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Potential Settlement Due to Seismic Effects in the Residential Area of Ilgin (Konya, Turkey)

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ABSTRACT

Ilgin lies on newly formed, loose, granular deposits, and there is substantial risk for surface liquefaction and foundation settlements due to the seismic effects resulting from groundwater close to the surface. This study evaluates potential settlement due to seismic effects in the residential areas of Ilgin using the Standard Penetration Test (SPT) performed on 45 geotechnical bores. In Turkey, where earthquakes occur frequently, the selection of residential areas is of great importance. In this research, the number of settlements was calculated considering an earthquake having a Local Magnitude of 6 (i.e., ML $\geq$6.0 and a$\geq$0.4 g) under a 0.4 g seismic force, and a potential settlement map of the residential area was prepared. The amount of settlement exceeds 20 cm at locations near Ilgin Lake and in the northern section of Ilgin residential areas; downtown, the settlement ranges from 10-20 cm. The settlements presented here exceed the allowable threshold limits for structures constructed using adobe and brick in this district. Thus, improvements to minimise earthquake-induced damages are required for structures in Ilgin. Moreover, the selection of new residential areas, along with the proper design of the structures before construction, should be examined further to avoid ground liquefaction and structure damage due to settlement.

Keywords: Soil settlement, soil dynamic, liquefaction, earthquake, Ilgin.

Asentamiento potencial del suelo debido a efectos sísmicos en el área residencial de Ilgin (Konya, Turquía)

RESUMEN

La localidad de Ilgin está ubicada sobre depósitos recién formados, granulares y no compactos, por lo que existe un riesgo sustancial de licuefacción de la superficie y la creación de asentamientos o deslizamientos debido a los efectos sísmicos resultantes del agua subterránea poco profunda. Este artículo evalúa el potencial de asentamiento debido a los efectos sísmicos en las áreas residenciales de Ilgin a través del Ensayo de Penetración Estándar (SPT, en inglés) realizado en 45 perforaciones geotécnicas. En Turquía, donde los terremotos ocurren frecuentemente, la selección de áreas residenciales es de gran importancia. En esta investigación, se calculó el número de asentamientos ante un terremoto con Magnitud Local (ML) de 6 y con una fuerza sísmica de 0.4 g para preparar un mapa de asentamientos en el área residencial. La cantidad de asentamientos supera los 20 centímetros en lugares cercanos al lago Ilgin y en la sección norte del área residencial; en el centro, los rangos de asentamiento van de 10 a 20 cm. Los asentamientos presentados exceden los límites de lo permitido para estructuras construidas en adobe y ladrillo en este distrito. Por esto, se requieren mejoras para minimizar los daños inducidos por terremotos en las estructuras de Ilgin. Además, la selección de nuevas áreas residenciales, junto con el diseño apropiado de las estructuras antes de la construcción, debe ser revisado atentamente para evitar la licuefacción del suelo y el daño de las estructuras debido al asentamiento.

Palabras clave: Asentamiento del suelo, dinámica de suelos, licuefacción, terremoto, Ilgin.

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1. Introduction

Ground oscillation, liquefaction, flows, slides, and settlements caused by seismic effects result in damage or destruction of transportation infrastructure, energy transmission lines, municipal water infrastructure, wastewater facilities, communication lines, and other engineered structures. Earthquakes can also lead to significant economic losses and loss of human lives (Bardet and Kapuskar, 1993; Clough et al., 1994; Kimura, 1996; Holzer, 1998). Displacements, which occur in various forms due to the variety of flows, slides, falls, precipitations, and settlements, may exceed 10 m at times (Zhang et al., 2004). Pore-water pressure, which appears to increase during seismic cycles in water-absorbable sandy soils, gradually dissipates after an earthquake, and the settlement, which is the vertical component of the volumetric deformations to the ground, can significantly damage nearby engineered structures. Settlements can even result in the destruction of structures. Furthermore, differential settlement caused by the nonuniformity of structures can result in increased structural damage.

Currently, the selection of residential areas and the implementation of earthquake-design constructions are of high importance. Recent studies have been focused on determining the most appropriate residential areas and designing earthquake-resistant structures (Bartlett and Youd, 1995; Hamada et al., 1996; Seed, 1979; Ishihara and Yoshimine, 1992; O'Rourke and Pease, 1992; Stewart et al., 2002; Stewart and Whang, 2003; Zhang et al., 2004; Kayabali and Beyaz, 2011). The selection of residential areas is particularly important in Turkey, where earthquakes occur frequently. Earthquake-induced damages can be devastating due to the limited number of earthquake-resistant structures that can tolerate both seismic settlements and differential ground settlements. (Kayabali, 1997; Ulusay et al., 2000; Cetin et al., 2002; Mollamahmutoglu et al., 2003). Thus, some researchers have investigated liquefaction and shear failures in soils. Zhang et al. (2002) examined the estimation of liquefaction-induced ground settlements from CPT data, while Andrus et al. (2004) compared the liquefaction evaluation methods using the penetration-Vs relations. Tatsuoka et al. (1987) observed settlement in saturated sand due to cyclic undrained simple shear. Yoshimine et al. (2006) showed the flow deformation of a liquefied sand layer under a constant shear load and analysed the slide flow of an infinite slope.

This study focuses on the determination of ground settlement potentials in the residential areas of Ilgin (Figure 1), which is located in the first-degree earthquake zone of the Region of Lakes (i.e., the central-southwest of Turkey). In situ test data were obtained by the Standard Penetration Test (SPT). Although there is much interest, previous studies have not studied ground settlement due to seismic effects. Generating fundamental data to inform the planning of residential areas (in both Ilgin and other regions) and the design of earthquake-resistant structures requires determining the ground deformations due to the seismic movements, as well as liquefaction susceptibility of medium-high and low resistance areas (Ozdemir and Ince, 2005). This particular study determines the level of the settlements in Ilgin and similar areas by performing a full evaluation of the morphology, geology, seismo-tectonics, and liquefaction potential of the residential areas in Ilgin. In the following sections of the study, the morphology, geology, and hydrogeology after seismo-tectonics, as well as the liquefaction potential of the study area, are examined. Furthermore, the calculation details for saturated and unsaturated soil settlements with seismic effects are given.

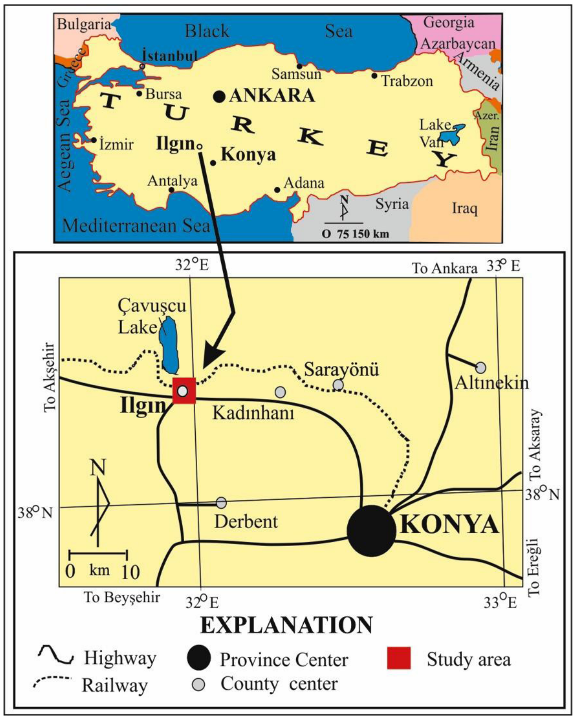

Figure 1. Map of the study area

2. Materials and methods

2.1 Location information, morphology, geology, and hydrogeology

Ilgin is located 90 km northwest of Konya in the south-central section of Central Anatolia (Figure 1). Ilgin is bordered by Hamam Sirti to the southwest and Sivri tepe to the northeast. The town is located on a flat area, and the study area has an altitude between 1025–1035 m. Cavuscu Lake is approximately 5 km northeast of Ilgin. The study area is located to the south and north of the central section, while the overall topographical inclination is from west to east due to the major hills in the region. The topographical inclination in the residential areas varies between 1 and 3%. There are irrigation canals in the western and northern sections that run from south to north and from west to east (Figures 1 & 2, respectively).

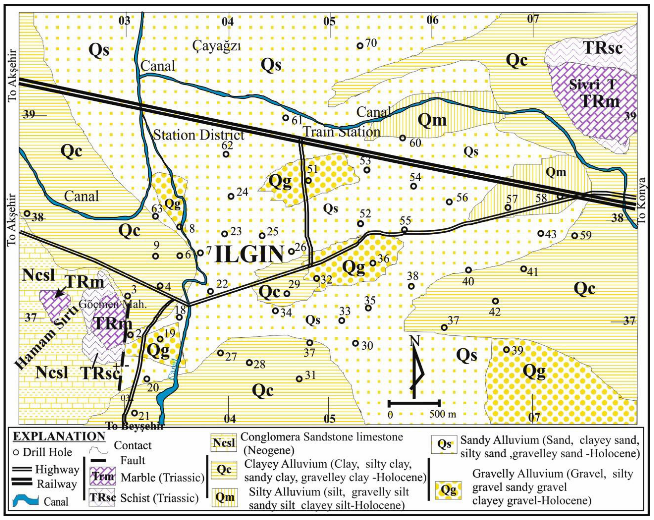

Figure 2. Geological map of the Ilgin residential area and vicinity (Ozdemir and Ince, 2005)

The geology and hydrogeology of Ilgin and its vicinity has been previously researched (Boray et al., 1985; Saroglu et al., 1987; Barka et al., 1995; Kocyigit et al., 2000; Canik, 1981). The regional geology, hydrogeology, tectonics, historical earthquakes, and potential for liquefaction of the study area has also been previously investigated in detail (Ozdemir and Ince, 2005). Data from previous studies that is relevant to this study is summarised in the next paragraph.

The region consists of Neogene and Pre-Neogene aged rock units along with Quaternary units. Triassic-aged marble (TRM) and schist (TRSC) are present in the region. These units do not show liquefaction-settlement potential resulting from seismic effects. Additionally, there are units such as Tertiary-aged conglomerate, limestone, sandstone, and marl (Nc-kg-s) that are not susceptible to liquefaction-induced settlement in the residential areas. Such units are unconformably overlain by Quaternary gravel (Qg), sand (Qs), silt (Qm), and clay (Qc).

2.2 Tectonics, seismo-tectonic, and ground liquefaction potential

The thicknesses of Quaternary-aged units, which have liquefaction and settlement potential, vary from 20-50 m and 0-20 m north of the selected study location and at the other locations, respectively. Vertical and lateral transitions at short distances are present within the Quaternary-aged units. Areas in Ilgin are underlain by loose Quaternary units, and liquefaction susceptibility of such loose precipitation is medium to high (Ozdemir and Ince, 2005). A groundwater map was drawn from data obtained by water depths measurements in 45 boreholes during July of 2000 (Figure 3). The groundwater table depth ranges from -2 m to -4 m.

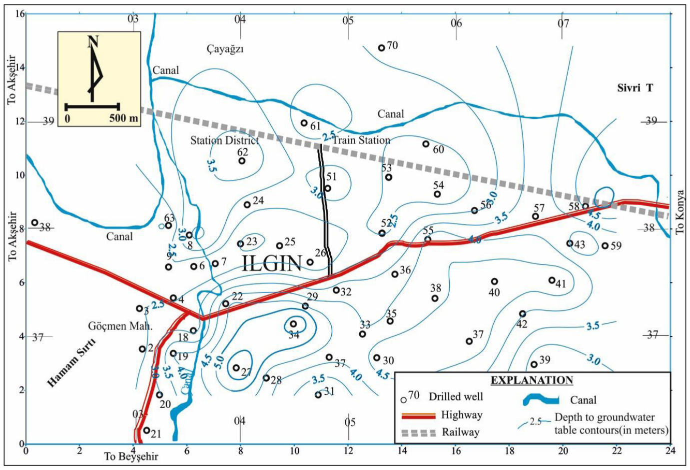

Figure 3. Locations and values of groundwater level measurements (Ozdemir and Ince, 2005)

Ilgin is located at the intersection of the following four active major faults: the southwest trending Sultandagi (Boray et al., 1985; Saroglu et al., 1987), the E-W trending Argithani fault (Kocyigit et al., 2000), the NNE-WWS trending Mecidiye fault, and the N-S trending Cavuscu fault. There are also numerous secondary faults in the region. Earthquakes ranging in magnitudes from 5.5-6.5 have been recorded. As Ilgin is located on recently formed and loose precipitations, there is a high potential for liquefaction following a seismic event (Figures 2 & 3).

2.3 Ground settlement due to earthquakes

Calculations of expected seismic settlements based on the unsaturated (i.e., dry) and/or saturated soil settlement resulting from seismic movements have been extensively investigated (Pyke et al., 1975; Tokimatsu and Seed, 1987; Ishihara and Yoshimine, 1992; Shamoto et al., 1998; Darendeli and Stokoe, 2001; Liu et al., 2001; Seed et al., 2001; Stewart et al., 2001; Stewart et al., 2002). In this study, seismic settlements were calculated using the most commonly used method, the Standard Penetration Test (SPT), developed by Tokimatsu and Seed (1987). The SPT blow counts obtained from the 45 borehole logs were used for the calculations. The correction factor of transferred energy for the SPT test was taken as 0.75 (Seed et al., 1985), and the correction coefficient for the diameter of the borehole was taken as 1 (Robertson, 1994; Robertson and Fear, 1996) to obtain the corrected blow counts N1(60) from the raw SPT blow counts (Equation 2.1). The correction factor for the effective overburden stress was determined according to Liao and Whitman (1986) (Equation 2.2). The cyclic stress ratio (CSR) was determined according to Seed and Idriss (1971) (Equation 2.3), and the stress reduction factor was determined according to NCEER (1997) (Equations, 2.4-2.7).

Where: $(N_1)_{60}$ is the corrected SPT blow count, C_{ER} is the energy ratio in percent, and C_N is the overburden stress correction factor (NCEER, 1997).

$$(N_1)_{60} = C_{\mathrm{ER}} C_N N \tag{2.1}$$

$$C_N = 1/\sqrt{\sigma_0'} \tag{2.2}$$

Where: σ_0' is the effective vertical overburden stress and N is the raw SPT blow count.

Where: CSR is the cyclic stress ratio induced by a given earthquake, σ_0 is the total vertical overburden stress, σ'_0 is the effective vertical overburden stress, amax is the peak horizontal ground acceleration (PGA) in g, and rd is an estimated stress reduction coefficient (NCEER, 1997).

$$CSR = 0.65\ (\sigma_0 / \sigma'_0)\ a_{\max}\ r_d \tag{2.3}$$

$$r_d = 1 - 0.00765\, z \qquad for \quad z \le 9.15\, m \tag{2.4}$$

$$r_d = 1.174 - 0.00267\, z \qquad for \quad 9.15\ m \le z \le 23\, m \tag{2.5}$$

$$r_d = 0.744 - 0.008\, z \qquad for \quad 23\, m \le z \le 30\, m \tag{2.6}$$

$$r_d = 0.5 \qquad for \quad > 30\, m \tag{2.7}$$

The volumetric deformations were estimated according to the corrected SPT blow counts and the cyclic stress rates (CSR) using the curves given by Tokimatsu and Seed (1987) (Figure 4). The settlement (S_{SAT}) of each layer (i) was calculated as the product of the volumetric deformation and the thickness (h_i) of the layer (Equation 2.8; Tokimatsu and Seed, 1987).

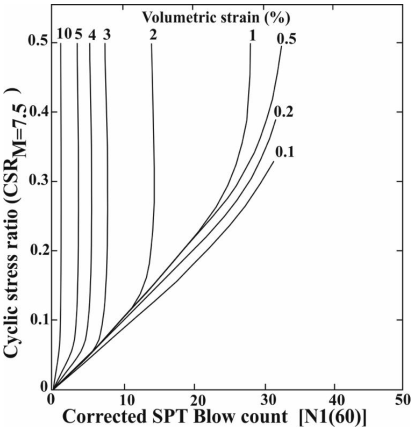

Figure 4. Volumetric strain versus corrected Standard Penetration blow count [(N1)60] and cyclic stress ratio (CSR) (Tokimatsu and Seed, 1987)

$$S_{sat} = \sum_{i=1}^{n} (\frac{\varepsilon_c}{100}) h_i \qquad 2.8$$

Where: S_{sa}s is the settlement of saturated soil; i is the number of layers; n is the total number of layers; ε_c, is the volumetric deformation; and hi is the thickness of layer i.

Because the minimum peak horizontal ground acceleration (PGA) of 0.4 g should be used when determining structural designs in Ilgin, which is located in the most dangerous first-degree earthquake zone (Aydinoglu, 1998), the PGA in this study was taken as 0.4 g when calculating the settlements.

The settlements on dry soil are calculated according to Tokimatsu and Seed (1987), using an estimated earthquake magnitude (Richter Magnitude, M_L) of 6.

For dry soil settlement calculations, the procedure is the same but uses the corresponding SPT input data. The dry soil settlement is calculated by the following six steps:

i. G_{max}, the shear modules of the soil at small strain, is estimated (Equation 2.9; Seed and Idriss, 1970).

$$G_{\max} = 4400\,[(N_1)_{60}]^{1/3} (\sigma_m)^{1/2} \qquad 2.9$$

Where: $(N_1)_{60}$ is the normalised SPT blow count (unitless) and σm is the mean normal total stress in kPa, which is approximated as 0.65 σ_v (σ_v is vertical stress).

ii. Shear strain-modulus ratio, $\gamma_{eff}(G_{eff}/G_{\max})$ is determined to evaluate the cyclic shear strain (Equation 2.10) by the shear modulus, G_{max}:

$$\gamma_{eff} \frac{G_{eff}}{G_{\max}} = 0.65 \frac{\sigma_0}{G_{\max}} a_{\max}\, r_d = CSR_{M=7.5} \frac{\sigma_0'}{G_{\max}} \qquad 2.10$$

Where: $\gamma_{eff}(G_{eff}/G_{\max})$ is a hypothetical effective shear strain-modulus ratio, a_{max} is the peak ground acceleration, and $CSR_{M=7.5}$ is the cyclic stress ratio for an earthquake with a magnitude of 7.5.

iii. Effective shear strain (γ_{eff}) is estimated using the previously calculated shear strain – shear modulus ratio (Figure 5).

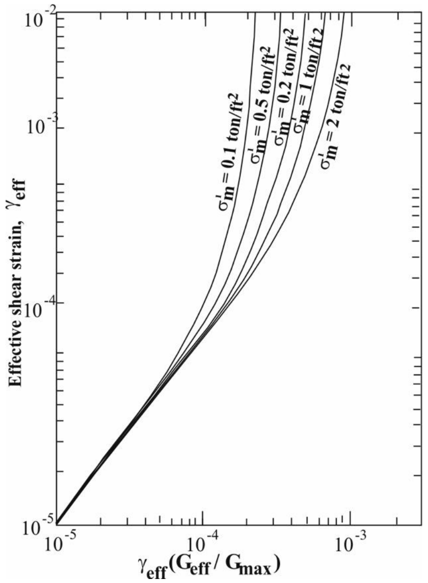

Figure 5. Plot for determining earthquake-induced effective shear strain in deposits (Tokimatsu and Seed, 1987)

iv. The volumetric strain due to compaction, εc, for an earthquake with a magnitude of 7.5 (15 cycles) is determined (Figure 6), and the shear strain is evaluated (Step 3; assuming that $\gamma_{eff} \approx \gamma_c$ (cyclic shear strain)).

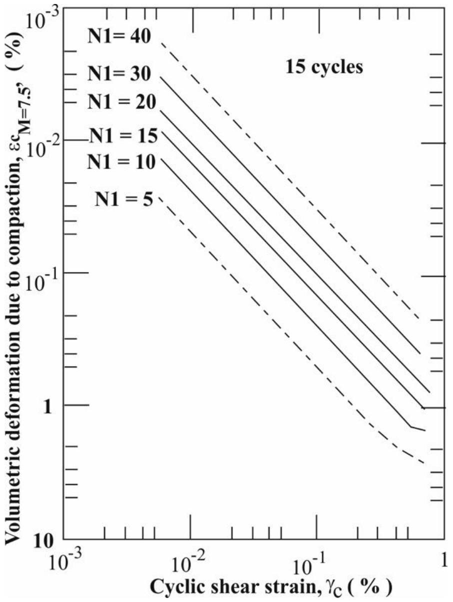

Figure 6. Relation between volumetric strain (ε_c), cyclic shear strain (γ_c), and corrected SPT blow count for (N_1) unsaturated sands (Tokimatsu and Seed, 1987)

v. Figure 6 corresponds to an earthquake with a magnitude of 7.5, with approximately 15 representative cycles. Magnitude correction of the volumetric strain was employed because the figures used above were developed for a magnitude 7.5 earthquake. For earthquakes with magnitudes other than 7.5, the volumetric strain (ε_c) is obtained from the volumetric strain scaling factor r_m (Equation 2.11). Values for r_m are obtained from a plot of magnitude correction factor versus magnitude:

$$r_m = \frac{(\varepsilon_c)_M}{(\varepsilon_c)_{M=7.5}} \qquad 2.11$$

Where: $\varepsilon_{c,M}$ is calculated by multiplying $\varepsilon_{c\ M=7.5}$ with the magnitude strain ratio (r_m).

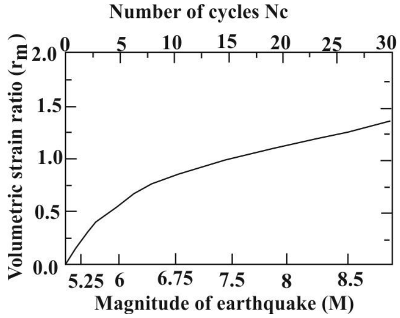

Figure 7. Magnitude correction factor versus magnitude (Tokimatsu and Seed, 1987)

vi. Dry soil settlement is calculated using the volumetric strain (Equation 2.1): 2.11

$$S_{dry} = \sum_{j=1}^{n} \frac{2(\varepsilon_{c,M})}{100}.h_j \qquad 2.12$$

Where: S_{dry} is the settlement of dry soil; $\varepsilon_{c,M}$ is the volumetric deformation [Magnitude (M_L) = 6]; hj is the thickness of the unsaturated or dry soil layer j; and n is the total number of soil layers.

Then, the total settlement (S_{total}) at any specified depth, d, in the saturated and unsaturated (S_{sat}) or in the dry soil (S_{dry}) is determined (Equation 2.13):

$$S_{total} = \sum_{bottom}^{GWT} S_{sat} + \sum_{GWT}^{d} S_{dry} \qquad 2.13$$

Where: S_{total} is the earthquake induced total settlement at a certain depth (d); GWT is the depth of groundwater level; and d is the certain depth.

The SPT blow counts used in this study, along with the other relevant data, are provided in Table 1. The settlements calculated for ground thicknesses of less than 10 m are presented in Table 2, and the map generated for the potential settlements according to the existing settlements at the depth of 2 m is shown in Figure 8.

Table 1. Data used for the calculation of seismically affected settlements (MERCAN-SU, 2000)

Borehole No	Depth to Groundwater (m)	Elevation of Groundwater Table (m)	Depth (m)	N_{SPT}	Unit weight (kN/m^3)	Fines Content (%)	Depth (m)	N_{SPT}	Unit weight (kN/m^3)	Fines Content (%)	Depth (m)	N_{SPT}	Unit weight (kN/m^3)	Fines Content (%)	Depth (m)	N_{SPT}	Unit weight (kN/m^3)	Fines Content (%)	Depth (m)	N_{SPT}	Unit weight (kN/m^3)	Fines Content (%)	Depth (m)	N_{SPT}	Unit weight (kN/m^3)	Fines Content (%)
2	2	1035	2	7	19.6	55	3.0	3	20	55	8.0	24	19.6	55												
3	2.5	1032	2	6	19.6	1	3.0	11	19.6	1																
4	2.5	1031	2	5	18.7	16	5.0	8	18.7	16	7.0	13		16	10	11	18.7	99								
5	2	1031	2	11	18.7	16	5.0	8	18.7	16	8.0	8	18.7	16												
6	2	1031	2.5	7	19.6	41	5.0	10	18.8	41	8.0	10	18.7	41	10	7	18.7	99								
7	2	1031	2	5	19.6	28	5.0	8	18.7	28	7.0	9	18.7	52												
8	4.5	1030	2	2	18.7	87	5.0	7	18.7	87	8.0	8	18.7	40	10	50	18.7	99								
9	2,5	1030	2	5	18.5	7	4.0	7	18.5	7	7.0	9	18.5	7	10	50	27.0	99								
18	2.8	1034	2.5	17	18.5	2	7.0	6	18.5	2	10.0	20	18.5	2	12	50	27.0	99								
19	4.1	1036	2.5	5	17.6	48	5.0	4	17.6	48	8.0	4	17.6	47	10	7	17.6	48	12.0	50	27.0	99				
20	3	1035	2.5	7	17.6	35	5.0	3	17.6	35	7.5	10	17.6	35	10	9	17.6	35	12.0	11	17.6	35	15	13	17.6	35
22	4.6	1035	2.5	3	19.1	16	5.0	5	19.1	91	7.5	5	19.1	87	10	6	19.1	87	11.0	50	27.0	99				
23	1.8	1029	2.5	2	19.0	84	50	3	19.3	91	7.5	5	19.3	91	10	6	27.0	29	11.0	35	19.3	99	15	16	19.3	99
24	2.7	1029	2.5	2	18.6	83	5.0	8	18.6	77	7.5	11	18.6	77	10	12	18.6	77	12.0	8	27.0	99	14	50	27.0	99
25	2	1028	2	2	18.6	30	5.0	7	18.6	76	8.0	9	18.6	56	10	8	18.6	73	12.0	9	18.6	73	16	9	18.6	73
26	2	1028	2	7	18.5	93	5.0	8	18.5	90	8.0	11	18.8	81	10	12	18.8	81	13.0	19	18.8	81	16	19	18.8	81
27	6.1	1036	2.5	4	18.3	76	5.0	6	18.3	76	8.0	11	18.3	78	15	7	18.6	90	20.0	11	18.6	90				
28	4.2	1033	2.5	8	19.1	86	5.0	2	19.1	76	8.0	5	19.1	80	12	5	19.1	84	15.0	12	19.4	84	17	23	19.4	84
29	4.2	1033	3.0	40	18.6	21	5.0	5	18.6	77	8.0	5	19.3	77	10	10	19.3	77	13.0	10	19.3	77	16	16	19.3	77
30	5	1030	2.0	9	19.8	80	5.0	1	19.8	13	8.0	42	19.8	99	10	17	19.8	68	13.0	8	19.8	68	15	19	19.8	68
31	2.8	1031	2.0	8	18.8	78	5.0	8	18.8	88	8.0	34	19.1	88	10	17	19.1	88	13.0	11	19.1	88				
32	3.8	1032	2.0	5	19.6	46	5.0	5	19.6	88	8.0	6	19.6	88	10	7	20.6	88	13.0	14	20.6	88				

Table 2. Calculated settlements

Borehole No	Depth to Groundwater table (m)	Total Settlement (cm) for Depth			
		Depth = 2 m	Depth = 4 m	Depth = 6 m	Depth = 8 m
2	2.0	5.91	2.31	0.16	0
3	2.5	20.46	16.93	11.67	5.98
4	2.5	16.28	12.28	7.2	3.28
6	2.0	10.99	9.28	6.45	3.03
7	2.0	16.39	12.09	7.96	4.1
8	4.5	7.45	7.09	4.52	0.5
9	2.5	15.59	10.65	4.45	0
18	2.8	17.36	16.21	11	3.84
19	4.1	13.22	12.85	8.55	3.62
20	3.0	13.23	11.45	6.72	2.87
22	4.6	11.91	11.47	8.25	3.56
23	1.8	19.1	13.56	8.46	3.59
24	2.7	11.96	9.06	5.58	2.43
25	2.0	16.91	12.27	8.18	4.17
26	2.0	12.22	10.33	6.85	3.4
27	6.1	4.6	4.32	3.95	1.88
28	4.2	13.34	13.11	8.6	3.64
29	4.2	10.67	10.61	8.03	3.35
30	5.0	2.7	2.22	0	0
31	2.8	2.99	2.34	0.17	0.17
32	3.8	14.21	13.59	9.19	4.6
33	4.0	3.25	3	0.82	0.09
34	5.9	8.92	8.53	7.91	3.77
35	4.0	8.62	8.31	7.07	3.67
36	3.8	4.54	4.34	2.75	0.7
37	4.8	0.35	0.19	0	0
38	4.4	1.61	1.43	0.04	0
39	2.5	7.33	5.9	3.21	2.48
40	4.9	0.31	0.2	0.11	0.11
41	5.0	2.25	2.04	0.63	0.28
42	3.9	3.3	3.13	2.83	2.46
43	3.0	3.27	2.87	0.63	0.3
51	3.4	12.8	12.72	8.52	4.07
52	2.4	5.64	5.63	4.3	2.83
53	2.4	17.19	13.42	8.39	3.64
54	2.0	14.41	10.8	6.53	2.16
55	4.5	8.77	4.48	6.46	3.74
56	3.0	10.46	9.29	4.63	1.19
58	5.2	8.06	7.82	5.89	1.99
59	3.8	11.32	10.86	6.7	3.46
60	2.5	7.8	7.57	5.14	1.81
61	2.1	13.47	11.91	8.63	4.19
62	4.0	13.92	13.55	9.42	4.47
63	2.0	16.68	11.63	6.57	1.94
70	3.2	22.54	21.98	15.84	6.9

3. Results and Discussion

Ilgin and its vicinity are located in a first-degree earthquake zone; are at the intersection of the Argithani, Mecidiye, and Cavuscu faults; are on the southeastern section of the active Sultandagi fault; and experience seismic movements in the range of 5.5≤M≤6.5. Earthquakes that hit Sultandagi and Cay towns, which are 75 km to the northwest of the centre of Ilgin, between 2000-2003 were measured in the range of 6-6.2, based on Local Magnitude. They caused significant damage and deaths in the region.

However, it is well-known that seismic energy on the northeast section of the fault (i.e., Ilgin and its surroundings) has not yet been discharged (Kocyigit et al., 2002). Studies indicate that there is a seismic gap around the Argithani fault (Demirtas and Yilmaz, 1996). The extent of the damage to structures is moderate, and damage was observed in the centre of Ilgin due to the effects of the recent earthquakes in Sultandagi and Cay towns. These data indicate that any future earthquake hitting the Ilgin epicentre or its proximity will cause considerable damage to structures, and the degree of damage largely depends on the settlements and ground liquefaction. Any earthquake of 6.0≤M≤6.5 would inevitably lead to fatal damage.

Pre-Quaternary rocky units and Quaternary-aged and loose deposits are present in the residential areas of Ilgin. There is a potential for liquefaction and settlement of the Quaternary units due to seismic effects. Quaternary-aged and loose precipitations not only have the potential for liquefaction but also the potential for settlement due to seismic effects. Ozdemir and Ince (2005) showed that the Ilgin soils have medium to high liquefaction potentials (i.e., 70-80%).

In general, the groundwater flows from the southwest to the northeast. The groundwater level depth is between 1.5 m to 6 m in most sections except for Hamam Sirti and Sivri Tepe; however, in several sections the water level is as high as 2-4 m. Groundwater levels near the surface contribute to the risk of liquefaction and oversettlement of the ground (dependent on the degree of liquefaction).

Statistical analysis of the settlement potential for a ground thickness of 10 m under the seismic movement caused by an earthquake (6 on the Local Magnitude), examined using the results of the SPT test (Table 3), shows that the maximum settlement is 2 m. Settlement varies from 0-22.5 cm for different depths, with an average settlement of 10.3 cm. At a depth of 4 m, settlement ranges from 0-22 cm, with an average settlement of 9 cm. However, the standard deviations of settlements are large and reflect the complexity of the ground.

Table 3. Statistical analysis of the calculated settlements

	Settlement-induced earthquake (cm)			
	Depth = 2 m	Depth = 4 m	Depth = 6 m	Depth = 8 m
Maximum	22.54	21.98	15.84	6.9
Minimum	0.31	0.19	0	0
Mean	10.32	8.79	5.75	2.54
Standard Deviation	11.13	10.98	8.02	3.49

Settlements larger than 20 cm are found at borehole 70 to the north of Ilgin, near the region of the Ilgin Lake, and settlements between 15 cm and 20 cm are observed in the western, northern, and central sections of Ilgin (Figure 5); settlements are to the lower south of Ilgin. When settlements were evaluated in conjunction with the geological map, the maximum settlement is observed around the borehole number 70; settlements between 15 cm and 20 cm are found in the sandy alluvium area (Qs). South of Ilgin, where the potential for settlement is relatively low, gravel and clayish alluvium are found together with sandy alluvium. Sandy alluvium is between gravel and clayish alluvium, indicating that sandy alluvium is largely comprised of clay and gravel. In this particular section, the lower settlement is partially due to deeper groundwater levels than those found in other sections. When the geological, hydrogeological, and settlement maps are combined, it is clear that the groundwater level is in close proximity to the surface, and in sections containing sandy alluvium, intense settlements can follow an earthquake. The map showing the settlement potential indicates numerous areas with settlements in the range of 10-15 cm.

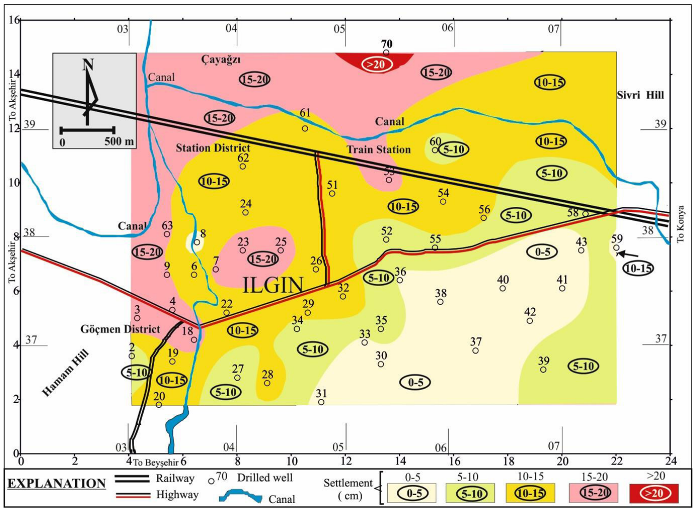

Figure 8. A map showing the settlement potential due to seismic effects in the residential area of Ilgin

The indications on the ground due to the settlement effect and their relation with the expected damage to the structures are presented in Table 4 (Ishihara and Yoshimine, 1992).

Table 4. Relation between settlement and degree of damage (Ishihara and Yoshimine, 1992)

Degree of Damage	Settlement in cm	Indications on the ground
Light–none	0-10	Small cracks
Medium	10-30	Small cracks, penetration of the sand
More	>30	Large cracks, sand gush, lateral movement

In general, the settlements due to seismic effects near Ilgin are between 10-20 cm. Small cracks and sand penetration to the surface of the earth can also be expected in conjunction with the medium-degree damage to structures.

It should be noted that the structures in Ilgin and the vicinity are in the form of heaps, and the major structural materials are adobe and briquettes. A few of these structures have had engineering services provided because their seismic resistance is quite low. Even an earthquake on the order of 5≤M≤ 5.5 in the region could cause substantial damage and a large loss of life due to the poor materials used in the structures.

The maximum allowable settlement for structures made of adobe and briquette is 8-10 cm (Whals, 1981). Settlements exceeding 10 cm were predicted in sections of Ilgin and the vicinity, indicating that settlements due to seismic effects have the potential to exceed the permissible threshold values for structures in the area. The settlements in the northern section of the Istasyon quarter of Ilgin (15 cm - 22.54 cm) exceed the maximum permissible limit for structural reinforced concrete (15.2 cm).

During the 2000 and 2003 earthquakes in Sultandagi and Afyon, respectively, cracks in Ilgin structures became visible, depending on the amount of the settlement. However, no systemmatical data were recorded for these settlements. Seismic activity above ML= 6 within 75 km of the centre of Ilgin would likely increase damage to a large extent due to settlement. To avoid damage, studies focused on earthquake damage minimisation should be conducted. In addition, recommendations of the best available planning/designing activities should be made and implemented for residential areas to avoid ground liquefaction and damage arising from settlement caused by earthquakes.

4. Conclusion

The following conclusions are made based on the outcome of this research. (1) The expected settlements of the residential areas in Ilgin, which bear medium and high degrees of liquefaction potential, were determined to exceed the allowable settlement limits of the structures. (2) Settlements of 5 cm were observed to the south of Ilgın, while in the northern and north-eastern areas, the settlement amounts reached 15-20 cm. (3) North of the selected area, at the sections near the region of the Lake of Ilgin, the settlements were observed to be 23 cm. (4) The structures in the region are not earthquake-resistant structures. (5) Any earthquake measuring 6-6.5 on the Richter scale that hits the Ilgin district and is regarded as a seismic gap poses substantial risk for damage and deaths.

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