Dynamic Properties of Soils in the Northern Coast of Izmir Bay Area

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***Abstract*— In this study, dynamic properties of soils in the northern coast of Izmir Bay area are investigated by dynamic site response analyses and microtremor measurements. Fundamental periods of soil profiles that are obtained from both methods are compared. Variation of dynamic soil properties in the northern coast of Izmir Bay are investigated depending on the bedrock depth and heterogeneous soil structure in the site. Dynamic site response analyses based on equivalent-linear methodology have been performed for 50 borehole locations. Liquefaction analyses are also performed at borehole locations, liquefaction potential index is calculated, and level of liquefaction risk is determined. While the liquefaction risk is very low or none for the moderate scale earthquake (M=5.3), medium-high levels of liquefaction risk for the scenario earthquake magnitude (M=6.5) is found. Fundamental periods obtained from microtremor measurements and those calculated from dynamic analyses are close to each other. Fundamental periods vary in the range of 0.65-1.2 s depending on the bedrock depth in the study area. Fundamental period is higher where the bedrock depth increases.**

***Keywords*— dynamic site response analysis; liquefaction analysis; microtremor; fundamental period; bedrock depth**

I. Introduction

Western Anatolia takes place in the major seismically active regions in Turkey. The city of Izmir, which is the third densely-populated city of the country, has been subjected to moderate scale earthquakes since April 2003. The 10.04.2003 Urla Earthquake (M=5.6), the 17.10.2005 Sigacik Bay (Seferihisar) Earthquakes (M=5.5~5.9), and the 21.10.2005 Uzunkuyu-Urla Earthquake (M=5.9) are the most serious earthquakes causing damages to medium-storey buildings on alluvial soil deposits. These earthquakes occurred at some distances to Izmir. However, the most recently occurred moderate scale earthquake in the city of Izmir was the 16.12.1977 Izmir Earthquake (M=5.3) nearby the Izmir Fault. Moderate–strong earthquakes were occurred close to the Izmir Fault during the historical period [1]. Magnitudes of major instrumental seismic period earthquakes vary between 5.3 and 6.5 [2, 3]. The possible scenario earthquake magnitude for the Izmir Fault was estimated as M=6.5 for the city of Izmir in RADIUS project [4]. The Izmir Fault can be determined as the most critical earthquake source for the city of Izmir based on the location and seismic events occurred on or very close to the Izmir Fault in historical and instrumental seismic periods.

In this study, dynamic properties of soils in the northern coast of Izmir Bay area are investigated. For this aim, geotechnical properties of 50 borehole locations in Alaybey-Karşıyaka-Bostanlı coastline were collected and dynamic behavior of soils was evaluated with one-dimensional dynamic site response analyses. Dynamic site response analyses were performed using EERA [5] software based on equivalent linear methodology. Liquefaction analyses were performed using peak ground acceleration values calculated from dynamic site response analyses. Microtremor measurements were taken in the study area, and they were evaluated by HVSR method. Variation of fundamental periods of soils along the coastline was determined. Fundamental periods that obtained from microtremor measurements and those calculated from dynamic site response analyses were compared.

II. Geology And Tectonics

Main geological units in the city of Izmir are shown in Fig. 1. Quaternary alluvial deposits take place along the coastline of Izmir Bay. The study area is located at the Quaternary alluvium formation, also.

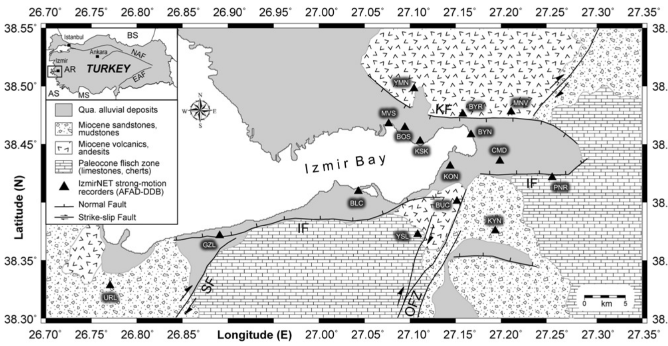


Figure 1. Map of the geology and main tectonic structures in the vicinity of Izmir (compiled from [6], [7], and [8])

The fundamental tectonic structures occurring earthquakes are the Izmir Fault (IF), the Seferihisar Fault (SF), and the Orhanlı-Tuzla Fault Zone (OFZ) in the vicinity of Izmir. These faults are shown in Fig. 1. The Karşıyaka Fault, which is in the neighborhood of the study area, is also shown in Fig. 1.

III. STUDY AREA AND GEOTECHNICAL PROPERTIES

Study area is determined as Alaybey-Karşıyaka-Bostanlı coastline. Fifty borehole locations and nineteen microtremor measurement points take place in the study area (Fig. 2). Borehole locations are shown using red points, and number of location is abbreviated such as "B1". Microtremor measurement points are represented with yellow points and number of point is shown as "M1".

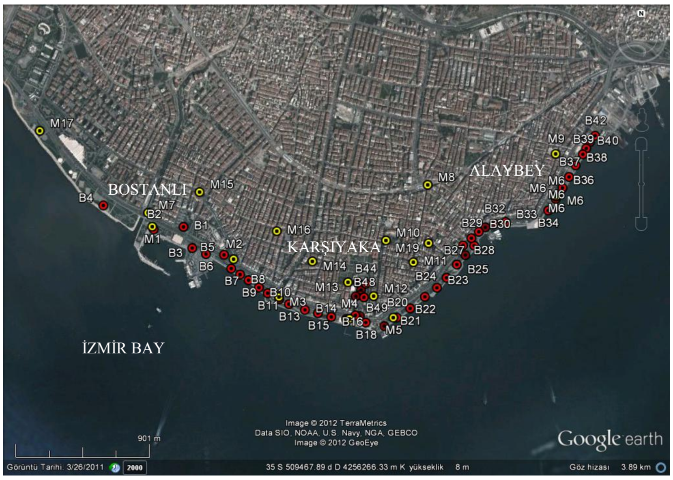


Figure 2. Borehole locations and microtremor measurement points in the study area

Soils in the study area display heterogeneous stratification in horizontal and vertical directions relating to thick alluvium formation. Geotechnical properties were determined with in-situ standard penetration test (SPT) and laboratory tests on samples obtained from boreholes. SPT blow counts and some index properties of soils of Alaybey-Karşıyaka and Bostanlı districts are given in Table I and Table II, respectively.

In these tables; soil classes according to Unified Soil Classification System (USCS), SPT-N_{30} blow counts, fines content (FC, %), liquid limit (w_L, %), plastic limit (w_P, %), plasticity index (I_P, %), natural unit weight (γ_n, kN/m^3), and specific gravity (G_s) values are presented. Geotechnical properties of soil layers are given to the depth of SPT-N_{30} measurements are available.

TABLE I. GEOTECHNICAL PROPERTIES OF SOILS IN ALAYBEY-KARŞIYAKA DISTRICT ([9], [10])

Depth (m)	USCS	SPT-N_{30}	FC (%)	w_L (%)	w_P (%)	I_P (%)	γ_n (kN/m^3)	G_s
0.0-1.5*	FILL	-	-	-	-	-	18.0	2.65
1.5-3.0	SC	15	22	30	18	12	17.0	2.70
3.0-12.0	SP-SM	16	11	30	NP	-	17.2	2.65
12.0-18.0	OH	4	70	55	23	32	16.5	2.60
18.0-22.0	SM	10	35	30	NP	-	18.0	2.65
22.0-28.0	SC	18	48	60	20	40	20.0	2.70
28.0-32.5	CL	25	70	45	20	25	20.0	2.71
32.5-34.0	CH	23	80	52	28	24	20.0	2.75
34.0-37.5	SC	22	38	47	26	21	20.0	2.68
37.5-42.5	CL	28	52	43	23	20	20.2	2.70
42.5-60.0	GC	50	10	30	18	12	20.5	2.65

*GWT varies between 0.5-2.5 m.

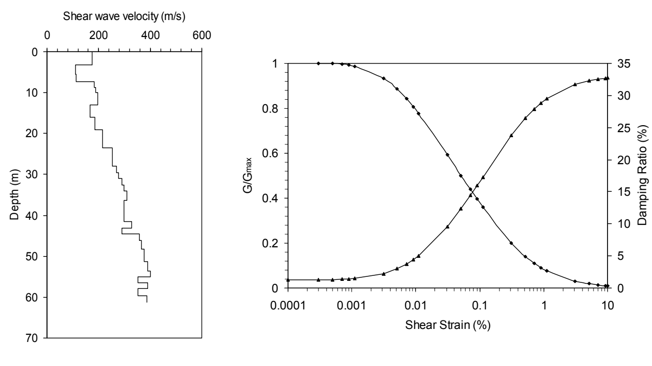
TABLE II. GEOTECHNICAL PROPERTIES OF SOILS IN BOSTANLI DISTRICT ([9], [10])

Depth (m)	USCS	SPT-N_{30}	FC (%)	w_L (%)	w_P (%)	I_P (%)	γ_n (kN/m^3)	G_s
0-3.3*	FILL	-	-	-	-	-	18.0	2.65
3.3-7.0	SC	10	20	48	22	26	19.0	2.70
7.0-10.0	SP-SM	14	18	35	NP	-	18.0	2.68
10.0-12.5	CL	24	55	48	23	25	17.5	2.70
12.5-16.0	ML	13	52	35	NP	-	17.3	2.69
16.0-20.5	CL	17	64	38	21	17	17.5	2.71
20.5-28.5	GC	50	10	30	17	13	20.5	2.65
28.5-34.0	CL	25	80	36	20	16	20.5	2.71
34.0-35.5	SC	47	48	41	17	24	21.0	2.65
35.5-44.5	GC	50	10	39	21	18	21.5	2.65
44.5-47.5	SM	49	25	33	NP	-	20.5	2.69
47.5-60.0	GC	50	10	30	18	12	19.5	2.66

*GWT varies between 0.5-2.5 m.

IV. DYNAMIC SITE RESPONSE ANALYSES

Dynamic site response analyses were performed using EERA [5] software. The EERA software is used to calculate one-dimensional equivalent-linear response of soil layers against earthquake motion. In equivalent-linear methodology, the non-linear behavior of soils under cyclic loading can be defined by equivalent linear approach [11]. In this approach, dynamic soil parameters (maximum shear modulus, G_{max} and damping ratio, ξ) are calculated for various shear strain values, and modulus reduction curves are obtained for each soil layer. Dynamic soil parameters can be calculated from empirical relationships using geotechnical parameters of soils. If shear wave velocity measurements are not available, firstly G_{max} is calculated from Hardin and Drnevich [12] relationship for clays and Seed & Idriss [13] formulae for sands. Besides, Ohta and Goto [14], Imai and Tonouchi [15] relationships can be used for G_{max} calculation taking into account corrected SPT-N values. Shear wave velocities are estimated from representative G_{max} values. Modulus reduction (G/G_{max}) and damping ratio (ξ) values for various shear strains in %0.0001-10 range are calculated using Ishibashi and Zhang [16] equation, and modulus reduction and damping curves are drawn for each soil layer. Variation of shear wave velocity with depth is shown in Fig. 3(a). A sample modulus reduction and damping curves are given in Fig. 3(b).



(a) (b)

Figure 3. (a) Variation of V_s (m/s) with depth in soil profile, and (b) a sample modulus reduction and damping curves for sandy soil layer at 8.0 m depth in Bostanlı district

Acceleration records of the December 16, 1977 Izmir Earthquake (M_s=5.3) and the scenario earthquake (M=6.5) for the Izmir Fault obtained from the modification of the Izmir Earthquake record are used in dynamic site response analyses of 50 dynamic soil models at borehole locations. The acceleration record is defined at bedrock depth of soil model, and peak ground acceleration (PGA, g), maximum spectral acceleration ($S_{a\max,s}$, g), amplification ratio (PGA/$a_{\max,rock}$), spectral amplification ratio ($S_{a\max,s}/S_{a\max,r}$), and fundamental period of soil profile (T_0, s) values are calculated using equivalent linear methodology. Dynamic parameters of the upper soil layer are calculated with an iteration technique when a proper convergence level is achieved in this methodology.

The maximum acceleration at bedrock level should be estimated before running the software EERA [5]. Magnitude of the earthquake, distance between the epicenter of the earthquake and the location of analysis, faulting mechanism, and local soil conditions are taken into consideration in estimation of maximum acceleration at bedrock depth. Attenuation relationships for acceleration may be used for this estimation. Attenuation relationships developed by Campbell [17], Boore et al. [18], and Ambraseys et al. [19] are used in estimation of maximum acceleration at bedrock depth. The average acceleration at bedrock level was calculated as 0.13g for the 1977 Izmir Earthquake (M=5.3), and it was estimated as 0.25g for the Izmir Fault scenario earthquake using the abovementioned attenuation relationships. These acceleration values are used as input motions in dynamic site response analyses.

Results of dynamic site response analyses are given in Table III for the 1977 Izmir Earthquake (M=5.3). Results of analyses for the Izmir Fault scenario earthquake (M=6.5) are presented in Table IV. According to the results of dynamic analyses for the 1977 Izmir Earthquake (M=5.3) in Table III, PGA varies within the range of 0.10-0.24g, and amplification ratio is calculated between 0.75-1.82. Spectral accelerations have values in the range of 0.33-0.85g, and spectral amplification ratios are found as 0.75-1.93. For the Izmir Fault Scenario Earthquake (M=6.5), PGA values are calculated as 0.15-0.41g, and amplification ratio is found between 0.60-1.64 (Table IV). Spectral accelerations are calculated as 0.51-1.45g, and spectral amplification ratio values vary in the range of 0.60-1.71. The fundamental period of soil varies between 0.65-1.20 s in accordance with the alluvium thickness.

V. LIQUEFACTION POTENTIAL ANALYSES

Liquefaction potential analyses were performed using a methodology proposed by NCEER report (Youd et al., [20]). Besides, liquefaction potential index was calculated using Iwasaki et al. [21] methodology, and liquefaction risk was determined. Values of liquefaction potential index and liquefaction risk statement at borehole locations are given in Table V. Liquefaction risk was found as very low or none in general for the 1977 Izmir Earthquake (M=5.3). However, 10 of 50 borehole locations including dominantly saturated sandy or non-plastic silty soils (e.g. B2, B5, B6, and B43-B50 locations) have low risk. Clayey soils are found in other locations, and liquefaction risk is none for this earthquake.

TABLE III. RESULTS OF DYNAMIC SITE RESPONSE ANALYSES FOR THE 1977 IZMIR EARTHQUAKE (M=5.3)

Borehole No.	1977 Izmir Earthquake (M=5.3)				T_0 (s)
	PGA (g)	PGA / $a_{max,rock}$	$S_{a,max,s}$ (g)	$S_{a,max,s}$ / $S_{a,max,r}$	
B1	0.18	1.38	0.82	1.86	1.11
B2	0.19	1.49	0.81	1.84	1.13
B3	0.18	1.41	0.75	1.70	1.07
B4	0.20	1.50	0.85	1.93	1.20
B5	0.20	1.50	0.75	1.70	1.06
B6	0.17	1.29	0.75	1.70	1.06
B7	0.12	0.93	0.41	0.93	1.00
B8	0.11	0.81	0.34	0.77	0.98
B9	0.19	1.42	0.69	1.57	0.99
B10	0.18	1.40	0.78	1.77	0.95
B11	0.19	1.45	0.84	1.91	0.89
B12	0.17	1.30	0.65	1.48	0.96
B13	0.15	1.15	0.62	1.41	0.89
B14	0.19	1.47	0.82	1.86	0.86
B15	0.12	0.90	0.44	1.00	0.89
B16	0.11	0.87	0.39	0.89	0.86
B17	0.18	1.39	0.71	1.61	0.88
B18	0.10	0.75	0.33	0.75	0.81
B19	0.18	1.38	0.75	1.70	0.78
B20	0.17	1.28	0.72	1.64	0.75
B21	0.16	1.21	0.66	1.50	0.73
B22	0.18	1.35	0.82	1.86	0.65
B23	0.15	1.12	0.63	1.43	0.65
B24	0.19	1.47	0.71	1.61	0.76
B25	0.13	1.01	0.45	1.02	0.70
B26	0.24	1.82	0.80	1.82	0.74
B27	0.16	1.24	0.56	1.27	0.74
B28	0.11	0.87	0.36	0.82	0.70
B29	0.15	1.13	0.53	1.20	0.69
B30	0.14	1.07	0.52	1.18	0.67
B31	0.15	1.17	0.62	1.41	0.69
B32	0.16	1.25	0.64	1.45	0.66
B33	0.16	1.26	0.71	1.61	0.69
B34	0.17	1.32	0.73	1.66	0.69
B35	0.17	1.32	0.67	1.52	0.67
B36	0.12	0.93	0.40	0.91	0.68
B37	0.17	1.30	0.70	1.59	0.66
B38	0.16	1.26	0.67	1.52	0.67
B39	0.16	1.24	0.57	1.30	0.71
B40	0.18	1.39	0.71	1.61	0.71
B41	0.20	1.55	0.73	1.66	0.68
B42	0.16	1.25	0.64	1.45	0.67
B43	0.19	1.46	0.70	1.59	0.73
B44	0.21	1.62	0.84	1.91	0.70
B45	0.16	1.22	0.66	1.50	0.81
B46	0.21	1.61	0.74	1.68	0.71
B47	0.18	1.42	0.78	1.77	0.77
B48	0.18	1.35	0.63	1.43	0.74
B49	0.19	1.49	0.83	1.89	0.84
B50	0.18	1.38	0.81	1.84	0.81

For the Izmir Fault Scenario Earthquake (M=6.5), liquefaction risk increases due to peak ground accelerations reaching 0.3-0.4g (Table IV). Some soil profiles nearby Bostanlı Pier (e.g. B1-B6 locations) and in the vicinity of Karşıyaka Stadium (e.g. B43-B50 locations) are determined to have medium-high liquefaction risk (Table V). Saturated sandy and non-plastic silty soils are dominant in these locations. The lowest risk is determined along Karşıyaka and Alaybey coastline (e.g. B7-B42 locations). Generally, clayey soils exist in these locations.

TABLE IV. RESULTS OF DYNAMIC SITE RESPONSE ANALYSES FOR THE IZMIR FAULT SCENARIO EARTHQUAKE (M=6.5)

Borehole No.	Izmir Fault Scenario Earthquake (M=6.5)				T_0 (s)
	PGA (g)	PGA / $a_{max,rock}$	$S_{a,max,s}$ (g)	$S_{a,max,s}$ / $S_{a,max,r}$	
B1	0.27	1.08	1.25	1.47	1.11
B2	0.31	1.22	1.17	1.38	1.13
B3	0.31	1.25	1.26	1.49	1.07
B4	0.30	1.19	1.32	1.56	1.20
B5	0.29	1.15	1.14	1.35	1.06
B6	0.25	1.00	1.14	1.34	1.06
B7	0.19	0.75	0.67	0.79	1.00
B8	0.17	0.67	0.56	0.65	0.98
B9	0.30	1.21	1.20	1.41	0.99
B10	0.29	1.17	1.31	1.55	0.95
B11	0.31	1.25	1.41	1.66	0.89
B12	0.24	0.94	0.92	1.09	0.96
B13	0.24	0.96	1.07	1.26	0.89
B14	0.31	1.25	1.40	1.65	0.86
B15	0.18	0.71	0.70	0.82	0.89
B16	0.17	0.68	0.59	0.69	0.86
B17	0.27	1.07	1.10	1.29	0.88
B18	0.15	0.60	0.51	0.60	0.81
B19	0.31	1.24	1.29	1.52	0.78
B20	0.27	1.08	1.24	1.46	0.75
B21	0.26	1.04	1.14	1.35	0.73
B22	0.28	1.14	1.38	1.62	0.65
B23	0.26	1.03	1.16	1.37	0.65
B24	0.29	1.17	1.19	1.40	0.76
B25	0.22	0.87	0.80	0.94	0.70
B26	0.41	1.64	1.45	1.71	0.74
B27	0.24	0.96	0.86	1.01	0.74
B28	0.19	0.77	0.63	0.74	0.70
B29	0.25	1.02	0.96	1.13	0.69
B30	0.24	0.95	0.94	1.10	0.67
B31	0.26	1.02	1.11	1.31	0.69
B32	0.28	1.13	1.11	1.30	0.66
B33	0.27	1.07	1.18	1.39	0.69
B34	0.29	1.16	1.24	1.46	0.69
B35	0.29	1.15	1.14	1.34	0.67
B36	0.19	0.77	0.67	0.79	0.68
B37	0.30	1.21	1.27	1.49	0.66
B38	0.28	1.14	1.20	1.42	0.67
B39	0.24	0.94	0.90	1.06	0.71
B40	0.28	1.11	1.13	1.33	0.71
B41	0.37	1.59	1.32	1.69	0.68
B42	0.25	1.08	0.93	1.18	0.67
B43	0.32	1.28	1.15	1.36	0.75
B44	0.35	1.41	1.35	1.59	0.72
B45	0.26	1.03	1.10	1.30	0.81
B46	0.36	1.45	1.27	1.49	0.73
B47	0.30	1.20	1.31	1.54	0.77
B48	0.30	1.21	1.06	1.25	0.75
B49	0.33	1.30	1.40	1.65	0.84
B50	0.32	1.27	1.32	1.55	0.81

TABLE V. LIQUEFACTION POTENTIAL INDEX VALUES AND STATEMENT OF LIQUEFACTION RISK AT LOCATIONS IN THE STUDY AREA

Borehole No.	Liquefaction Potential Index	Liquefaction Risk
B1	7.8	Medium
B2	17.0	High
B3	14.4	Medium
B4	13.1	Medium
B5	22.9	High
B6	20.8	High
B7	-	None
B8	-	None
B9	-	None
B10	2.3	Low
B11	-	None
B12	-	None
B13	-	None
B14	-	None
B15	-	None
B16	-	None
B17	-	None
B18	-	None
B19	-	None
B20	-	None
B21	-	None
B22	0.4	Low
B23	0	None
B24	0	None
B25	0	None
B26	2.9	Low
B27	0.3	Low
B28	0	None
B29	0	None
B30	0.9	Low
B31	0	None
B32	0	None
B33	1.4	Low
B34	0.2	Low
B35	2.6	Low
B36	0	None
B37	0	None
B38	2.0	Low
B39	0	None
B40	0	None
B41	1.6	Low
B42	1.8	Low
B43	13.4	Medium
B44	28.1	High
B45	27.8	High
B46	29.5	High
B47	25.3	High
B48	24.3	High
B49	14.2	Medium
B50	10.4	Medium

VI. MICROTREMOR MEASUREMENTS

Natural periods of soils were measured with microtremor in the study area, and fundamental periods of soils calculated from dynamic site response analyses were compared with those obtained from microtremor measurements.

Microtremor measurements were performed using CMG-5TD type digital accelerometer at 19 locations along Alaybey-Karşıyaka-Bostanlı coastline and inside of the shoreline.

Microtremor measurement records were analyzed with HVSR method [22], and fundamental periods of soils were determined. Reference line correction was applied to each measurement record. Measurement data were filtered with 0.5-20 Hz Bandpass filter. Minimum 10 windows with 20 s period were selected, and 5% cosine window was applied. Spectra were obtained with Fast Fourier Transform (FFT). H/V spectral ratio values were calculated for each window. Fundamental periods that obtained from microtremor measurements and those calculated from dynamic site response analyses were given in Table VI.

TABLE VI. FUNDAMENTAL PERIODS OF SOILS OBTAINED FROM DYNAMIC ANALYSES AND MICROTREMOR MEASUREMENTS

Borehole No.	Microtremor Measurement Point No.	$T_{0,microtremor}$ (s)	$T_{0,analysis}$ (s)
B1-B6	M1, M2, M7, M15, M17	1.04	1.11
B7-B14	M2, M3, M14, M16	0.98	0.94
B15-B19	M4, M5, M12, M13, M14	0.94	0.84
B20-B26	M10, M11, M19	0.75	0.71
B27-B33	M6, M8, M9, M18, M19	0.67	0.69
B34-B42	M6, M9	0.75	0.68
B43-B50	M4, M5, M12, M13	0.88	0.78

According to Table VI, fundamental periods calculated from dynamic site response analyses and those obtained from microtremor measurements are compatible. The regression coefficient was calculated as 0.88. Fundamental periods vary in the range of 0.67-0.94 s in Alaybey-Karşıyaka coastline, and they are obtained as 0.94-1.04 s in Karşıyaka-Bostanlı coastline depending on the bedrock depth.

VII. CONCLUSIONS

In this study, dynamic properties of the northern coast of Izmir Bay area soils are investigated by dynamic site response analyses and microtremor measurements. Variation of dynamic soil properties along the Alaybey-Karşıyaka-Bostanlı coastline are examined depending on variable bedrock depth and heterogeneous soil stratification.

Dynamic site response analyses were performed using EERA [5] software based on equivalent-linear response of soil layers against earthquake motion. Site response analyses of 50 dynamic soil models at borehole locations along Alaybey-Karşıyaka-Bostanlı coastline were performed. Acceleration records of the December 16, 1977 Izmir Earthquake (M_s=5.3) and the scenario earthquake (M=6.5) for the Izmir Fault obtained from the modification of the Izmir Earthquake record were used.

According to the results of dynamic analyses for the 1977 Izmir Earthquake (M=5.3), PGA values vary in the range of 0.10-0.24g, and amplification ratio is found between 0.75-1.82. Spectral accelerations are calculated as 0.33-0.85g, and spectral amplification ratio values are obtained as 0.75-1.93. For the Izmir Fault Scenario Earthquake (M=6.5); PGA varies within the range of 0.15-0.41g, and amplification ratio is calculated between 0.60-1.64. Spectral accelerations have values between 0.51-1.45g, and spectral amplification ratios are calculated as 0.60-1.71. The fundamental periods of soils vary between 0.65-1.20 s in accordance with the alluvium thickness.

Liquefaction analyses were performed using peak ground acceleration values calculated from dynamic site response analyses. Liquefaction potential index was calculated, and liquefaction risk was determined at borehole locations. Liquefaction risk was evaluated as very low or none in general for the 1977 Izmir Earthquake (M=5.3) due to the low PGA values. For the Izmir Fault Scenario Earthquake (M=6.5), liquefaction risk increases due to peak ground accelerations reaching 0.3-0.4g. Some soil profiles nearby Bostanlı Pier (e.g. B1-B6 locations) and around Karşıyaka Stadium (e.g. B43-B50 locations) are determined to have medium-high liquefaction risk. Saturated sandy and non-plastic silty soils are dominant in these locations. The lowest risk is determined along Karşıyaka-Alaybey coastline (e.g. B7-B42 locations) due to the presence of thick clayey soils.

Microtremor measurements were taken in the study area, and they were evaluated by HVSR method. Variation of fundamental periods of soils along the coastline was determined. Fundamental periods obtained from microtremor measurements and those calculated from dynamic site response analyses have close values to each others. Fundamental periods are measured between 0.67-0.94 s in Alaybey-Karşıyaka coastline, and they have values of 0.94-1.04 s in Karşıyaka-Bostanlı coastline depending on the bedrock depth.

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