.1 Hz to 10Hz was used following processing.

Figure 3 shows thus estimated ground motions in terms of acceleration and velocity. The equivalent hypocentral distances of SKR, ADC, and ADU are 10.1 km, 11.4 km, and 14.1 km, and then correction factors become 0.89 and 0.72 at ADC and ADU, respectively. The estimated peak acceleration at ADC is not so high relative to SKR (factor of 1.1), may due to large damping at high frequency range, while the peak velocity is a factor of approximately 2 that would be significant damage to building. This is the case that we assumed the surface layers of both sites to be sand.



Figure 3. Estimated strong ground motion during the mainshock in downtown Adpazari by and the equivalent linear method using the observed earthquake records at SKR that were corrected for distances and responses of surface layers.

SOURCE MODEL AND SYNTHETIC MOTIONS BY THE EMPIRICAL GREEN'S FUNCTION METHOD

Near source effects on ground motion are not only distance but also source geometry and fault rupture processes. In order to consider the effects, we employed the empirical Green's function (EGF) method developed by Irikura [12], Irikura [13] and Kamae [14].

Empirical Green's function

We used the records from the largest aftershock (M5.8) of September 13, 1999, at SKR, IZT, and YPT as EGF. At first, we deconvolved the responses of the surface layers from strong motion records based on the above-mentioned equivalent linear method. The effects of nonlinear behavior of soils at SKR and IZT are negligibly small but we processed to keep uniformity of the analyses. We used the deconvolved bedrock motions from the largest aftershock, thus obtained, as Green's functions for those sites. The synthetic motion was first constructed as a bedrock motion at each site and then it was convolved the response of surface layers by the equivalent linear method as mentioned above.

Effects of radiation pattern

Source radiation effects are sometimes ambiguous or frequency dependent. Kamae [14] suggested a method to consider the frequency dependency of source radiation pattern that the observed radiation pattern in a longer period range has a tendency to follow the theoretical one, however, it tends to uniform for all directions in short period range. We assumed the low frequency to be 0.2 Hz and the high frequency to be 2 Hz, and the weights between two frequencies were given following Kamae [14]. In order to include the source radiation pattern effects, because of the differences of strike and dip of a fault between the main- and the aftershock and the geometry of the extended fault (asperities) of the mainshock, we first rotated the axis of the bedrock horizontal (NS and EW) motions into radial and transverse motions. Next, the rotated waveforms of the small event are corrected concerning to the radiation pattern, source time function, and time shift for including rapture propagation and then they are summed. Thus obtained synthetic bedrock motions were convolved the response of surface layers by the equivalent linear method as described before and they rotated again to NS and EW directions.

Asperity model

The complex fault processes for the Kocaeli earthquake have been investigated using strong motion records by Sekiguchi [15] and Bouchon [16], as well jointly with the other data by Yagi [17], Li [18], and Delouis [19]. We only intend to estimate strong ground motion of relatively high frequency, say from 0.3 to 10 Hz, therefore, the constraint by static or long-period motion is not necessarily required. We selected five asperities, as shown in Figure 4, referring mostly to the source inversion results by Sekiguchi [15]. We, in addition, assumed that the strong motion was generated by only these asperities. In order to confirm the validity of our procedures, we obtained the synthetic motions for the mainshock at SKR, IZT, and YPT. Figure 5 compares the synthetic strong motion with the observations with velocity waveforms and Fourier spectra. Minor modifications, like forward modeling, from the model by Sekiguchi [15] were made, so as to obtain good match between synthetics and observations. The final characterized asperity model is shown in Table 2. The frequency ranges in the analyses were restricted to 0.1-10 Hz for SKR and YPT, and to 0.4-10 Hz for IZT, due to the S/N ratios of the aftershock records. A somewhat disagreement in the synthesized strong motion for IZT at high frequency, however, generally the synthetics are in good agreement with the observations. Therefore, we inferred that these procedures and the fault model represented by five asperities would be valid. The numbers of subfaults are 6x4, 2x1, 4x3, 3x2, and 2x2for the asperities from No.1 to No. 5, respectively, and the ratios of stress parameters are 1.5, 1.0, 1.5, 3.0, and 1.0 for the asperities from No.1 to No.5, respectively, as shown in Table 3.



Figure 4. Complex fault model, which have five asperities referring to Sekiguchi [15] and Kamae [20]. Locations of earthquakes and observation sites are also plotted.

Asperity	Rapture starting point		Mech. (degree)		Size (km)		Vs	Vr	Stress		
	Lat.	Long.	Depth	Dip	Strike	Slip	L	W	(km/sec)	(km/sec)	Drop (bar)
1	40.700	29.910	15.9km	80	89	180	30	20	3.6	2.5	120
2	40.699	29.999	4.5km	80	91	180	10	5	3.6	2.5	80
3	40.692	30.301	13km	80	95	180	20	15	3.6	2.8	120
4	40.701	30.017	15.9km	80	91	180	15	10	3.6	3.0	240
5	40.695	29.483	15.9km	80	89	180	15	10	3.6	3.0	80

Table 2. The source parameters of each asperity.

 Table 3. The source parameters of the largest aftershock and parameters for synthesis

 from the largest aftershock records to strong motion during the mainshock.

	Hypocent	er	Si	ze	Stress Drop	
Latitude	Logitude	Depth (km)	L (km)	W (km)	(bar)	
40.80	30.03	4.3	5	5	80	

ESTIMATION OF GROUND MOTION IN DOWNTOWN ADAPAZARI BASED ON EGF

A lack of the NS component of strong ground motion at SKR during the mainshock brought large ambiguity on estimating the severity of ground motion in downtown Adapazari. A forward directivity effect (e.g. Somerville [21]) on NS motion is the one plausible suggestion. The EGF method enables us to estimate the NS motion at SKR and at downtown Adapazari using both horizontal motions from the largest aftershock. Figure 6 shows the estimated ground motions at SKR, ADC, and ADU. The EW motion at SKR is only compared with the observation. The NS component of strong motion at SKR is estimated to be 126% in the peak ground acceleration, however, the peak ground velocity is 87% of the synthesized EW motion, which is smaller than that we expected. Estimated strong motions are prominent in long period (3-4 sec.) The peak velocities at ADC and ADU are factors of 2.8 and 1.2 to that at SKR.



Figure 5. Comparison of the synthetic waveforms during the mainshock from strong motion records during the largest aftershock with the observed earthquake motions during the mainshock.

ESTIMATION OF STRONG GROUND MOTION IN GOLCUK AREA

We examined whether we were possible to synthesize the strong ground motion during the mainshock near Izmit Bay area and Adapazari, using the largest aftershock motion. This would be applicable for Golcuk area, however, unfortunately no strong motion record from the largest aftershock was available in Golcuk area. Therefore, we have to estimate the largest aftershock motion in order to synthesize strong ground motion during the mainshock. We will apply two-step estimation, that is, we first simulate the ground motion in Golcuk area during the largest aftershock using two small aftershock data, and next we estimate the ground motion during the mainshock using the simulated aftershock motion as EGF.

Synthesis of the largest aftershock motion using small (M3) aftershocks.

Quite temporal aftershock observations were carried out in Golcuk area (Kudo [3]), however, a sparse of instruments, we were obliged to separate observations into 2 groups. The aftershock data of September 13, 1999, (event A) were obtained at GLS, GLA, GLF, and YPT (Group A). Those of September 15, 1999, (event B) were acquired at GLF, GLJ, and GLN (Group B). We estimate earthquake motion during the largest aftershock in Golcuk area using these small events as EGF, similar to the study in Adapazari area.



Figure 6. Synthetic NS component of strong motion at SKR and simulated waveforms at ADC and ADU during the mainshock using the empirical Green's function method.

At first, we use the site YPT as a constraint for determining the source parameters, because both records from the largest and small (event A) aftershocks were obtained. We assumed the small event had the isotropic radiation pattern of 0.63 (Boore [22]), and used the bedrock motions, which the response of surface soil were deconvolved, as the empirical Green's functions at those sites. As a result of forward modeling, we obtained the synthetic parameters that a number of subfaults and ratio of stress parameter were 9x9 and 20, respectively, as shown in Table 4.

Figure 7(a) shows a comparison of the synthetic waveform for the largest aftershock with the observed one at YPT. The synthetic waveform matches well with the observations, and then we synthesized the largest aftershock motions at the Group-A sites (Figure 7(b)). Next, we determine necessary parameters for synthesizing the largest aftershock motions at other sites using the small event B. Both A and B events were recovered at GLF, therefore, the parameters were determined so as to match the synthetic motions of the largest aftershock at GLF by comparing their waveforms. Figure 8(a) shows comparison of synthetics for the largest aftershock at GLF using the small event A and B. They are in good agreement, therefore, it is possible to synthesize earthquake motions for GLJ and GLN during the largest aftershock using records from the small event B. The determined parameters for the synthetics are subfaults of 9x7 and the stress parameter ratio of 12 and the others are shown in Table 4. Figure 8(b) shows the synthetic waveforms during the largest aftershock at Group B stations.



Table 4. The source parameters of the aftershocks A and B.

Figure 7. (a): Comparison of strong motions at YPT during the largest aftershock synthesized from the earthquake records of the aftershock A with the observed earthquake motions. (b): The earthquake motions during the largest aftershock at GLS, GLA, and GLF synthesized by using the aftershock A.



Figure 8. (a): Comparison of the earthquake motions at GLF during the largest aftershock synthesized from the earthquake records of the aftershock A with those of the aftershock B. (b): The earthquake motions at GLJ and GLN during the largest aftershock synthesized from the earthquake records of the aftershock B.

The estimated bedrock motions at individual sites during the largest aftershock synthesized from small events have differences of a factor 2 in amplitude; however, the phase characteristics are similar among the sites in Golcuk area. Therefore, we postulated that the incident waves or the bedrock motions during the largest aftershock in Golcuk area is identical, because the Golcuk area is relatively narrow and comparatively far from the largest aftershock. Therefore, bedrock motions should be almost identical in the area. At first we computed the average of Fourier amplitude spectra among four sites except for GLS. Next, we estimated the common input motion at individual sites by the Fourier inverse transformation using the averaged amplitude and each original phase characteristic. The reason why we exclude only GLS is that Vs near the surface at GLS is higher than that of the common bedrock at the other sites. Figure 9 shows the averaged bedrock motion during the largest aftershock in sedimentary area of Golcuk.

Synthesis of the mainshock strong ground motion using the estimated largest aftershock motion

We apply the parameters for synthesizing the mainshock motion in Golcuk area used in the previous section. The common synthetic motion is used as EGF at bedrock for the individual sites. Figure 10 shows the NS component of synthesized strong ground motion during the mainshock. The strong ground motion at GLS is wealthy with short period motions.



Figure 9. The Averaged velocity waveforms on the bedrock during the largest aftershock in Golcuk area.

The PGA is larger than the other sites (649 cm/sec²), while the PGV is not so large (47 cm/sec). The PGA and PGV at GLA are estimated to be 400 cm/sec² and 80 cm/sec, respectively. Severe damage around GLA is due to this large seismic motion. Although the PGA and PGV at both of GLF and GLJ are estimated to be 300-400 cm/sec² and approximately 50 cm/sec, respectively, the period contents included in the synthetic waveform are longer than those of GLS.

The NS component of estimated strong ground motion at GLN is the largest among the studied sites and the PGA and PGV are 642m/sec² and 88 cm/sec, respectively. The underground structure at GLN estimated by the array observations of microtremors is rather stiff than that at GLF; therefore, the site amplification factor computed using the structure at GLN based on 1D propagation theory is predominated with short period motion. Nevertheless the amplification factor at GLN is smaller than that of GLF, the ground motion at GLN is much larger than GLF. As one of the reason of this, it is possible that damping of soil did not become large since strong nonlinearity of the soil did not occur. Furthermore, although the amplitude of the NS component at GLF and GLJ is almost same as one of the EW component, NS component at GLN is larger than EW component and also that at GLF and GLJ. This is considered to be the influence of forward directivity by fault rapture having propagated toward GLN from GLF.

COMPARISON OF ESTIMATED STRONG GROUND MOTION WITH THE SIGNIFICANT EARTHQUAKE RECORDS

We verify strong motion level at damaged area compared with the significant strong motion records, using acceleration response spectra of 5% damping computed from vectorial summation of two horizontal time histories of responses.

Figure 11 shows acceleration response spectra of strong ground motion estimated using the EGF method at Adapazari and Golcuk areas together with those of some historical recordings. Response spectra at SKR in the shorter period range than 0.5 sec. are larger than ones at Hachinohe from the Tokachi-oki earthquake of 1968 and at El Centro from the Imperial Valley earthquake of 1940; on the other hand, those are similar in the longer period range. The strong



Figure 10. Estimated strong ground motions in Golcuk area during the mainshock.

ground motion level at ADC, moderately damaged area in Adapazari, is larger than those in the longer period range than 1 sec., especially at the period of about 2 sec., it becomes factor of 3 to those of Hachinohe and El Centro. This is qualitatively consistent with the severe damage to medium-rise buildings. While, the acceleration response at ADU, where the buildings were mostly one or two stories and scarcely damaged, is smaller than that at SKR and Hachinohe in the shorter period range than 1.5 sec. This is also correlated with less damage to low-rise buildings near ADU.

Response spectra in Golcuk area, except at GLS, show very high level in the longer period range than 1.0 sec., exceeding to that of JMA Kobe from Hyougo-ken numbu earthquake of 1995. Although we are required to find quantitative relation between ground motion and damage to buildings, however, heavy damage to medium-rise buildings in Golcuk area is much easier to understand qualitatively. Arai [23] also estimated the mainshock ground motion as well as the damage to buildings. The site effects are considered similar to us; however, bedrock motion is estimated by the empirical Green's function method. The both levels of ground motion in terms of acceleration response spectra are similar; however, frequency contents are clearly different. The high level ground motion estimated by us appears at lower frequency than 1 Hz.



Figure 11. Comparison of the acceleration response spectra with damping of 5percent of estimated strong ground motion during the mainshock with those of some significant earthquakes.

CONCLUSIONS

We estimated strong ground motion during the Kocaeli, Turkey earthquake of 1999 at damaged area based on underground structures estimated by array observations of microtremors, the empirical Green's function method, and the equivalent linear method. We employed EGF method for bedrock motion as a first stage of simulation for the surface strong motion. This is applied because it is inevitable for the strong ground motion in sedimentary basins to include the effects of nonlinear of basin response. In this study, nonlinear behavior of soil layers is evaluated by an equivalent linear method. Our approach has a possibility to extend the application for estimating strong ground motion that was not recorded.

As results, the ground motion at a period of 1-2 sec. in downtown Adapazari (ADC) during the mainshock is estimated to be two or three times larger than that of Hachinohe from the Tokachi-oki earthquake of 1968. The estimated strong ground motion at ADU is smaller than that at SKR in shorter period range than 1 sec., and this is qualitatively consistent with the damage level.

We have not investigated into details, however, ground motion due to synergetic effects of surface soils and source would be very important. Directivity effects were not distinct in the results of Adapazari, however, the ground motion near Golcuk would be influenced by not only site condition but also source process or rupture propagation of a fault. The ground motion in a longer period than 1 sec. at damaged area in Golcuk during the mainshock is estimated to be larger than that of JMA-Kobe from Hyogo-ken Nanbu earthquake of 1995.

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