Liquefaction-induced settlement, site effects and damage in the vicinity of Yalova City during the 1999 Izmit earthquake, Turkey

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Yalova City (Turkey) is in a tectonically active location that is particularly affected by the northern branch of the North Anatolian Fault Zone. Magnitudes 7.4 and 7.2 earthquakes in 1999 caused great destruction in Yalova. The heavy damage to buildings and other civil engineering structures was mainly due to liquefaction-induced settlement and site effects such as resonance and amplification. In the first phase of this study, the soil liquefaction potential index (*PL*) and the induced soil settlement were estimated. In the second phase, the effects on sites in Yalova soil were investigated using microtremor and earthquake data. The fundamental periods and amplification in soft soil were compared with microtremor data and strong ground motion records obtained by a local array of eight accelerograph stations deployed in Yalova. Thirty-seven 'single site' ambient noise measurements were taken in a dense grid of points covering the centre of the city. A comparison between fundamental periods obtained from strong ground motion records and from microtremor measurements showed similarities, in the 0.1–5 Hz range. Finally, soil liquefaction and amplification (or resonance) were divided into regions according to the extent of damage and the geotechnical/geophysical results.

1. Introduction

Soil/site conditions, as has been reported in many studies (e.g., Borchardt and Gibbs 1976; Iglesias 1988; Lekkas 1996; Seed *et al.* 2001; Özel *et al.* 2002) play an effective role as one of the triggers of earthquake damage. The determination of site conditions requires, identification of the soil stratification and properties of soil layers based on detailed geotechnical and geophysical tests.

Yilmaz and Yavuzer (2005) carried out liquefaction-potential studies and susceptibility

mapping in Yalova for a single ground motion level ($M=7.4$ and related acceleration). Ozcep and Zarif (2009) investigated variations in soil liquefaction safety factors for several hypothetical earthquakes in Yalova, determining the safety factors for different ground motion levels (magnitudes 6.5, 7.0 and 7.5) and accelerations (0.2–0.50 g).

Several works have investigated site effects, both liquefaction-induced settlement and earthquake damage. Gueguen *et al.* (1998) reported on the site effects and damage distribution in Pujili (Ecuador) after the earthquake there on 28 March

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1996. Lermo and Chavez-Garcia (1994) investigated site effects in Mexico City using dominant-period and relative-amplification data from strong motion and microtremor records. Chou *et al.* (2001) studied the risk of liquefaction-related damage at a tunnel site in the Taipei Rapid Transit System, Taipei County. Juang *et al.* (2005) estimated the severity of liquefaction-induced damage near foundations.

In recent years, geophysicists and geotechnical/earthquake engineers in many countries have been involved with the investigation of more earthquake damage problems related to soils than ever before. These problems are vitally important both for the people and the economic development of the affected countries. For this important situation to be understood, a combined effort will be needed to resolve soil-earthquake-structure interaction problems.

The present investigation set out to determine what role the soil properties play as one of the main factors causing earthquake damage in Yalova, and to compare the influence of two soil problems – amplification and liquefaction – on earthquake damage. This study presents and discusses the causes of the earthquake damage in the Yalova region related to soil liquefaction (as indicated by the PL and settlement quantities) and site effects (microtremor motions, earthquake motions, and V_{S30}).

This study compared a known empirical method with field geophysical/geotechnical data for assessing ground damage triggered by liquefaction and/or soil amplification at or near buildings in the vicinity of Yalova City during the 1999 Izmit earthquake in Turkey, including damage observations from the earthquake.

2. Geology and local soil conditions in the region

The geology and more than 200 drilling sites are shown in figure 1. The site is characterized by very large Quaternary alluvial deposits, and the Tertiary Yalakdere and Kilic formations. The Quaternary deposits consist of stratified materials having varied grain sizes, and are derived from the various geological units in the vicinity (Yilmaz and Yavuzer 2005).

The main drainage system is dominated by the Samanlı, Safran, Balaban and Kazimiye rivers. Borehole records throughout the study area show that the groundwater table is generally very shallow. It is closely associated with the amount of precipitation and may rise significantly following high monthly precipitation to depths between 0.5 and 3.0 m (e.g., see static groundwater depth map, Yilmaz and Yavuzer 2005).

3. Earthquake hazard analysis of Yalova region

Deterministic and probabilistic analyses were used to evaluate the seismic hazard in the region. The potential earthquake source area was considered to be the North Anatolian Fault beneath the Marmara Sea. Historical (32 AD–1900) and measured (1900–2002) seismicities of major earthquakes in the region are shown in figure 2(a); major and minor fault systems, including the northern branch of the Anatolian Fault and the Golcuk, Izmit, and Çınarcık Faults, among others, are shown in figure 2(b).

Figure 1. Study area, geology of Yalova region and borehole sites.

Figure 2. (a) Historical and instrumental seismicity of Yalova City and its vicinity (redrawn from Erdik *et al.* 2004a). (b) Main and minor fault systems in study area and its vicinity (redrawn from Emre *et al.* 2011).

3.1 Deterministic seismic hazard analysis

Required input for deterministic hazard analysis is a means of designating active faults or earthquake sources in the region. The following models have been proposed for the Marmara region (JICA-IBB, 2002):

Model A: Approximately 119 km rupture length;
 Model B: Approximately 108 km rupture length;
 Model C: Approximately 174 km rupture length
 (figure 3a).

Table 1 shows these model estimations of expected earthquakes. Also, Erdik *et al.* (2004a, b) followed the same approach. These models (figure 3a)

essentially identify the fault segments for different structural, tectonic and geometrical features and historical earthquake occurrences for the main Marmara Fault. Magnitudes of the hypothetical earthquakes were estimated (table 1).

3.2 Probabilistic seismic hazard analysis of region

Table 2 gives the number and magnitude of earthquakes in the study area within a 100 km radius of Yalova. Earthquake data was obtained from Kalafat *et al.* (2007), who catalogued seismic activity in Turkey for 105 years since 1900. Relevant to the present study, about 81 earthquakes of magnitude $M > 4.5$ occurred during

Figure 3. (a) Proposed models A, B, C for deterministic seismic hazard analysis in the Marmara region. A: approximately 119 km rupture length; B: approximately 108 km rupture length; C: approximately 174 km rupture length (redrawn from JICA-IBB, 2002 and Erdik *et al.* 2004a, b). (b) Hazard curve for region by using Joyner and Boore (1981) attenuation model, and (c) pseudo-spectral acceleration estimations for study area.

this period. The catalogue includes the regions with high seismic activity in Turkey and adjoining areas. One destructive and damaging earthquake ($M_s > 7.0$) occurred in the study region during that period of 105 years. The catalogue entries are homogeneous, and all of the earthquake data was modified into a standard

format for this study. The M_w values were used to estimate the probability of earthquake occurrence in the region.

The Gutenberg–Richter recurrence relationship is determined as:

$$\log(N) = 2.55 - 0.58 M. \quad (1)$$

Table 1. *Earthquake magnitude estimates for Model A: approximately 120 km rupture length; Model B: approximately 109 km rupture length; and Model C: approximately 174 km rupture length.*

Researcher	M (magnitude) range for		
	Model A	Model B	Model C
Ambraseys and Zatopek (1969)	7.4	7.4	7.6
Douglas and Ryall (1975)	7.5	7.5	7.7
Patwardhan <i>et al.</i> (1980)	7.4	7.4	7.6
Toksöz <i>et al.</i> (1979)	7.3	7.2	7.5
Wells and Coppersmith (1994)	7.5	7.4	7.7

Table 2. *Earthquakes within approximately 100 km radius of Yalova.*

Magnitude (M_w)	$4.5 \leq M < 5.0$	$5.0 \leq M < 5.5$	$5.5 \leq M < 6.0$	$6.0 \leq M < 6.5$	$7.0 \leq M < 7.5$
Numbers	54	15	9	2	1

Table 3. *Probability of earthquake occurrence in the region.*

Magnitude	For $D = 10$ (years)	For $D = 50$ (years)	For $D = 75$ (years)	For $D = 100$ (years)
	Probability (%)	Probability (%)	Probability (%)	Probability (%)
5	98.5	100.0	100.0	100.0
5.5	82.0	100.0	100.0	100.0
6	50.4	97.0	99.5	99.9
6.5	24.9	76.2	88.4	94.3
7	11.1	44.4	58.5	69.0
7.5	4.7	21.3	30.2	38.1

The probability of earthquake occurrence is given by:

$$Rm = 1 - \exp^{-[N(M) \cdot D]}, \quad (2)$$

where Rm is the risk value (%), and $N(M)$ is the number of earthquakes of magnitude M occurring during time D . Table 3 shows the earthquake occurrence probability for the region predicted by equation (2).

Attenuation relationships are defined by two models. From a set of attenuation relationships, the hypothetical acceleration values for the city were calculated as 0.43 g (from the Joyner and Boore 1981 model) and 0.47 g (from the Campbell 1997 model) with exceeding probability of 20% in 50 years. Finally, a hazard curve for the region was estimated (figure 3b).

The ground motion scaling relationships were reviewed for the current study; more recent relationships with much improved datasets were applied for the region of interest using the Akkar and Boomer (2010) approach. Figure 3(c) shows the estimated pseudo-spectral acceleration in the study area for the ground motion relationships $M_w = 7.0$ and 5% damping.

4. Theory for liquefaction analysis and liquefaction induced settlements

The most widely used simplified SPT- N method is that proposed by Seed *et al.* (2001) for liquefaction analysis. This method calculates the earthquake-induced cyclic stress ratio (CSR) in a soil layer from the simplified equation:

$$CSR = \frac{0.65 (A_{\max}/g) (\sigma_0/\sigma'_0) rd(z)}{MSF(M)}, \quad (3)$$

where σ'_0 and σ_0 are the effective and total vertical overburden pressures at some specified depth; $A_{\max}$ is the peak horizontal ground acceleration; $rd(z)$ is the stress reduction factor at depth z ; and $MSF(M)$ is a magnitude scaling factor that considers the duration effect of different earthquake magnitudes. In equation (3), σ'_0 and σ_0 are directly computed from borehole logs and laboratory test data, and can therefore be regarded as deterministic values with no variance; $rd(z)$ and $MSF(M)$ vary with depth and earthquake magnitude. The factor of safety with respect to liquefaction, FS , can then be calculated from:

$$FS = \frac{CSR}{CRR}, \quad (3.a)$$

where CRR is the cyclic resistance ratio.

The criteria for evaluating the liquefaction resistance based on SPT, CPT or shear-wave data are largely embodied in the *CRR vs. N₁, 60* plot (Youd et al. 2001). This procedure is based on the relationship of SPT *N*-values, corrected for both effective overburden stress and energy, equipment and procedural factors affecting SPT testing (to *N₁, 60*-values) versus intensity of cyclic loading, expressed as magnitude-weighted equivalent uniform cyclic stress ratio (*CSR_{eq}*). The correlation between corrected *N₁, 60*-values and the intensity of cycling required to trigger liquefaction is also a function of fines content.

Iwasaki et al. (1982) quantified the severity of possible liquefaction at any site by introducing a factor called the liquefaction potential index, *PL*, defined as:

$$PL = \int F(z) w(z) \cdot dz, \quad (4)$$

where *z* is the depth of the watertable (metres); *F(z)* is a function of the liquefaction resistance factor, *FS*, where *F(z)* = 1 – *FS* (note that *F(z)* = 0 when *FS* > 1.0); and *w(z)* = 10 – 0.5*z*. Equation (4) gives values of *PL* ranging from 0 to 100.

In the last phase of the liquefaction analysis, by using Ishihara and Yoshimine's (1992) approach, total soil settlement, *S*, was estimated from:

$$S = \sum H \varepsilon, \quad (5)$$

where *H* is the thickness of the soil layer, and ε (= $\Delta H/H$) is the volumetric strain in the layer, estimated as in Ishihara and Yoshimine (1992).

5. Theory for site-effect estimations from microtremor and earthquake data

The site effect is expressed in terms of a transfer function. Its basic principle comprises a simple two-layer model: a hardrock basement is covered by a soft sedimentary layer of thickness *h* and shear-wave velocity *V_S*. Resonant frequencies of this system in the small-strain range occur when the layer thickness is an uneven multiple of $\lambda/4$. The transfer function has maxima at the frequencies given by Ibs-von Seht and Wohlenberg (1999):

$$f = \frac{nV_S}{4h} \quad \text{for } n = (1, 3, 5, \dots). \quad (6)$$

Nakamura (1989, 2000) proposed a straightforward technique for evaluating local site effects by calculating the spectral ratio between the horizontal components and vertical components of the observed motion at the same site.

6. Liquefaction analysis and induced settlements for region

In this study, a practical reliability-based method was developed for assessing the soil liquefaction

Table 4. Some borehole logs in the study area.

Depth	SPT(<i>N</i>)	Lithology
BH-80		
1,5	7	S
3	7	S
4,5	8	S
6	9	S
7,5	9	S
9	11	S
10,5	6	S
12	10	S
13,5	6	MC
	GWL	2,15m
BH-83		
1,5	10	CS
3	9	S
4,5	9	S
6	10	S
7,5	17	C
9	22	C
10,5	26	C
12	27	C
13,5	28	C
15	32	C
	GWL	2,41
BH-101		
1,5	6	S
3	8	S
4,5	6	S
6	7	S
7,5	8	S
9	7	S
10,5	6	C
12	8	C
13,5	12	C
	GWL	2,41
BH-71		
1,5	12	S
3	12	S
4,5	17	S
6	26	C
7,5	31	C
9	29	C
10,5	29	C
12	40	C
13,5	39	C
15,3	40	C
	GWL	2,41

GWL = Groundwater level, S = Sand, C = Clay, MC = Silty clay, CS = Clayey sand.

Figure 4. Variations of PL values for hypothetical earthquake (0.40 g and $M = 7.4$), using Iwasaki *et al.* (1982) approach.

Figure 5. Variations of settlements for hypothetical earthquake (0.40 g and $M = 7.4$) using Ishihara and Yoshimine (1992) approach.

Figure 6. Distribution of microtremor and permanent strong ground motion station in Yalova region.

potential in the Yalova region. Some typical borehole logs of SPT- N , lithology and ground water levels in the study area are illustrated in table 4. In selecting a scenario earthquake, we used not only deterministic hazard analysis, but also integrated the deterministic and probabilistic seismic hazard analyses to estimate the level of ground motion (i.e., its magnitude and acceleration).

For liquefaction analysis, magnitudes of 6.5, 7.0, 7.4 and 7.5 and accelerations of 0.25, 0.40 and 0.50 g were selected for the hypothetical earthquake. Variations of PL values (by the Iwasaki *et al.* 1982 approach) for a hypothetical earthquake (0.40 g and $M = 7.4$) are shown in figure 4,

and liquefaction-induced settlements (using the Ishihara and Yoshimine 1992 approach) are shown in figure 5.

7. Site effects from geophysical (microtremor and earthquake) and geotechnical data for region

7.1 Geophysical field experiments

The first experiment was carried out from 9 October 1999 to 6 March 2000. A network of nine stations was deployed in Yalova (figure 6).

Table 5. The list of recorded local earthquakes (Red: 12 November, 1999 Duzce earthquake (M_w 7.2), Green: evaluated earthquake records, Yellow: S/N is high).

Event Date	TIME	Mag	BAG	BAH	GIR	KAS	HIL	HAS	RUZ	TAR
09.10.1999	6:23	3.20							ruz_01	
11.10.1999	3:47	3.90	bag_001			kas_001		has_001	ruz_02	
11.10.1999	15:26	3.40	bag_002		gir28401	kas_002		has_003	ruz_03	tar_002
15.10.1999	18:08	2.80							ruz_04	
21.10.1999	0:08	4.40			gir29400				ruz_05	
23.10.1999	3:49	3.10							ruz_002	
07.11.1999	16:54	5.00					hil_002			
11.11.1999	14:41	5.70		bah_009						
11.11.1999	15:42	3.20	bag_003			kas_003	hil_003	has_004		
12.11.1999	16:57	7.20	bag_004	bah_010	gir31600	kas_004	hil_004	has_005	ruz_040	tar_004
12.11.1999	17:17	5.20					hil_005		ruz_041	tar_005
12.11.1999	17:18	5.40	bag_005			kas_005	hil_006	has_006	ruz_043	
12.11.1999	17:23	5.10							ruz_044	
12.11.1999	17:47	4.80							ruz_045	
12.11.1999	17:54	4.70							ruz_046	
12.11.1999	18:14	5.00							ruz_047	
13.11.1999	0:54	4.70							ruz_048	
13.11.1999	10:55	3.60						has_007	ruz_049	tar_006
13.11.1999	15:16	3.30					hil_007	has_008	ruz_052	tar_007
13.11.1999	21:33	3.30							ruz_053	tar_008
14.11.1999	6:04	3.00	bag009		gir31802		hil_010			tar_012
14.11.1999	5:17	3.40	bag_006	bah_011	gir31800	kas_006	hil_008	has_009	ruz_054	tar_009
14.11.1999	5:43	2.80	bag_007						ruz_055	tar_010
14.11.1999	5:55	3.50	bag_008	bah_012	gir31801	kas_007	hil_009	has_010	ruz_056	tar_011
15.11.1999	5:05	3.20			gir31900				ruz_058	
17.11.1999	8:15	5.00							ruz_064	
17.11.1999	14:51	3.00							ruz_066	
18.11.1999	21:49	3.30							ruz_069	tar_013
19.11.1999	19:59	5.00							ruz_075	
20.11.1999	20:42	3.00							ruz_077	tar_014
21.11.1999	2:15	2.60							ruz_078	
22.11.1999	4:36	3.10	bag_010				hil_018		ruz_081	tar_015
23.11.1999	20:38	3.40	bag_012				hil_020	has_011	ruz_092	tar_017
25.11.1999	16:13	3.20							ruz_099	tar_018
25.11.1999	17:54	3.20							ruz_100	tar_019
25.11.1999	19:16	3.10								tar_020
27.11.1999	2:42	3.30	bag_013	bah_013		kas_008	hil_022	has_012	ruz_107	tar_021
07.12.1999	14:46	3.60	bag_014	bah_014		kas_009	hil_024	has_014		tar_022
09.12.1999	11:38	3.80	bag_015			kas_010	hil_025	has_015		tar_023
10.12.1999	2:03	3.60	bag_016				hil_026			tar_024
16.12.1999	1:38	3.50	bag017	bah015		kas_011	hil027			
16.12.1999	1:44	3.20				kas_012				
16.12.1999	12:32	3.50	bag018			kas_013	hil028	has016		
11.01.2000	14:38	3.40	bag019							
15.01.2000	10:32	3.10								tar017
17.01.2000	10:34	3.20				kas_014	hil030	has018		
31.01.2000	14:38	4.10	bag020			kas_015	hil031	has019		tar025
31.01.2000	14:44	3.50				kas_016	hil032	has020		
06.03.2000	15:44	3.30					hil033

Figure 7. Comparison of H/V ratios obtained from microtremor and earthquake records. Red: H/V spectral ratio of microtremor. Other colours are H/V ratio of earthquake data. Scale X: 0–10, Y: 0–10.

Table 6. *Recorded ambient noise.*

Microtremor station code	Latitude	Longitude	Altitude (m)	Range of measurement time
1	40 39 39.6	29 17 01.8	1	13:25–13:40
2	40 39 31.9	29 16 49.0		14:10–14:30
3	40 39 25.0	29 14 42.3	7	14:50–15:10
4-TAR	40 39 28.6	29 14 54.9	5	15:20–15:35
5	40 39 17.1	29 14 59.2		15:55–16:15
6	40 38 58.9	29 14 34.1	7	16:30–16:45
7	40 39 02.6	29 14 53.5	44	17:00–17:15
8	40 39 00.3	29 15 16.9	34	17:30–17:45
9	40 39 02.4	29 15 25.6	23	18:15–18:40
10	40 39 00.2	29 15 39.7	7	18:55–19:20
11-HAS	40 39 10.6	29 15 47.0	6	19:35–19:55
12	40 39 05.5	29 15 56.8	12	20:15–20:35
13	40 39 05.5	29 16 08.1		20:50–21:05
14	40 39 05.5	29 16 20.0	21	21:25–21:45
15	40 38 50.7	29 16 37.7	97	22:05–22:25
16	40 39 11.5	29 16 47.6	17	22:45–23:00
17	40 39 00.4	29 16 55.2	50	23:10–23:30
18-BAH	40 39 07.0	29 16 55.2	14	00:50–01:05
19	40 39 13.3	29 17 03.8	6	01:15–01:30
20	40 39 26.3	29 16 40.2	2	01:47–02:05
21	40 39 24.4	29 16 26.5	10	02:20–02:40
22	40 39 23.8	29 16 12.9	4	02:50–03:10
23	40 39 22.4	29 16 00.5	1	03:20–03:40
24	40 39 22.2	29 15 48.0	14	03:50–04:10
25	40 39 23.3	29 15 29.7	1	04:15–04:35
26	40 39 23.4	29 15 13.8	3	04:40–05:00
27-KAS	40 39 24.8	29 17 17.5	7	05:20–05:35
28-GIR	40 39 20.2	29 17 43.9	5	07:40–08:00
29-RUZ	40 38 54.7	29 16 35.4	48	08:20–08:40
30-BAG	40 39 10.3	29 16 26.3	7	09:05–09:25
31-HIL	40 38 49.7	29 15 52.1	1	09:45–10:00
32	40 38 37.8	29 15 54.4	12	12:10–12:30
33	40 38 23.2	29 15 38.5	5	12:45–13:00
34	40 38 58.4	29 17 27.6	9	13:35–13:50
35	40 39 00.9	29 17 19.3	3	14:05–14:15
36	40 38 42.4	29 17 13.0	2	14:25–14:40
37	40 38 28.6	29 16 59.3	18	14:50–15:05

(Bold: place of strong ground motion station).

SSA-12 recording stations equipped with Kinematics sensors were installed at eight sites inside buildings. Data was recorded at a sampling rate of 200 Hz. The stations were synchronised to a GPS reference time. Subsequently, 49 local earthquakes were recorded. The station information and magnitudes of the recorded earthquakes are shown in table 4.

The second experiment was carried out from 10 pm (local time) on 11 April 2009 to 12 pm (local time) on 12 April 2009 with the aim of recording ambient noise. Data was recorded at 37 sites using Guralp CMG-6TD sensors (standard flat velocity

Table 7. *Soil Model A estimation of soil amplification.*

Model A	$z = 15$ m	$V_S, 15$
$z = 15+$, V_S is unknown		
$V_{S30} = (V_S, 15 + V_S, \text{last layer})/2$		

response between 0.033 and 50 Hz) located were shown in figure 6. The recorded ambient noise measurements are listed in table 5. At each site the signal was recorded with a sampling rate of 100 Hz for at least 15 min. The stations were synchronised to a GPS reference time.

7.2 Comparisons between ambient noise and earthquake data

For comparison of ambient noise and earthquake data, H/V spectral ratios were used to calculate all of the data. Since the earthquakes on 17 August and 12 November 1999, Yalova City has been affected by many major earthquakes, two of which caused more than 1000 deaths. USGS and KOERI (Department of Earthquake Engineering) installed a local array of eight accelerographs in the centre of the city (station codes: TAR, HIL, BAG, BAH, RUZ, HAS, KAS and GIR). All of the stations were installed on soft soil at the locations shown in figure 6. This local array recorded 49 earthquakes of magnitudes ranging from 3.0 to 7.2, as well as some shallow events. If the fundamental resonance of the soil overlaps the natural frequencies of buildings, damage can be increased. (Figure 7 shows the comparison of H/V ratios obtained from microtremor and earthquake records.) In particular, results from the HIL, GIR, HAS and KAS stations were in agreement with microtremor ratios.

Station HIL is near station 31. Comparison of the H/V ratios of these stations shows fundamental resonance frequency agreement near 1 Hz, but amplification in the earthquake record is greater than that of the microtremor: for example, amplification of microtremor is 4 and for earthquake is 7.

Station BAG is near station 30. Comparisons of the H/V ratios show fundamental resonance frequency agreement near 1 Hz. When the H/V spectral ratio from four earthquakes was calculated, different amplification values are evident. While BAG_004 and BAG_005 had strong ground motion, BAG_001 and BAG_006 had weak motion; strong ground motion amplification was less than for weak ground motion. While the microtremor spectral ratio showed reduced amplification near the 3 Hz frequency, the earthquake amplitude data was amplified.

For the BAH earthquake station, the fundamental period was approximately 2.75 and 5.2 Hz for the earthquake spectra, but the ratio of the microtremor measurement was 0.5 and 2.75 Hz

Figure 8. Soil amplification map for the region according to Borchardt *et al.*'s (1991) Model A for strong motion.

Figure 9. Soil amplification map for the region according to Borchardt *et al.*'s (1991) Model A for weak motion.

at the same point. The amplitude was also larger for earthquakes than for microtremors. Concurrent values of amplitude signal in the microtremor record were reduced to around 5.2 Hz, while the earthquake record was amplified.

Station GIR is near station 28. Comparing the H/V ratios at these stations, two different fundamental frequencies were in evidence, but all were stable at 0.5 for frequencies lower than 1 Hz, but at frequencies above 1 Hz the ratios were 2.0 and 4.2 for earthquakes and within the broad range of 2.0–6.0 for microtremors. Amplification in the earthquake record was also greater than for the microtremor. Below 1 Hz, the amplification for microtremors was 5, and for earthquakes it was 8; above 1 Hz, it was 2 for microtremors and 7 for earthquakes. Damage distribution showed that the range of these frequencies might overlap the natural frequencies of both the soil and structures in the vicinity of station GIR.

Station HAS is near station 11. Compared to the H/V ratios at these stations, the fundamental

resonance frequencies were in agreement around 1 Hz, but the amplification of the earthquake record was greater than for the microtremors (7 for earthquakes and 5 for microtremors). There was a second fundamental frequency peak around 4 Hz evident in the earthquake data.

Station KAS is near station 27. The H/V spectral ratio at station 27 exhibited a broad range of peaks between 0.3 and 1 Hz, and at 0.1 Hz. On comparison of H/V ratios at these stations, fundamental resonance frequencies were seen to be in agreement near 0.7 Hz, but amplification in the earthquake record was greater than that for the microtremor (8 for earthquakes and 4 for microtremors). The general shape of the spectrum was the same for both.

Station RUZ is near station 29. The shapes of the spectrum were the same, but the amplifications differed.

Station TAR is near station 4. The shape of the spectrum was different at the two stations. The H/V spectral ratio of the microtremors showed

Figure 10. Comparison between damage due to the 17 August 1999 earthquake and liquefaction-induced settlements for a similar earthquake (0.40 g and $M = 7.4$).

Figure 11. Comparisons between damage from 17 August 1999 earthquake and soil amplifications for the region, using Borcherdt *et al.*'s (1991) Model A for strong motion.

two fundamental resonance frequencies, at 0.3 and 1.2 Hz; the shape of the H/V spectrum of the earthquake data showed four separate peaks, at 0.3, 1.2, 1.56 and 2.54 Hz.

Observations of the dependence of elastic-wave velocities on stress in soil reveal that significant nonlinear elastic effects may occur during seismic wave propagation. The site materials, whether soil or rocks, are nonlinear materials with a dynamic behaviour strongly dependent on loading level. This affects the whole dynamic response, including the system natural period values (Bratosin *et al.* 2009). In the present study, the resonance frequencies obtained from the microtremors at many sites were lower than those from actual earthquakes. This may imply that the strain level during microtremors was greater, and the soil

modulus was therefore less, than during actual earthquakes. Because a microtremor is an extremely weak ground motion, it cannot produce such a large strain. The deformation characteristics of soils are highly variable and depend on the magnitude of the shear strain in the soil.

According to the scientific literature, ambient seismic noise is thought to be composed of ‘microseisms’ and ‘microtremors’. Whereas microseisms represent long-period noise mainly generated by natural causes, microtremors are short-period noise events with artificial origins. The cutoff point between microtremors and microseisms should not be fixed at a single marginal frequency, for example, at 1 Hz. Microtremor records in our study (as seen in figure 7) are inconsistent at frequencies less than 1 Hz.

Figure 12. Comparisons between damage from 17 August 1999 earthquake and soil amplifications for the region, using Borcherdt *et al.*'s (1991) Model A for weak motion.

Figure 13. Comparisons between damage of 17 August 1999 earthquake and site fundamental period data, obtained from microtremor measurements.

7.3 Soil amplifications obtained from geotechnical data

In this study, geotechnical data from more than 200 boreholes was evaluated. SPT(N) values were converted into the equivalent shear-wave velocity values using the relationship given by Iyisan (1996):

$$V_S = 51.5 (\text{SPT})^{0.516}. \quad (7)$$

It is known that V_S is an index property for evaluating soil amplifications. The shear-wave and soil amplification relations from Borchardt *et al.* (1991) were obtained. Since the borehole data was for depths of only 15 m, we used their soil Model A to estimate soil amplifications (shown in tables 6 and 7).

Figures 8 and 9 show soil amplification maps for the region according to the Borchardt *et al.* (1991) approach for weak and strong motion for Model A.

7.4 V_{S30} map of soil from geophysical (MASW) data

The MASW method deal with surface waves at lower frequencies (e.g., 1–30 Hz) and allows a much shallower depth range of investigation than is otherwise possible (e.g., a few to a few tens of metres) (Park *et al.* 2007). The shear-wave velocities and profile were obtained by MASW in the study area. The phase velocity–dispersion curve and shear-wave velocity were obtained by inversion distance profile for the upper 30 m of the soil at 100 sites.

Figure 14. Comparisons between damage of 17 August 1999 earthquake and soil geology.

Figure 15. Comparisons between damage of 17 August 1999 earthquake and V_{S30} .

Figure 16. Regions of soil liquefaction and amplification (and/or resonance) produced according to relationships between the damage and geotechnical/geophysical results.

8. Earthquake damage, liquefaction and site effects

Comparisons between earthquake damage and liquefaction-induced settlements are given in figure 10.

Comparisons between 1999 earthquake damage and soil amplifications obtained from geotechnical data are given in figures 11 and 12 for the region according to the Borchardt *et al.* (1991) Model A for both strong and weak motion.

Figure 13 compares the damage caused by the 17 August 1999 earthquake and fundamental period data from microtremor site measurements. Figure 14 shows comparisons between the earthquake damage and soil geology. Figure 15 compares the earthquake damage and V_{s30} .

Finally, the map in figure 16 of the regions affected by soil liquefaction and amplification (and/or resonance) shows the relationships between earthquake damage and the geotechnical and geophysical data.

9. Conclusions

Detailed liquefaction-induced ground settlement from geotechnical data, and local site effects from geophysical data, were estimated for Yalova City in order to relate them to the damage to civil engineering structures, triggered by the 1999 earthquake.

The damage patterns from the 17 August 1999 Izmit earthquake were analysed. A wide range of factors affected the damage patterns. Building damage in Yalova was predominantly related to the earthquake-induced behaviour of the soils in the affected areas. Based on the results of our analysis, the following conclusions were drawn:

- For saturated soil conditions, the geological and geomorphological features were considered

together with the liquefaction index, PL , and induced settlements (figure 4 for PL index, and figure 5 for liquefaction-induced settlement). It was concluded that some Quaternary deposits in the study area sustained mainly light-to-moderate damage levels, with a minor proportion of extensive damage (the criteria are set out in Ishihara and Yoshimine 1992) occurring with increasing values of earthquake variables.

- The strong ground motion data and ambient noise measurement recordings carried out in Yalova allowed us to compare microtremors and earthquakes. Comparisons of the H/V ratio from the microtremor and earthquake results illustrated that there is generally a good agreement in the shape of the H/V curve, especially where the fundamental peak occurs at frequencies above 1 Hz. This agreement was not observed for the whole signal shape, however. For periods <1 s, due to the nonlinear effect of earthquake motion in these types of weak soils, no strong relationship was seen between microtremor and earthquake data. Moreover, despite their variability, the H/V results may provide the lower bound level of amplification with respect to earthquake data. Significant amplifications (i.e., exceeding 5) were observed at all of the stations located on very thick sediments. This indicates that those higher frequencies, which may overlap the resonance frequencies of buildings, might not necessarily be damped out under such conditions. Therefore, the fundamental resonance frequency from the H/V ratio should be adopted as the lower-bound frequency for site amplifications. Figure 13 is a map of fundamental period and damage distribution for sites in Yalova after the 17 August 1999 earthquake. In particular, while heavy damage focused (figure 13) on the period range 0.5–0.7 s (1.42–2 Hz), moderate damage was sustained for 0.8–1 s periods (1–1.25 Hz). The fundamental frequency of H/V ratios

for both microtremor and strong ground motion (figure 7) are not in agreement below 0.625 s (1.6 Hz).

- Figures 5 and 10 indicate that critical soil settlement occurred in the alluvial deposits. This area focuses on the coastal areas of the study area. Any damage to this area can be associated with liquefaction (especially settlements between 10 and 30 cm). As we know from soil mechanic studies, settlements up to 10 cm can be neglected in terms of structural damage. There was also significant damage in the region outside the liquefiable area. Geologically, the area is in the Tertiary Kılıç formation (figure 14). The V_{S30} values in this area (figure 15) exceeded 250 m/s. This value is insufficient to cause liquefaction, but it is significant for soil amplification; therefore, it may be inferred that soil amplification was responsible for damage in this region. Comparisons between damage and soil amplification for strong motion (figure 11) for this area show that soil amplification values varied between 2.5 and 4.0, and the period values (figure 13), seem to have a threshold value of 0.7 s. Sites with period values >0.7 s may be related to soil liquefaction-induced damage, and sites where the period <0.7 s incurred damage solely due to soil amplification and/or resonance.
- Soil amplification has a linear effect on soil behaviour, but soil liquefaction has a nonlinear effect. In Yalova sites, the soil amplification effect may predominate at nonsandy soil sites. There is a striking liquefaction effect in sandy soils. In the vicinity of fields, soil behaviour becomes increasingly complex. For this reason, no distinction could be drawn between the two types of soil behaviour in Yalova City. Relating to the damage, the critical boundary between site amplification and soil liquefaction is determined by shear-wave velocity, V_S , and site resonance period: if $V_S < 250$ m/s, soil liquefaction is dominant; if resonance period <0.7 s, soil amplification and/or resonance may be dominant.
- The work of Borchardt *et al.* (1991) on amplifications for low strain or strong motion data and corresponding regressions as a function of shear-wave velocity is a theoretical approach to estimating the average horizontal spectral amplifications in the period range 0.4–2.0 s. Theoretical considerations are also valid for settlement estimation; in most cases, earthquake damage is related to three types of factor–soil behaviour, earthquake motion and building quality. Each factor contains within it some degree of uncertainty, and this is the reason for the weak agreement between actual events and calculated amplifications and settlements.

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