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Liquefaction Potential of the Settlement Area of Susurluk (Balıkesir, Turkey) In the Context of Earthquake Sensitive Urbanization

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Abstract. The settlement area of Susurluk (Balıkesir) is located in a region with a high seismic risk and its territory is in the first degree of earthquake zone according to the earthquake hazard map of Turkey. In addition, the area is suitable for liquefaction in terms of geological criteria. For this reason, the liquefaction potential maps of this settlement area have been prepared. Standard pentatlon test data provided by the Susurluk (Balikesir) municipality were used directly in the so-called simplified methods. According to the results of the study, Almost all of the area where the terrace is observed has "None" or "Low" liquefaction susceptibility while the liquefaction susceptibility of the area where the alluvium is observed range "Low" to "High".

1. Introduction

Soil liquefaction is a major cause of damage during earthquakes. It is defined as the loss of strength due to transfer of inter granular stress from grains to pore water [1].The standard method for evaluating in situ liquefaction potential of soils has been proposed by Seed and Idriss [2] using the Standard Penetration Test (SPT) data. Later updates of this simplified procedure relied almost entirely on case histories involving liquefaction or non-liquefaction ([1], [3], [4], [5], [6], [7], [8], [9]). The factor of safety against to the liquefaction of the soil layer is defined as the ratio of liquefaction resistance (e.g. cyclic resistance ratio, CRR) over cyclic stress of soil (e.g. cyclic stress ratio, CSR). The factor of safety (F_L) is not a sufficient parameter for evaluation of liquefaction and its damage potential at any site ([6], [10], [11], [12]). However, the thickness and depth of the liquefiable layer and the factor of safety are very important inputs for damage potential based on liquefaction [12]. Since it was proposed by Iwasaki and co-workers [10], the liquefaction potential index (LPI) has been a very popular tool due to the inclusion of the thickness and depth of the liquefiable layer and the factor of safety as inputs (from [12]).

The settlement area of Susurluk (Balikesir), the study area is located in a region with a high seismic risk. It is mainly under the influence of the southern branch of The North Anatolian Fault Zone (NATZH) and the Havran-Balikesir Fault Zone. In the area, alluvium and terrace unit are observed and the depth of the ground water level ranging 0.5 to 6m. For this reason, the liquefaction potential analysis for this settlement area were carried out. In these analysis, the method purposed by Youd and co-workers [4], based on SPT data, was applied to obtain the factor of safety against to the liquefaction of the soil layer investigated. Also, the liquefaction potential of the soil profiles which represents the whole vertical section at the boreholes were obtained by two methods; one of them given in [11] the other purposed Sonmez and Gokceoglu [6]. To prepare the liquefaction potential map for the study area, Inverse Distance Weighting (IDW) method, a type of deterministic method for multivariate interpolation with a known scattered set of points was applied.

2. Geological and Tectonic Setting

The Balikesir region including the settlement area of Susurluk is located in one of the geodynamically active parts of Turkey. The tectonic evolution of region is greatly affected by the collision of the Arabian and African plates with the Eurasian plate [13]. This compressional tectonic regime in the Miocene gave rise to the formation of North Anatolian and East Anatolian fault zones, along which the Anatolian block moved westwards. The study area, the settlement area of Susurluk (Balıkesir) is mainly under the influence of the southern branch of NATZH and the Havran-Balikesir Fault Zone (Fig.1). The North Anatolian Fault Zone (NAFZ) is made up of at least two fault splays at its western termination, namely the northern and southern fault splays in the Marmara region (Fig. 1, [14]) .Towards the Biga Penninsula, the southern branch separates from the other by rightward step-overs. Yenice-Gönen Fault (YGF) is one of the main fault segment of the NAFS in Biga Peninsula. It is about 70 km long and generated destructive earthquake (M_w=7.2) of 18th March, 1953.

The HBFZ is a 10–12 km wide, 100–120 km long, approximately N70°E-trending fault zone comprising several riddle faults that display a well-developed shear zone pattern with an echelon elongated hills (from [15]). The fault zone comprised six main segments and displays morphological and kinematic evidences for dominantly dextral movement during the Holocene (from [15]). According to Sözbilir and co-worker [15], geologic, geomorphologic and palaeo-seismologic studies along the HBFZ indicate that the Kepsut, Gökçeyazı and Ovacık fault segments are capable of generating an earthquake with a moment magnitude of up to 7.2 and have an average recurrence interval of 1000–2000 years for surface-ruptured earthquakes.

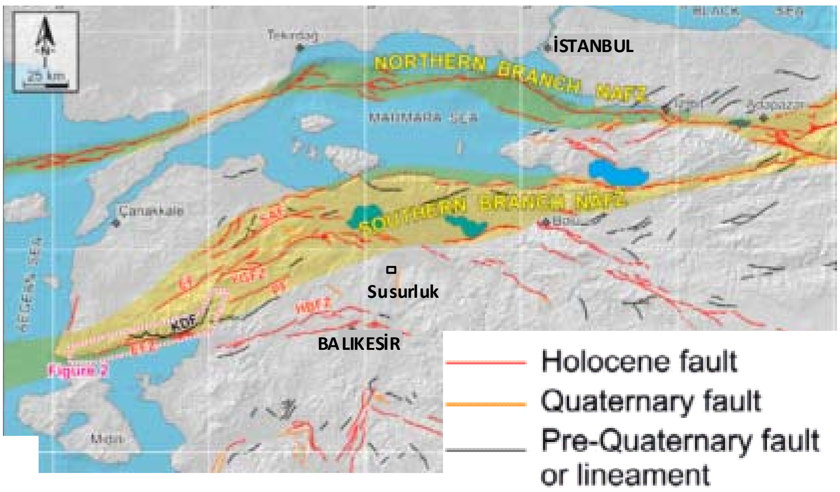

Figure 1. Active fault map of Marmara region (estimated branches of the NAFZ are shown in yellow shaded area) (from [14])

Acidic and intermediate volcanic rocks exposed in the immediate east of the Susurluk settlement area. In the west of the area, granitic rocks exposed. The settlement area is built on Neogene units. Pleistocene aged Savastepe formation composed mainly of Conglomerate, sandstone, claystone, marl and tuffit uncomfortably overlie the Quaternary units. These units, alluvium and terrace are the youngest units in the study area.

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3. Geotechnical Characteristic of the Soil Units

In Susurluk (Balıkesir) settlement area, the topographic level increases to the east to the west.(Fig. 2a). In the area where alluvium is propagated, the slope is <5 °. The slope of the area where the terrace spreading is ranging mostly 0-10 degrees, reaching a maximum of 35 degrees (Fig. 2a-b) The maps of the level of the groundwater table was created by using the level of the groundwater values measured in drilling wells; It is seen that the groundwater surface is approximately parallel to the topographic surface and the height from the shore to the west increases steadily to reach 64 m (Figure 2c-d). The depth of the groundwater table is ranging 0.5 to 6m and the mean of the said level is 3.3 m

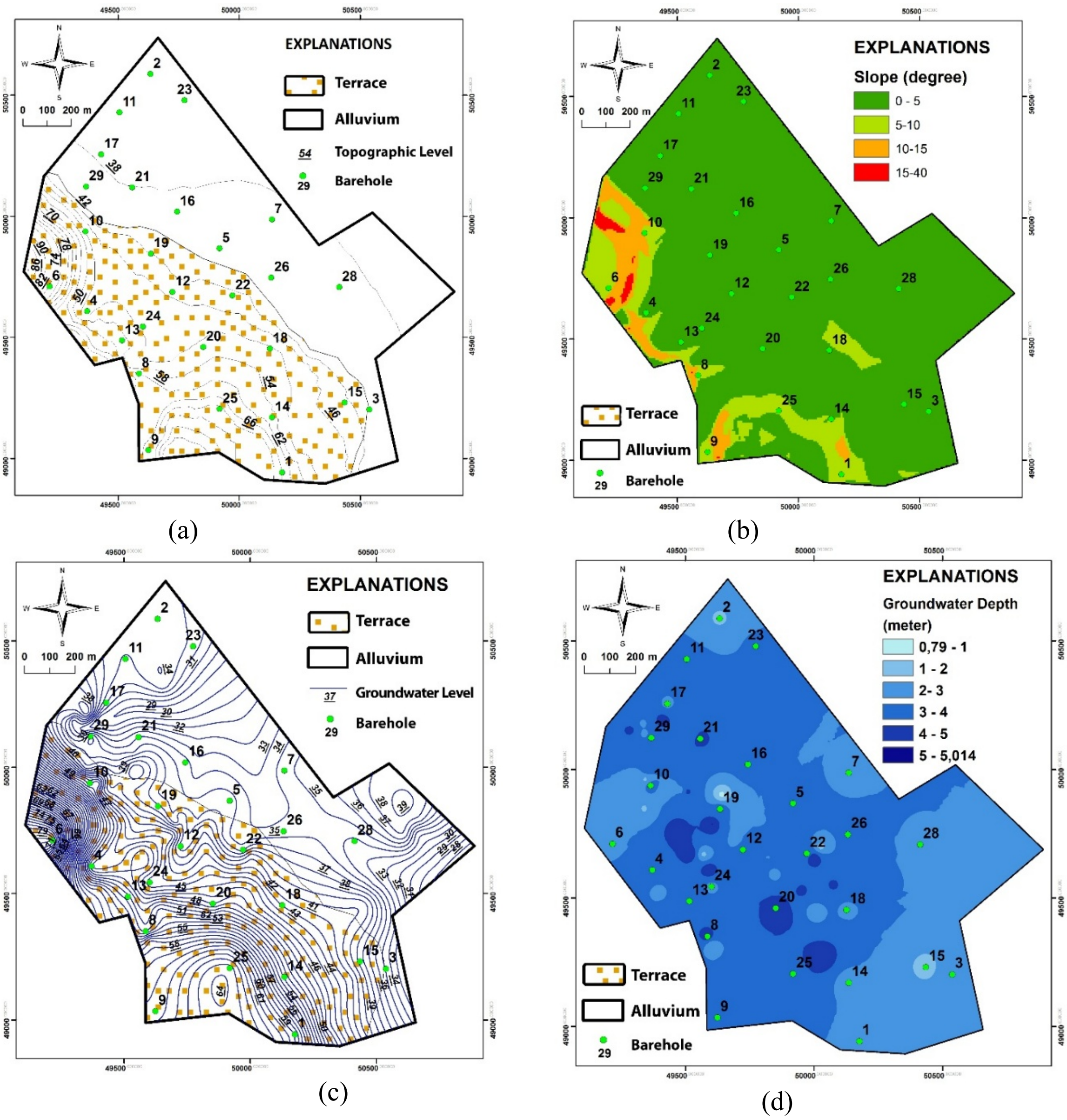

Figure 2.Topographical map (a), slope map (b), groundwater level map (c) and groundwater depth map of the Susurluk (Balikesir settlement area

The terrace unit in the study area were classified as silt with low and high plasticity (ML and MH), and clayey sand (SC), silty sand (SM) and based on Unified Soil Classification System. Liquid limit of the terrace range between 17 and 35 % and plasticity index changes between 4 and 16%. The alluvium were classified as clayey silty sand, silty sand and gravel-sand. In the Figure 3, Examples to the grain distribution curves of the terrace and the alluvium in the study area were given.

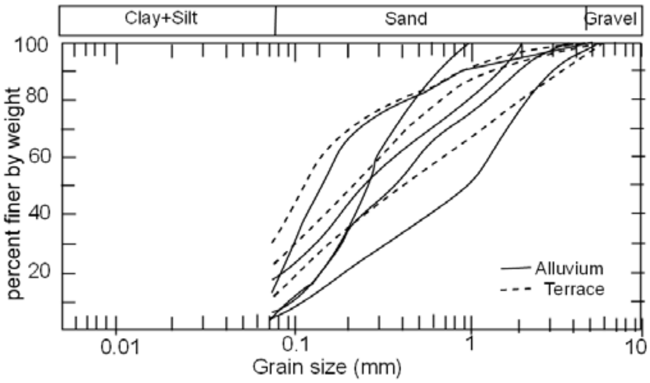

Figure 3.The grain distribution curves of the terrace and the alluvium

The corrected SPT-N values of the terrace and alluvial soils in the study area were evaluated in the GIS, and the maps showing these values varying from 3, 6 and 9, 12 and 15 m depth from the topographic surface were produced (Fig. 4). Recorded data of SPT results collected provided by the Susurluk municipality should be corrected to as seen in Eq. 1 ([4]), and the correction factors will be calculated according to Table 1

$$(N_1)_{60} = N_{SPT}\ C_N\ C_E\ C_B\ C_R\ C_S \tag{1}$$

where $(N_1)_{60}$ corrected standard penetration test blow count, N_{SPT} represents the measured standard penetration resistance, C_N is a factor to normalize, N_{SPT} represents the effective overburden stress, C_E, represents the correction for hammer energy ratio (ER), C_B is the correction factor for borehole diameter, C_R is the correction factor for rod length, and C_S is the correction factor for samplers with or without liners (Table 1).

Table 1. Correction factors of N_{SPT} value [7]

Factor	Equipment Variable	Term	Correction
Overburden Pressure		C_N	for Pa=100 kPa
Energy ratio	Donut Hammer		0.5 to 1.0
	Safety Hammer	C_E	0.7 to 1.2
	Automatic-Trip Donut Type Hammer		0.8 to 1.3
Borehole diameter	65 mm to 115 mm		1 0
	150 mm	C_B	1.05
	200 mm		1.15
Rod length	3 m to 4 m		0.75
	4 m to 6m	C_R	0.85
	6 m to 10 m		0.95
	10 m to 30 m		1.0 <1.0
	>30m		
Sampling method	Standard sampler	C_S	1.0
	Sampler without liners		1.1 to 1.3

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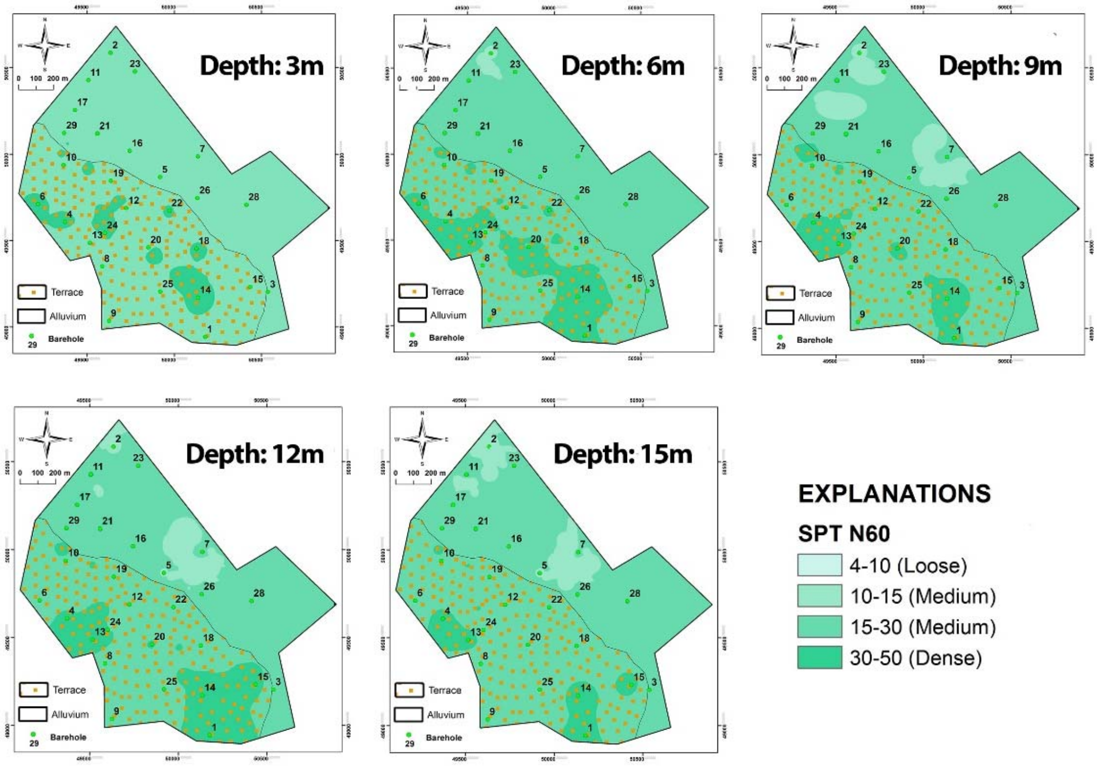

Figure 4. The map representing the value of corrected N_{SPT} at different depths

These maps were evaluated according to Terzaghi and Peck[16] classification, which defines the relationship between N_{SPT} and relative density (D_r). The $(N_1)_{60}$ value ranges generally from 15 to 50 in terraces and from 10 to 30 in alluvium.

4. Liquefaction Potential of The Soil Layer Investigated

4.1. Safety factor against liquefaction

In this study, the method suggested by Youd and co-workers [4] was used in the calculation of factor of safety (FL) against liquefaction of the soil layers (Eq.2)

$$F_L = \frac{CRR_{7.5}}{CSR} MSF \tag{2}$$

where CSR is Cyclic stress ratio, $CRR_{7.5}$ is the cyclic resistance ratio for Mw = 7.5 earthquake and MSF is Magnitude scaling factor according to M_w=7.5

4.2. Magnitude scaling factor and maximum ground acceleration

In the literature, there are several different methods of calculation for MSF. Idriss [17] proposed following equations to calculate MSF (Eqs. 3-4)

$$MSF = 6.9 \exp\left(\frac{-M_w}{4}\right) - 0.058 \leq 1.8 \;\; for\; M_W < 7.5 \tag{3}$$

$$MSF = \frac{10^{2.24}}{10^{2.56}} \qquad for \;\; M_w \geq 7.5 \tag{4}$$

The estimated moment magnitudes (M_W) of earthquake scenarios are obtained using the formula suggested by Wells and Coppersmith [18] (Eq. 5 and table 2. The formula based on the lengths of the fault segment (SRL) (Eq. 5, Table 2)

$$M_W = a + b \log(SRL) \tag{5}$$

where the SRL is the length (km) of surface rupture (or the fault segment which produces the scenario earthquake) and the coefficients a and b depend on the fault type and are taken from Table 2.

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Table 2. The coefficients a and “b in the Equation 5 representing the scenario earthquake magnitude based on fault segment approach [18]

Fault type	**a**	**b**
Strike slip	5.16	1.12
Normal	4.86	1.32
Reverse	5.00	1.22
All type	5.08	1.165

The maximum horizontal ground acceleration, which may occur as a result of a scenario earthquake at the study area, is estimated from attenuation relationship (Eq. 6, [19])

$$a_{max} = 2.18e^{0.0218(33.3M_W - R_e + 7.8427S_A + 18.9282S_B)} \tag{6}$$

where, a_{max} is the peak ground acceleration, S_A and S_B are site condition constants (S_A=0 and S_B=0 for rock sites, S_A=1 and S_B=0 for soil sites, S_A=0 and S_B=1 for soft soil sites) and Re is the distance to epicenter.

The length of the faults, the closest distances to the Susurluk settlement area (Fig.5), moment magnitudes obtained from Eq.5 and maximum horizontal accelerations of the scenario earthquakes obtained from Eq. 6 are given in Table 3. The most severe damage may occur if the scenario earthquake occurs on the southern branch of the NAFZ (Yenice-Gönen Faults) on which the highest maximum horizontal ground acceleration value was obtained among the earthquake scenario (Table 3). Therefore, Mw and a_{max} considered in the liquefaction analyses are assumed to be equal to 7.3 and 302 gal, respectively

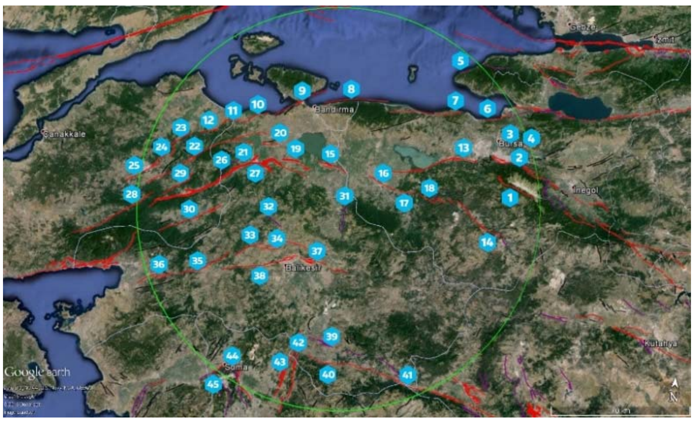


Figure 5. The active faults affecting the Susurluk (Balıkesir) settlement area (The center of the circle is the Susurluk (Balıkesir) settlement area and its diameter is 100 km. The number in parentheses is given in Table 3)

Table 3. The magnitude of possible scenario earthquakes and maximum ground acceleration based on the active faults affecting the Susurluk Balıkesir) settlement area

No	Fault Name	Segment	Re	SRL	Mw	amax	No	Fault Name	Segment	Re	SRL	Mw	amax
1	Soğukpınar Fault		81,36	18,38	6,55	42,87	24	Biga-Çan Fault Zone	Yuvalar Segment	89,73	14,27	6,42	32,56
2	Bursa Fault		80,16	38,26	6,92	57,54	25	Biga-Çan Fault Zone	Çan Segment	91,37	19,93	6,59	35,5
3	Barakfakı Fault		98,97	8,06	6,13	21,6	26	Akçapınar Fault		53,79	18,4	6,55	78,22
4	Barakfakı Fault		94,09	13,61	6,4	29,1	27	**Yenice-Gönen Fault**		**18,1**	**87,1**	**7,3**	**301,87**
5	Armutlu Fault		90,74	4,55	5,84	20,97	28	Evciler Fault		92,01	46,4	7,01	47,69
6	Genç Ali Fault		86,52	23,72	6,68	42,05	29	Bekten Fault		73,69	16,2	6,48	48,38
7	Zeytinbağı Fault		54,98	36,25	6,89	97,67	30	Pazarköy Fault		58,27	34,54	6,86	89,32
8	Bandırma Fault		53,35	32,41	6,83	97,14	31	Susurluk Fault		2,7	13,89	6,41	214,97
9	Edincik Fault		55,85	29,95	6,79	89,37	32	Şamlı Fault		29,13	9,38	6,21	104,66
10	Sinekçi Fault		58,93	10,35	6,26	56,66	33	Havran-Balya Fault Zone	Ovacık Segment	24,41	21,76	6,63	157,81
11	Sinekçi Fault		62,42	15,77	6,47	61,25	34	Havran-Balya Fault Zone	Turplu Segment	28,47	16,3	6,49	129,96
12	Sinekçi Fault		72,16	9,45	6,21	41,08	35	Havran-Balya Fault Zone	Osmanlar Segment	40,37	28,32	6,76	122,71
13	Ulubat Fault		32,11	45,04	7	174,09	36	Havran-Balya Fault Zone	Havran Segment	58,12	18,98	6,56	71,99
14	Orhaneli Fault		59,31	30,7	6,81	83,63	37	Balıkesir Fault	Kepsut Segment	27,88	27,31	6,75	158,99
15	Mustafa Kemal Paşa Fault		18,28	16,2	6,48	161,92	38	Balıkesir Fault	Gökçeyazı Segment	30,52	39,25	6,93	171,39
16	Mustafa Kemal Paşa Fault		22,4	16,29	6,49	148,31	39	Düvertepe Fault Zone		64,51	53,01	7,08	91,18
17	Mustafa Kemal Paşa Fault		31,5	8,26	6,14	94,88	40	Simav Fault Zone	Sındırgı Segment	73,44	49,03	7,04	72,94
18	Mustafa Kemal Paşa Fault		40,66	10,04	6,24	83,45	41	Simav Fault Zone	Çaysimav Segment	88,91	43,03	6,98	49,63
19	Manyas Fault Zone		23,87	16,32	6,49	143,73	42	Gelenbe Fault Zone	Doğu Segment	70,98	35,51	6,88	68,39
20	Gündoğan Fault		43,04	10,92	6,28	81,7	43	Gelenbe Fault Zone	Batı Segment	62,27	36,58	6,89	83,6
21	Gündoğan Fault		52,71	12,5	6,35	69,53	44	Soma-Kırkağaç Fault Zone		90,99	31,78	6,82	42,46
22	Sarıköy Fayu		51,77	66,6	7,2	130,85	45	Soma-Kırkağaç Fault Zone		94,97	39,31	6,93	42,08
23	Biga-Çan Fault Zone	Biga Segment	82,15	15,34	6,46	39,44							

4.3. Determination of cyclic stress ratio

Cyclic stress ratio (CSR) characterizes the seismic demand induced by a given earthquake, and it can be determined from peak ground surface acceleration that depends upon site-specific ground motions [11]. The expression for CSR induced by earthquake ground motions formulated by Youd et al [4] is as follows:

$$CSR = 0.65 \frac{a_{max}}{g} \frac{\sigma_v}{\sigma'_v} r_d \tag{7}$$

where 0.65 is a weighing factor to calculate the equivalent uniform stress cycles required to generate same pore water pressure during an earthquake; a_{max} is the peak horizontal ground acceleration; g is acceleration of gravity; σ_v and σ'_v are total vertical overburden stress and effective vertical overburden stress, respectively, at a given depth below the ground surface; r_d is depth-dependent stress reduction factor; MSF is the magnitude scaling factor.

This stress reduction factor (rd) accounts for the dynamic response of the soil column and represents the variation of shear stress amplitude with depth. The factor and is defined as following quation [4], (Eq. 8)

$$r_d = \frac{(1.00 - 0.4113z^{0.5} + 0.0452z + 0.001753z^{1.5}}{(1.000 + 0.4177z^{0.5} + 0.05729z - 0.006205z^{1.5} + 0.001210z^2)} \tag{8}$$

where z is the depth (in m)

4.4. Determination of cyclic strength ratio

In order to calculate the cyclic strength ratio of the soil layer investigated, the equations in the methods given in [4] was applied (Eqs. 9-12)

$$CRR_{7.5} = \frac{1}{34-(N_1)_{60CS}} + \frac{(N_1)_{60CS}}{135} + \frac{50}{\lfloor 10(N_1)_{60CS}+45 \rfloor^{\,2}} - \frac{1}{200} \tag{9}$$

$$(N_1)_{60CS} = \alpha + \beta (N_1)_{60CS} \tag{10}$$

$$\alpha = 0\ (İTO \leq \%5)\ , \alpha = exp\left[1.76 - \left(\frac{190}{İTO^2}\right)\right] (\%5 < İTO \leq \%35), \alpha = exp\left[1.76 - \left(\frac{190}{İTO^2}\right)\right] (\%5 < İTO \leq \%35)\ \alpha = 5.0 \tag{11}$$

$$\beta = 0 \quad (FC \leq \%5)\ , \quad \beta = 1.2 \quad (FC > \%35) \quad and\ \beta = \left[0.99 - \left(\frac{FC^{1.5}}{1000}\right)\right] \quad (\%5 < FC \leq \%35) \tag{12}$$

where $CRR_{7.5}$ is the cyclic resistance ratio for M_w=7.5 , $(N_1)_{60CS}$ is the $(N_1)_{60CS}$ value corrected for fines content(FC), α and β are coefficients that depend on the fines content.

5. Liquefaction potential index and Liquefaction severity index of the soil profile investigated

LPI was originally proposed by Iwasaki and co-workers ([10], [20]) to evaluate the potential for liquefaction to cause foundation damage. LPI assumes that the severity of liquefaction is proportional to (1) the thickness of the liquefied layer; (2) proximity of the liquefied layer from the ground surface; and (3) amount by which the factor of safety (FL) is less than 1.0. LPI is defined as:

$$L_I = \int_0^{20} F(z)W(z)dz \tag{13}$$

$$W(z) = 10 - 0.5z\ for\ z < 20m \quad and \quad W(z) = 0\ for\ z > 20m \tag{14}$$

$$F(z) = 1 - F_L\ \ for\ F_L < 1, \qquad F\ (z) = 0\ \ for\ \ \leq 1 \tag{15}$$

where z is depth from the ground surface in meters. F(z) values given by Iwasaki and co-workers ([10], [20]) was rearranged by Sonmez [11] as following equations (Eq. 16)

$$F(z) = 1 - F_L\ \ (\,F_L < 0.95), F\ (z) = 0\ \ (F_L \leq 1.2), F(z) = 2x\ 10^6\ e^{-18.427F_L}\ \ (0.95 < F_L < 1.2) \tag{16}$$

The liquefaction potential of the study area was prepared by two different methods. In the first (Fig.6a), the approach proposed by Youd et al [4] is based on (Eqs 9-12) and the method given in [11] was applied. In the other map (Fig. 6b), the method given in [6] was applied to obtain the liquefaction potential of the study area. Sonmez and Gokceoglu [6] introduce the probability of liquefaction (P_L) proposed by Juang et al. [21] based on the factor of safety to the LPI concept. The calculation of the LPI based on P_L modified by Sonmez and Gokceoglu [6] was given following equations (Eqs. 17-19). In addition, Sonmez and Gokceoglu [6] rearranged the classification of liquefaction severity by considering Chen and Juang's [22] probability of liquefaction classes based on P_L values.

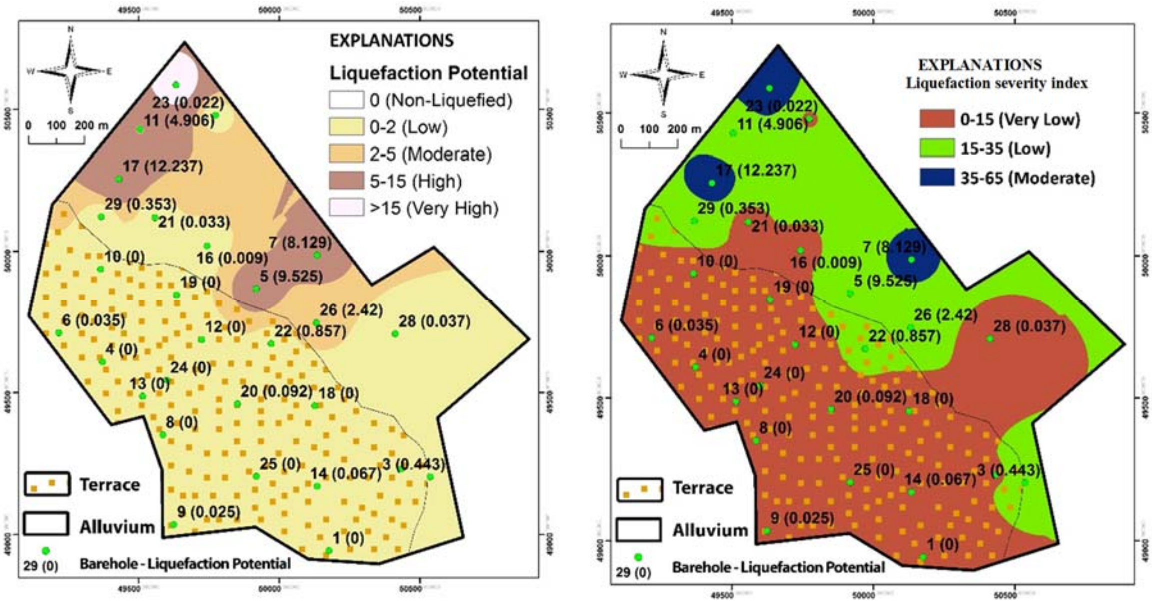
$$L_S = \int_0^{20} P_L(z)W(z)dz \tag{17}$$

$$P_L(z) = \frac{1}{1 + (F_L/0.96)^{4.5}}\ \ for\ F_L \leq 1.411 \tag{18}$$

$P_L(z)=0$ for $F_L>1.411$

(or the soil layer FL ≤ 1.411can be considered as non-liquefiable considering clay content and liquid limit). (19)

where L_S is Liquefaction severity index, the term W(z) is as same as those Eq. 14



(a) (b)

Figure 6. Liquefaction susceptibility maps of the Susurluk (Balikesir) settlement area on the liquefaction potential index classification modified by Sonmez [11] (a) and the Liquefaction severity index purposed Sonmez and Gokceoglu [6]

6. Result and Conclusion

In the study area, terraces and alluvium are observed on the surface. Scenario earthquakes were created taking into account the lengths of active faults near the survey area (within a 100 km circle). The maximum ground acceleration (a_{max}) is obtained by using the attention relationship. As a result of these analysis, to calculate the factor of safety (F_L) against liquefaction of the soil layers, Mw and a_{max} considered are assumed to be equal to 7.3 and 302 gal, respectively.

In the liquefaction analyses for the study area, to obtain liquefaction susceptibility maps of the study area, liquefaction potential index classification modified by Sonmez [11] and the Liquefaction severity index purposed Sonmez and Gokceoglu [6] were applied. Iwasaki et al. ([10], [20]) defined the effect of the factor of safety on liquefaction potential as linear from zero to one. It is obviously known that the layer having the smallest factor of safety may cause more damage on the surface. The studies carried out by Sonmez [11] and Sonmez and Gokceoglu [6] were performed to overcome the use of linear relation for impact of the factor of safety on liquefaction potential.

Almost all of the area where the terrace is observed has "None" or "Low" liquefaction susceptibility according to the methods purposed by Sonmez [11] and as the same, these are has “Very low” susceptibility according to the methods purposed by Sonmez and Gokceoglu [11]. 21.1% of the areas where alluvium is observed have "Low", 43.3% "Moderate ", 27.4 % have “High” and 6.3% have “Very High” liquefaction susceptibility according to the methods proposed by Sonmez [11]. Considering liquefaction severity index purposed Sonmez and Gokceoglu [6] values, 85% of the area where the terrace is observed has "None" or "Very Low" liquefaction susceptibility while 15% of the area has “Low” liquefaction susceptibility. And, 18.7% of the areas where alluvium is observed have "Moderate” while 81.3% of the areas have “Low” and “Very low” liquefaction susceptibility.

Taking into account these liquefaction susceptibility maps in the urban planning for the Susurluk (Balıkesir) settlement area is the useful in the reducing of earthquake hazards.

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