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Seismic Vulnerability Indices for Ground in Derince-Kocaeli (Turkey)

İsmail Talih Güven¹

Abstract

Derince town is one of the most densely industrialized (oil refineries, ports, etc.) and populated urban areas which is located in one of the highest seismically active regions in Turkey. The area was damaged by a severe earthquake on 17 August 1999 in Kocaeli ($M_w=7.4$). The geotechnical properties of layers play the most important role in the formation of damage. One of the weakness indicators for the soil structure in a region is the ground vulnerability indices (K_g). The reduction of damage from earthquakes is related to the knowledge of these ground properties. Therefore, the microtremor horizontal-to-vertical spectral ratio (HVSr) method was applied to single site measurements at 43 stations over an area of 40 km² to evaluate local site effects in terms of ground vulnerability indices (K_g), fundamental frequency and amplification factor. Structural damage occurring during the August 17, 1999 Kocaeli ($M_w=7.4$) earthquake is compared with the estimated ground vulnerability indices. The results indicate that the K_g values are in good agreement with damage distribution. Large K_g values indicate weak points in the study area. According to results, the areas with K_g values greater than 14 seem to be the most vulnerable locations in the study. The K_g and soil types overwhelmingly comply with each other very well. Poor ground conditions are seen in areas with high vulnerability. Ground conditions should be taken into account during the planning and design of urban areas. The results obtained by considering ground conditions can be used as a quick method to identify risky areas.

Keywords: Site Effect, Resonance Frequency, Seismic Hazard, Ground Vulnerability Indices Marmara, Turkey

1. Introduction

The amplitude of seismic waves can be significantly amplified by near surface sedimentary deposits because of their low density, low strength, and high compressibility. Damage caused by an earthquake is closely related to the thickness and ground properties of the layers. The structural damage during earthquakes, called "field effects", may result from the effects of surface geology on ground motion (Bard, 1999). The local modification by these characteristics of the ground affects the damage size. Therefore, estimation of local site effects based on characteristics of the subsurface soil conditions is very significant to predict the seismic hazard for densely populated residential areas. Thus, prior knowledge of site effects plays an important role in reducing the damage level. For this purpose, a great deal of studies were conducted by many authors (Bard, 1999) (Borcherdt, 1970) (Papazachos, Panagiotopoulos, Tsapanos, Mountrakis, & Dimopoulos, 1983) (Chávez-García, Pedotti, Hatzfeld, & Bard, 1990) (Anastasiadis, Raptakis, & Pitilakis, 2002) (Scherbaum, Cotton, & Smit, 2004) (Delgado, et al., 2002) (Leventakis, 2003) (Skarlatoudis, et al., 2003) (Kurtuluş, Bozkurt, & Kıyak, 2005) (Livaoğlu H. , Irmak, Güven, & Özer, 2015) (Livaoğlu, Irmak, & Güven, 2019).

The vulnerability indices for ground (K_g) was proposed by Nakamura (1997). K_g depends on the amplitude of H/V peak and v_s (30) velocity. When Nakamura (1997) examined the structural damage distribution in San Francisco Bay during the Loma-Prieta Earthquake in 1989, there was a correlation between K_g and damage distribution. The relationship obtained from the results of this research showed that weak areas of the ground can be detected with K_g values. As a result, K_g is a value that can be considered to be the vulnerability indices of the soil. K_g can also be used to detect weak areas of the ground. Using such knowledge in disaster management provides an important value for the selection of urban areas. The use of such information will reduce the damage to structures after an earthquake. The use of the ground vulnerability indices (K_g) contributes to the disaster mitigation budgets of metropolitan municipalities. The vulnerability indices (K_g) is calculated from the fundamental frequency and amplitude of the H/V peak obtained from microtremor measurements.

Northwestern Turkey is significantly affected by seismicity (1912 $M=7.4$; 1963 $M=6.4$; 1967 $M=7.1$; and 1999 $M=7.4$; $M=7.2$ earthquakes) in the last decades (Ambraseys & Finkel, 1995) (Irmak, The source-rupture

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processes of recent large Turkey earthquakes., 2000). Moreover, NW Turkey is a highly populated region, with 19 million people living in large cities such as Istanbul, Bursa, and Kocaeli, where Derince is located, hosting significant industries and infrastructure in Turkey. The consequences of these earthquakes are very significant. The 1999 earthquake alone killed more than 18,000 people officially causing losses of \$10 to \$25 billion (Parsons, Toda, Stein, Barka, & Dieterich, 2000). Parsons (2004) indicated that there is still a high probability of a destructive earthquake ($M > 7$) in the Marmara Sea, west of the 1999 M 7.4 Izmit earthquake rupture (Parsons, 2004). Derince, which is located in this active area, contains many oil storage tanks and industrial facilities and is the largest port in the region. It was affected by the severe earthquake in 1999 with magnitude of 7.4 causing significant damage and loss of life. The heavy damage observed in the southwest part of the city occurred in a large industrial district, as well in the residential and government buildings. The soil conditions in this region are generally poor and mostly contain clays and silt-clay mixtures. Serious loss of life occurred along the Cenesuyu creek due to liquefaction effects and structural damage. Derince district was chosen as the study area in order to reveal the relationship between structural damage and K_g value. In order to obtain the fundamental frequencies and amplitude, measurements were made at forty-three points in the study area. V_{s30} velocities were compiled based on previous engineering studies (S wave refraction, MASW analysis, etc.).

2. Geological and Geotechnical Setting

The study area was shaped by the North Anatolian Fault Zone (NAFZ) and its effects on the Marmara region (Karakaş & Coruk, 2011). The eastern Marmara region consists of two tectonic units (northern and southern) which are brought together by the NAF. The northern tectonic unit comprises Paleozoic to Quaternary sedimentary units. The southern tectonic unit consists of metamorphic basement rocks (Pm) covered by Cretaceous sedimentary rocks (K), Tertiary volcanic rocks (Tv) and Pliocene terrestrial sedimentary units (Ta) (Karakaş & Coruk, 2011). A depression area developed on the NAFZ along the boundary between northern and southern units. The northern tectonic unit consists of a thick folded and faulted sandstone-limestone sequence, mainly. The northern tectonic unit was deposited in broad time interval (Paleozoic to Eocene). Younger sediments were deposited on the thick sedimentary units in a time interval from Pliocene to Quaternary. These younger sediments contain generally weakly cemented (Ta and Qs) and alluvial deposits (Qal) (Karakaş & Coruk, 2011)(Fig. 1).

Figure 1. Geological map of Derince town and vicinity (modified from (Karakaş & Coruk, 2011))

In order to establish a soil classification for the study area, NEHRP (Natural Earthquake Hazard Reduction Program) descriptions were considered. Regarding to NEHRP (Karakaş & Coruk, 2011) descriptions, soil is classified into six different classes by means of V_{s30} parameter. Descriptions of classes from A to F are shown in Table 1. The fundamental periods of the ground surface and average $V_{s(30)}$ have to be taken into consideration in this classification. Care is taken that these two criteria should not be much different so that the soil type can be classified accurately. In this context, these parameters were obtained from previous engineering studies, and Zor et al. (Zor, et al., 2010). According to available data, the town's northern part and coastline correspond to D type soil. Even though there is no sharp discrimination between soil types E and F, very small landfill areas at the coastline could be classified as E-F.

Table 1 NEHRP Soil Classification and explanations (BSSC, 2003)

Soil Type	General Description	Average SWv to 30 m (m/s) ($V_{s(30)}$)	Predominant Periods (s)
A	Hard Rock	>1500 m/s	$T \leq 0.08$
B	Rock	760-1500 m/s	$0.08 \leq T \leq 0.16$
C	Very dense soil and soft rock	360-760 m/s	$0.16 \leq T \leq 0.33$
D	Stiff soil	180-360 m/s	$0.33 \leq T \leq 0.67$
E	Soil or any profile with more than 3 m of soft clay defined as soil	<180 m/s	$T \geq 0.67$
F	Soils requiring site-specific evaluations	<180 m/s

Figure 2. Estimated bedrock depth, and damage severity of the 1999 earthquake map. Black points indicate microtremor recording sites. Contour values indicate seismic bedrock depth inferred from Ozalaybey et al. (Özalaybey, Zor, Ergintav, & Tapırdamaz, 2011). Geological units are given in Figure 1.

Figure 3. Estimated bedrock depth, damage severity of the 1999 earthquake and V_{s30} velocity classification map. Black points indicate microtremor recording sites. Geological units are given in Figure 1.

3. Method, data acquisition and processing

3.1 Horizontal to Vertical Spectral Ratio (HVSr)

Ambient noise measurements or the HVSr technique are commonly used to analyze characteristics of sediments and site effect studies. HVSr, which is obtained from spectral ratios of horizontal and vertical components of microtremor data recorded in the same region, can be used as a method to obtain ground properties. The HVSr peak frequencies and the amplitudes can be obtained easily (Kanai, Tanaka, & Osada, 1954). The HVSr method provides much denser measurement points compared with the other geophysical investigations, drilling, or earthquake recordings. The HVSr noise ratio technique was used in many studies and detailed information about this technique has been given in these studies (Nogoshi & Igarashi, 1970) (Nogoshi & Igarashi, 1971) (Nakamura, 1989). Mucciarelli and Gallipoli, 2001 explained the theoretical background and offered some applications of HVSr in a detailed review (Mucciarelli & Gallipoli, 2001).

The increase in damage in soft soil or thick sediments is known to result from the trapping of S waves in low rigidity materials because local surface waves and their subsequent trapping within soft layers leads to increased amplification. The shear wave velocity distribution with depth within the sedimentary column depends on the thickness of the column. Long period microtremors in a sedimentary basin were observed by Ohta et al. (Ohta, Kagami, & Goto, 1978). Ohta et al. found a systematic variation in the predominant frequencies with a decrease in basement depth (Ohta, Kagami, & Goto, 1978). Kagami et al. also found similar behavior (Kagami, Duke, Liang, & Ohta, 1982). Their results showed a regular increase in the amplitude of the microtremor Fourier spectra with the depth to basement rock. Therefore, knowing sediment thickness is important in terms of urban planning and earthquake engineering. Drilling boreholes gives detailed information about soil, but it is expensive

and slow. Quantitative relationships between sediment thickness and the fundamental frequency determined from HVSR were shown in many studies (among others) (Yamanaka, Takemura, Ishida, & Niwa, 1994) (Ibs-von Seht & Wohlenberg, 1999) (Delgado, et al., 2000) (Parolai, Bormann, & Milkereit, 2002) (Birgören, Özel, & Siyahi, 2009). Thus, frequency distribution can give a clue about sediment thickness.

The HVSR technique is largely used in order to obtain the peak amplitude and fundamental frequencies which characterize the shallow subsoil. A large number of studies deal with the comparison between the fundamental frequencies obtained from HVSR and receiver functions of earthquake records or explosion/quarry blast data (Yamanaka, Dravinski, & Kagami, 1993) (Field & Jacob, 1995) (Teves-Costa, Matias, & Bard, 1996) (Bindi, Parolai, Spallarossa, & Cattaneo, 2000) (Delgado, et al., 2000) (Ojeda & Escallon, 2000). All these studies concluded that the HVSR method provides reliable estimates of fundamental frequencies, if stiff soil overlies hard rocks. On the other hand, there is no clear evidence regarding the reliability of the peak amplitude value given by the HVSR method. The comparison between the peak amplitude value obtained from the HVSR and receiver functions of earthquake recordings give less consistent results compared to fundamental frequency. Lachetl and Bard 1994 concluded that the amplitude of HVSR peaks is dependent on the Poisson ratio for the uppermost layer and these HVSR peaks are therefore not suitable for soil amplifications (Lachetl & Bard, 1994). This conclusion was also supported theoretically by Field and Jacob 1995 (Field & Jacob, 1995). Field et al. 1995 indicate that when considering the intrinsic variability of site response with respect to the different incidence angles, azimuths and ensemble wave types expected from sources, it may well be that the only persistent feature is the fundamental frequency (Field, et al., 1995). Additionally, the soil nonlinearity is influential for strong ground motion and the amplification at higher modes may be significantly diminished (Field, et al., 1995). This point seems to be a weak point of the method. Nevertheless, the principal advantages of the HVSR or microtremor method are direct estimation of the fundamental frequency of soil or sediments, lack of requirements for geological structure and shear wave (S) velocity of the subsoil, and simple, low-cost measurements.

Microtremor measurements were completed at 43 sites (Table 2) in Derince town (Figure 1). A velocity-based three component broadband sensor (CMG-40T) (flat response between 0.03-50 Hz) was used for all measurements with a sampling rate of 100 Hz. The frequency range between 0.1 and 20 Hz was used in data analysis. According to the study by Ohta et al 1978, 10-20 min recording length is good for analysis (Ohta Y. , Kagami, Goto, & Kudo, 1978). However, the minimum recording time was chosen as 30 min. Attempts were made to avoid nonstationary sources of noise (cultural activities) and roads with heavy traffic, and therefore studies were performed at nighttime and also used a longer time window (20 sec). Also, attempts were made to avoid underground structures such as water channels, fiber lines, channels, etc. The GEOPSY software developed by the SESAME team was used to investigate microtremor data. Figure 4 shows samples of HVSR curves for the 4th and 18th recording points (Table 2).

The stationary part of the signal was selected using at least 20 windows of 20 sec length in order to eliminate sections with noise-dependent large amplitudes or spikes. Each window of the signal was detrended (offset correction) and 5% cosine tapered, Fast Fourier Transformed (FFT) (after removing unwanted noise), and then smoothed using the Konno and Omachi 1998 algorithm (Konno & Omachi, 1998). A band-pass Butterworth filter of order 2 (0.1-20 Hz) was applied before FFT. The two horizontal components in the spectra were combined into root mean square values before dividing by the vertical component spectrum for each frequency using the following equation (Delgado, et al., 2000):

$$H/V = \sqrt{(F_{NS}^2 + F_{EW}^2)/2F_{UD}^2} \quad (2)$$

Here, F_{NS} , F_{EW} and F_{UD} are the Fourier amplitude spectra for three components (in the north–south (NS), east–west (EW) and vertical (UD) directions, respectively). On rock sites, it was assumed that $(F_{NS}^2 + F_{EW}^2)/2F_{UD}^2 = 1$, while $(F_{NS}^2 + F_{EW}^2)/2F_{UD}^2 \neq 1$ on the stiff soil. Thus, each measurement point provides a spectral ratio (H/V) and enables an estimation of the fundamental frequency.

Figure 4. HVSr curves for the 4th and 6th observation points (Table 2)

3.2 K_g Values

The prediction of weak points in the ground, as well as the estimation of the damage from destructive earthquakes, can be achieved using the vulnerability indices for ground (K_g) Nakamura (1997). Ishihara (1978) indicated that from $\gamma \approx 1000 \times 10^{-6}$ ground begins to show non-linear character and at $\gamma > 10,000 \times 10^{-6}$ large deformation and collapse occur. The average shear strain γ of surface ground can be estimated by the equation given in Eq. (3) which was obtained by simplifying the shear strain deformation of surface ground (Nakamura, 1997).

$$\gamma = A_g \times d/H \quad (3)$$

where, A_g , d and H are the amplitude of H/V peak, seismic displacement of engineering bedrock or the basement ground and the thickness of surface layer, respectively. The natural frequency of the surface layer f_g can be expressed in terms of the S-wave velocities of the basement v_b and surface layer v_s as given in Eq (4).

$$f_g = v_b/(4A_g \times H) \quad (4)$$

α_b is defined as the acceleration of basement ground:

$$\alpha_b = (2\pi f_g)^2 \times d$$

γ is expressed by f_g , A_g and v_b as follows:

$$\gamma = (A_g \times \alpha_b / (2\pi f_g)^2) \times (4A_g \times (f_g/v_b)) = (A_g^2/f_g) \times (\alpha_b/(\pi^2 v_b)) \quad (5)$$

Considering that the efficiency of the applied dynamic force is a percentage of the static force, γ_e can be calculated by equation (6):

$$\gamma_e = K_g(e) \times \alpha_b \quad (6)$$

$$K_g(e) = e \times (A_g^2/f_g)/(\pi^2 v_b)/100 \quad (7)$$

The value of v_b is expected to be nearly constant in a broad area. Nakamura (1997) accepted this value as 600 m/s for the same situation. A depth of 30 m is the typical depth of drilling for detailed site characterizations and can be used in geotechnical studies. The properties inside the upper 30 m are generally used in site-effect studies for earthquake ground motions. In this study, due to the studied area not being constant, basement velocity (v_b) in Eq. (7) was used as v_{s30} for each site.

The soil samples are classified into six different categories from A to F according to NEHRP norms given in Table 1 (Wills, et al., 2000). The predominant periods for the ground surface and average shear wave velocity up to 30 m were taken into account for the classification of the soils. The soil type in the investigated region was mapped with damaged structures according to these circumstances as depicted in Figure 3. According to microgravimetry measurements made by Ozalaybey et al. (2011), the seismological bedrock depth for the southern coastline of Derince town, which is located at the edge of a sedimentary basin, is around 800 meters (Özalaybey, Zor, Ergintav, & Tapırdamaz, 2011). Using NEHRP classification, as seen in Figure 3, there are 5 different types of ground in the investigated region and coastlines located to the south are classified as mostly soil type of E (represented by red color in Figure 3). The soil type changes toward the north, but a small part of the town characterized by B (represented by light green in Fig. 3) and A (represented by blue color in Fig. 3) soils. The observed damage is also shown in Figure 3. The observed damage was classified into 3 categories: while spalling of concrete cover, buckling of reinforced rods or totally collapsed buildings means "heavily damaged", shear cracks in columns and beams and in structural walls means "moderately damaged". The shear cracks in non-structural walls mean "lightly damaged".

Table 2. Coordinates for the recording points in UTM format and the value of fundamental frequency f_0 (Hz) and amplification A_0 . RP stands for recording point.

R P	Latitude	Longitu de	f_0	A_0	V_{s30} (m/se c)	Kg	R P	Latitude	Longitu de	f_0	A_0	V_{s30} (m/se c)	Kg
1	4516811. 51	740908. 77	1.0 2	4.1 0	243.4	41. 2	23	4516552. 41	740586. 86	0.8 6	3.2 5	239.4	31. 1
2	4517485. 66	741054. 04	3.6 0	2.1 0	396.0	1.9	24	4516846. 02	740329. 13	0.8 3	2.7 5	254.0	21. 8
3	4517520. 55	739801. 78	1.5 5	2.8 0	280.8	11. 0	25	4516895. 85	739857. 60	0.6 8	2.6 6	276.9	22. 8
4	4517758. 88	739435. 72	4.4 8	3.5 3	1250. 0	1.4	26	4515981. 34	739698. 77	0.7 1	3.6 4	235.9	48. 1
5	4517320. 50	739424. 47	1.0 0	2.0 5	318.5	8.0	27	4515788. 55	739273. 98	0.7 0	3.6 2	225.9	50. 4
6	4517416. 24	739130. 29	1.2 1	2.9 6	345.3	12. 7	28	4515787. 74	738518. 80	0.6 1	2.9 2	239.2	35. 5
7	4518047. 27	738529. 97	2.0 5	2.8 1	381.4	6.1	29	4516218. 42	738332. 52	0.6 5	2.0 0	265.5	14. 1
8	4518335. 04	738196. 10	2.4 7	3.7 0	1250. 0	2.7	30	4516522. 67	738620. 86	0.5 9	2.8 9	286.0	30. 1
9	4517748. 39	737991. 09	0.8 8	2.6 5	360.5	13. 5	31	4515935. 43	737837. 53	0.6 9	2.2 8	250.4	18. 3
10	4517358. 88	738047. 39	0.6 4	2.6 0	340.4	18. 9	32	4515917. 15	737202. 09	0.6 1	2.0 0	254.0	15. 7
11	4517254. 75	738475. 75	0.6 7	2.1 8	333.4	12. 9	33	4517544. 34	737267. 73	0.7 0	2.5 3	336.9	16. 5
12	4516242. 00	740740. 87	0.9 0	3.1 4	229.8	29. 0	34	4518378. 18	737391. 20	0.7 2	2.0 7	338.1	10. 7
13	4515778. 68	740704. 55	1.2 0	3.9 6	209.0	38	35	4518290. 38	736836. 26	0.7 9	2.9 3	304.3	21. 7
14	4515832. 60	739763. 00	1.0 5	3.9 0	223.9	39. 3	36	4517464. 24	736838. 62	0.6 1	4.0 5	329.8	49. 6
15	4515753. 40	739499. 93	0.8 9	2.0 8	221.9	13. 3	37	4514811. 65	734830. 59	0.6 5	3.6 0	235.2	51. 5
16	4515604. 33	739327. 18	0.7 7	2.2 0	220.0	17. 4	38	4516370. 77	736283. 10	0.6 8	3.8 0	288.6	44. 7

17	4515539.	739000.	0.6	2.1	217.2	19.	39	4516964.	736344.	0.6	2.1	310.0	13.
21	60	6	2		1	98	24	5	0		3		
18	4515551.	738370.	0.6	2.0	219.3	17.	40	4515958.	734360.	0.5	2.0	270.8	15.
68	47	7	8		9	02	72	7	0		8		
19	4515671.	737920.	0.6	2.7	232.2	29.	41	4517725.	734566.	0.6	3.2	257.7	39.
59	97	6	4		8	85	91	2	0		0		
20	4515634.	737476.	0.6	2.0	233.2	16.	42	4518145.	735343.	0.6	2.8	1250.	5.7
75	17	4	3		8	62	93	7	0	0			
21	4515667.	737273.	0.6	3.8	236.0	63	43	4517473.	735816.	0.6	2.5	318.5	18.
37	31	0	3			82	14	4	0		6		
22	4515166.	737276.	0.5	4.0	207.7	85.							
90	66	6	4		3								

3. Results and Discussion

The fundamental frequency and H/V contours map are shown in Figure 5. The tendency of fundamental frequencies increases and H/V peak amplitude decreases towards the north, which is consistent with seismic bedrock thickness. The results are similar to Gueguen et al. 2007 who found frequency values increase when there is a decrease in the observed depth or vice versa (Guéguen, Cornou, Garambois, & Banton, 2007). Values for fundamental frequencies increase up to 4.48 Hz, with similar values observed on the edges of the basin where the sediment thickness decreases. Delgado et al. 2000 also found similar results and a map which reflects the spatial distribution of soft soils was produced by using their resonance frequency determined from the HVSR method (Delgado, et al., 2000).

Due to the thickness being expected to be greatest in the southern part of the town, as can be seen in Figure 5, the total thickness of Quaternary deposits on the north side may be related to the fundamental frequencies of Derince (Özalaybey, Zor, Ergintav, & Tapırdamaz, 2011) (Livaoğlu H. , Irmak, Güven, & Özer, 2015). The dominant frequencies around 0.56 - 1 Hz, indicating soft and thick sediments, were observed in the southern part of Derince town which had the heaviest damage. Özalaybey et al. 2011 indicated that the seismological bedrock depth obtained by microgravimetry measurements lies at around 800 meters on southern coastline of Derince town (Figure 2) (Özalaybey, Zor, Ergintav, & Tapırdamaz, 2011). Figure 5a shows the fundamental frequency contour map and damage distribution. As shown in Figure 5a, low values for fundamental frequencies ($f_0 < 1.0$ Hz) appear near the coastlines. The general tendency of fundamental frequencies increases towards north consistent with seismic bedrock ($V_s > 3.0$ km/sec) depth estimated by Özalaybey et al. 2011 (Figure 5b) (Özalaybey, Zor, Ergintav, & Tapırdamaz, 2011). Figure 5b shows that the fundamental frequencies in Derince can be related to the total thickness of Quaternary deposits in the south, since the thickness is expected to be the greatest in the southern part of the town. The southwestern part of Derince town, which had most heavy damage in the study area, shows the same dominant frequencies around 0.56 - 0.70 Hz indicating soft and thick sediments. The damage distribution in the study area is divided into 3 categories:

Heavy damage: where the structural elements of buildings were damaged so that they cannot be repaired or strengthened. It means that the building must be demolished.

Moderate damage: generally, the carrying capacity of the building is reduced due to the earthquake. This group of structures must be strengthened by repair or reinforcement.

Light damage: there is no damage to the structural elements of the building, damage caused by plaster cracks in the non-bearing structural elements, and use of the building is allowed to continue.

As seen from Figure 5b, places where damage is observed correspond to the places where the thickness of the sediment is high. Damage concentration within Derince town increased to the southwest over deep sediments where the alluvial soil thickness ranges between 200 and over 800 m. In particular, the three types of damage overlap in the area with similar sediment depth, lower fundamental frequencies and almost the same V_{s30}

velocity, as obtained from Özalaybey et al 2011. However, if the resonance frequency values mapped in Fig. 5a, which vary between about 0.56 and 4.48 Hz, and the thickness of the sediments based on gravimetry were used in the simple formula $T = 4h/v$, completely different V_{s30} values are obtained of 1.9- 2 km/s in 800 meters of thickness and about 0.6 km/s when the thickness is only 150 m. This means that there are considerable lateral heterogeneities in the structural model as well as V_{s30} velocity structure and that 2D or 3D effects cannot be neglected. Therefore, possible 2D or 3D effects could affect the resonance frequencies and make these difficult to correlate with the depth of the basement.

Figure 5. (a) Damage distribution and fundamental frequency (Hz) map for the study area. (b) damage distribution and V_{s30} velocity map of the study area. Geological units are given in Figure 1.

Although the amplification values obtained by single-station HVSr are controversial, a short discussion is written to give an idea of local site effects. A peak frequency in the 0.56 – 4.48 Hz range was found throughout

Derince, some with an amplitude factor of 4.1. The peak amplitudes of HVSR are mainly in the range 2.0 – 4.1 (Fig. 6). There is no clear physical reason to support a correlation of maximum amplitude or amplification of HVSR points with observed damage. Parolai et al. 2002 concluded that if the sedimentary cover below the station is very thick, higher harmonics may be strongly damped by the thick sedimentary cover (Parolai, Bormann, & Milkereit, 2002). Seo 1998 indicated that night and day measurements provide distinct amplitude variations in the frequency range (about a factor 3) (Seo, 1998). Volant et al. 1998 also reported a slight, but statistically significant, change in the amplitude of the fundamental peak (from 2.9 ± 0.4 in the night to 4.1 ± 0.6 in daytime) (Volant, Cotton, & Gariel, 1998). However, all measurements were done at nighttime to avoid such effects. An example map shows variation of amplification in predominant periods (Fig. 7).

Figure 6. Amplitude versus frequency graph for HVSR peaks.

Figure 7. Damage distribution and amplification (A_0) map for the study area. Geological units are given in Figure 1.

The V_b velocity can be used instead of V_{s30} velocity for the investigated region according to Nakamura (1997). Figure 8 shows the distribution of K_g values in the study area. The obtained K_g values range from 1 to 85. Looking at the relationship between the distribution of damage in the study area and K_g values, damage occurred in places where high K_g values are observed. This relationship is better observed in cross-sections (Figure 9). Fig. 9 shows much higher values for heavily damaged areas (coastlines) and decreases in good trim toward the northern part of the study area with no damage. In places where there are high K_g values in all cross-sections, the damage appears to be higher. Livaoglu et al. (2019) studied the southern part of the study area and indicated that places with a K_g value greater than 10 are the most vulnerable locations. The results obtained in this study are similar to Livaoglu et al. (2019). In all cross-sections, places where the K_g value is greater than 20 are the most vulnerable places in the study area. However, looking at the G-G' section, damage occurred only at one point, north of the study area with low K_g values (14). Sezen et al. (2003) indicated that both poor construction practices and the continued use of nonductile seismic detailing had a significant impact on damage from the August 17, 1999 Kocaeli Earthquake (Sezen, Whittaker, Elwood, & Mosalam, 2003). The fact that no other damage occurs around this damaged structure supports the study by Sezen et al. (2003). In addition, structural damage is likely to occur in regions with a K_g value greater than 10. In the twenty years before the earthquake in 1999, the southern part of the city developed rapidly, with the rapid increase in industrial facilities in addition to residences and government buildings in this part of the city, which were all heavily damaged. Most of the earthquake damage in the town of Derince occurred in parts very close to the coastline. The losses and casualties were large due to severe structural damage. During the 17 August 1999 Kocaeli earthquake ($M_w = 7.4$), the most damaged area was 60 Evler districts ($K_g > 20$) located on the coastline. The K_g and soil types correspond with each other.

Figure 8. K_g distribution map for the study area.

Figure 9. Cross-sections shown in Figure 8.

4. Conclusions

The HVSR results obtained in this study are quite consistent with the results of fundamental frequencies and variation in sediment thickness proposed by Özalaybey et al. 2011. The fundamental frequencies vary from 0.56 to 4.48 Hz in most of the investigated area. Lower frequencies are estimated for the southern part of study area where the basin has maximum thickness and frequencies gradually increase towards the north. A northward regular increase in the fundamental frequency is in agreement with the augmentation of soil thickness.

Damage distribution is concentrated in the southern part of the study area where sediment thickness is greater than the northern part. The largest observed damage occurs between 0.56 to 0.70 Hz and according to a previous study these areas have almost the same v_{s30} velocity. However, by using the simple formula $T = 4h/v$, completely different Vs values were obtained. This means that the study area has considerable lateral heterogeneities in the structural model and V_{s30} velocity structure. Therefore, 2D or 3D effects on damage distribution cannot be neglected. This study showed that detailed study of the v_{s30} velocity structure in a region will allow more accurate clarification of the ground effects. Interpretation of HVSR results together with detailed v_{s30} velocity will play an important role in the level of damage that will occur. Such detailed analyses can also help disaster mitigation studies.

The damage distribution in the town of Derince also shows good correlation with the seismic vulnerability indices (Kg) for Derince. The crucial point here is the comparable Kg values and soil characteristics. The result in this study suggests that areas with high Kg values contained more damaged buildings compared to areas with smaller Kg. According to the results obtained, a substantial argument can be made to interpret the weak points of ground before the dynamic load. Since the investigated area, including the northern part, are included in zoning development, the results obtained in this study show that the soil ground effect should be considered during the planning process for construction and infrastructure in urban areas. The evaluated values may provide much more precise damage prediction and can also be used for mitigating natural disasters such as earthquake, floods and landslides. The resistant capacity of the study region can be used to establish a database about the vulnerability of ground and structures. This and similar types of studies can help disaster reduction budgets of city planners and metropolitan municipality.

5. Declarations

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Conflicts of interest/Competing interests: There is no conflict of interest/competing interests

Availability of data and material: Data is not available for public

Code availability Geopsy is a free code

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Figures

Figure 1

Geological map of Derince town and vicinity (modified from (Karakaş & Coruk, 2011)) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Estimated bedrock depth, and damage severity of the 1999 earthquake map. Black points indicate microtremor recording sites. Contour values indicate seismic bedrock depth inferred from Ozalaybey et al. (Özalaybey, Zor, Ergintav, & Tapırdamaz, 2011). Geological units are given in Figure 1. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Estimated bedrock depth, damage severity of the 1999 earthquake and Vs30 velocity classification map. Black points indicate microtremor recording sites. Geological units are given in Figure 1. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

HVSR curves for the 4th and 6th observation points (Table 2)

Figure 5

(a) Damage distribution and fundamental frequency (Hz) map for the study area. (b) damage distribution and Vs30 velocity map of the study area. Geological units are given in Figure 1. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or

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Figure 6

Amplitude versus frequency graph for HVSR peaks.

Figure 7

Damage distribution and amplification (Ao) map for the study area. Geological units are given in Figure 1. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 8

Kg distribution map for the study area. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 9

Cross-sections shown in Figure 8.