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Analysis of Liquefaction during Van Earthquake

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Abstract: The destructive Van Earthquake that struck eastern Turkey on Sunday, 23 October 2011 caused significant damage in the Southeastern Turkish City of Van. It resulted in the collapse of hundreds of buildings and buried numerous victims under the debris. The earthquake killed and injured thousands of people. More than 11,000 buildings sustained various degrees of damage, including more than 6,000 that were rendered uninhabitable, resulting in around 60,000 people being homeless. The moment magnitude of the Van earthquake, Mw = 7.2 (USGS), its epicenter was about 16 kilometers north-northeast of the city of Van, and the focal depth was estimated to be 7.2 km.

This study focuses on the seismic liquefactions occurred in Ercis Plain, where Irsat and Zilan streams are discharged to Lake Van. The liquefaction potential in this area was studied using various analytical methods. The assessment of liquefaction triggering and estimation of seismic induced settlement and lateral spreading were performed. The results of site specific ground response analyses showed that the ground motions were amplified significantly during the earthquake, which resulted in larger Cyclic Stress Ratio (CSR) values relative to those, estimated using simplified methods. The comparison of analytical results with post liquefaction observation indicated that a proper evaluation of CSR results in a realistic estimation of liquefaction triggering and post liquefaction deformations.

1. Introduction

Earthquakes can result in massive and tragic destruction of buildings and associated loss of lives. The global fatality count from earthquakes continued to rise in the last few decades; several Earthquakes resulted in an average of more than 100,000 fatalities per year. The destructive Van earthquake that struck Eastern Turkey near the city of Van on Sunday, 23 October 2011 caused significant damage in the city. Hundreds of buildings collapsed and buried numerous victims under the debris. The earthquake killed 604 people and injured 4,152 people. At least 11,232 buildings sustained various degrees of damage, 6,017 of which were found to be uninhabitable. After the earthquake, around 60,000 people were left homeless. The moment magnitude of the Van earthquake, Mw = 7.2 (USGS), its epicenter was about 16 kilometers north-northeast of the city of Van, and the focal depth was estimated to be 7.2 km.

Liquefaction is a seismic geotechnical hazard that is driven by the site specific conditions. Liquefaction occurs when saturated, cohesionless soils lose their strength as a result of an increase in pore water pressure, often due to earthquake shaking. Liquefaction can have numerous detrimental effects on natural and man-made structures, including settlement, bearing capacity failure, downdrag on deep foundation elements, lateral spreading, and large-scale slope instability (or flow failure). The factors that affect liquefaction susceptibility include: the type and the degree of compaction in the soil; natural water content and plasticity of fines; and the magnitude and duration of the ground motion. Several studies and experimental tests have been conducted to better understand the soil liquefaction potential in both free and/or near-field soil regions and the effect of soil liquefaction on various types of structures (Ishihara 1993; Liu and Dobry 1995; Norris et al. 1997 Finn and Fujita 2002; Ashour and Norris 2003; Rollins et al. 2005). Several areas in the city of Van experienced liquefaction hazards. Low lying delta areas with high ground water table near town of Ercis, which is located North East of Lake Van experienced liquefaction damages during 23 October 2011 Van Earthquake.

This study focuses on the seismic liquefactions observed in part of Ercis Plain, where Irsat and Zilan streams are discharged to Lake Van. The liquefaction potential in this area was studied by Ozvan (2008) using simplified analytical methods. The study comprises the review of geological setup and seismo-tectonic structure of Ercis Plane along with existing subsurface information in the area in the light of the seismic induced geotechnical hazards caused by the Van Earthquake. Based on the existing subsurface information, dynamic soil properties were estimated using an empirical relationship. Subsequently, site specific ground response analyses were performed. The results of these analyses were used in the liquefaction assessment and estimation of seismic induced settlement and lateral spreading that were observed in Ercis Plane. The qualitative and quantitative evaluations were performed. This study presents a case history and application of commonly used design approaches to this particular case.

2. Methodology

2.1. Seismo-tectonic Structure

The seismiciy of Eastern Turkey, where city of Van is located, is dominated by northerly movement of Arabic Plate towards Euroasian Plate. The mantle upwelling leading to lithospheric thinning is responsible for the high elevations in this area. The most important tectonic feature is high and young topography in the seismically active zone along Zargos-Bitlis suture resulting from the intercontinental convergence between the Arabic Plate and Euroasian Plate (Dhont and Chorowicz, 2006).

The new tectonic regime of Eastern Turkey is well documented in a number of studies (Şengör and Kidd, 1979; Şengör and Yılmaz, 1983; Dewey et al., 1986; Şaroğlu and Yılmaz, 1986; Yılmaz et al., 1987; Koçyiğit et al., 2001). This area is one of the youngest intercontinental collision zones on earth, where the Arabian plate collides with the Eurasian plate to form the Turkish-Iranian plateau, causing movement along the North and East Anatolian fault zones (Niyazi et al., 2003). Figure 1 shows tectonic boundaries and plate motions in Eastern Turkey and surrounding regions that include the City of Van.

The northward motion of the Arabian plate relative to Eurasia causes lateral movement and rotation of the Anatolian block to the west, which manifes itself as a right-lateral strike-slip movement along the North Anatolian fault system (NAF) and the left lateral strike-slip movement along the Eastern Anatolian fault system (EAF) (Sengor, 1979; Dewey and Sengor, 1979; McClusky et al., 2000, Niyazi et al. 2003). The Anatolian block escapes westward due, in part, to the northward motion of the Arabian plate. The NAF and EAF have been active since the Miocene (Barka and Kadinsky-Cade, 1988) and are associated with large pull apart basins, such as the Karliova Basin located at the junction of these two fault systems (Hempton, 1985).

The geodynamic models proposed to the date to explain the Arabia/Anatolia continental collision zone include the continental subduction by Rotstein and Kafka (1982); the Arabian plate convergence being accommodated entirely by microplate escape by McKenzie (1976); Sengor and Kidd (1979) and Jackson and McKenzie (1988); lithospheric thickening by Dewey et al., (1986) and lithospheric delamination by Pearce et al., (1990). Niyazi et al (2003) indicated that a combination of these processes formed the seismo-tectonic nature of the area. Figure 2 depicts the seismo-tectonic map of the area.

A comprehensive summary of the historical seismic activities are given in TMMOB-JMO, (2011. Figure 3 (a) and (b) depicts the locations and magnitudes of historical earthquakes (1990-2011) and October 2011 Van Earthquake (main shock) and aftershocks, respectively.

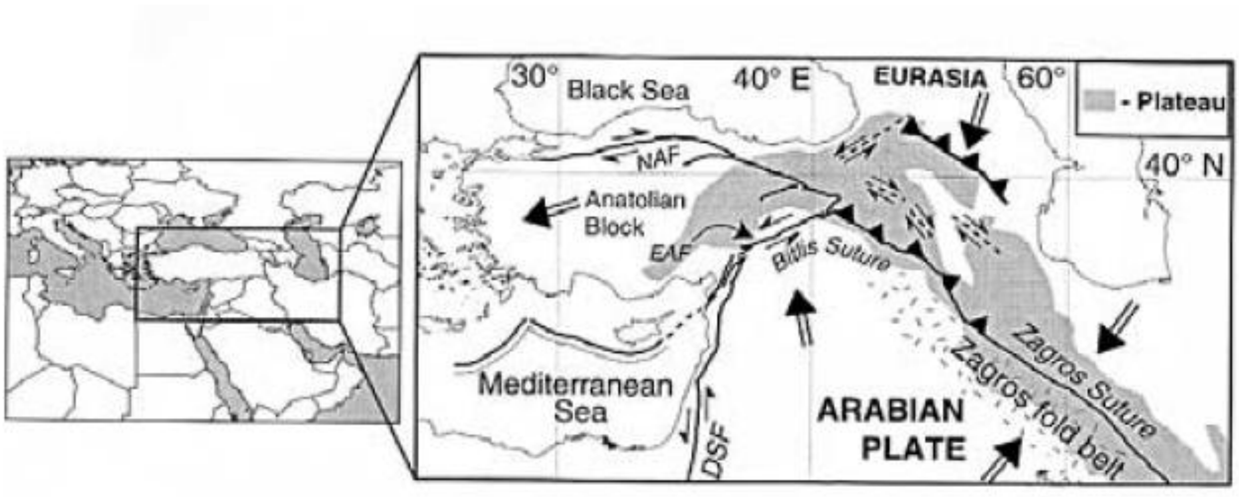


Figure 1. Tectonic boundaries and plate motions in Eastern Turkey (after Niyazi et al. 2003).

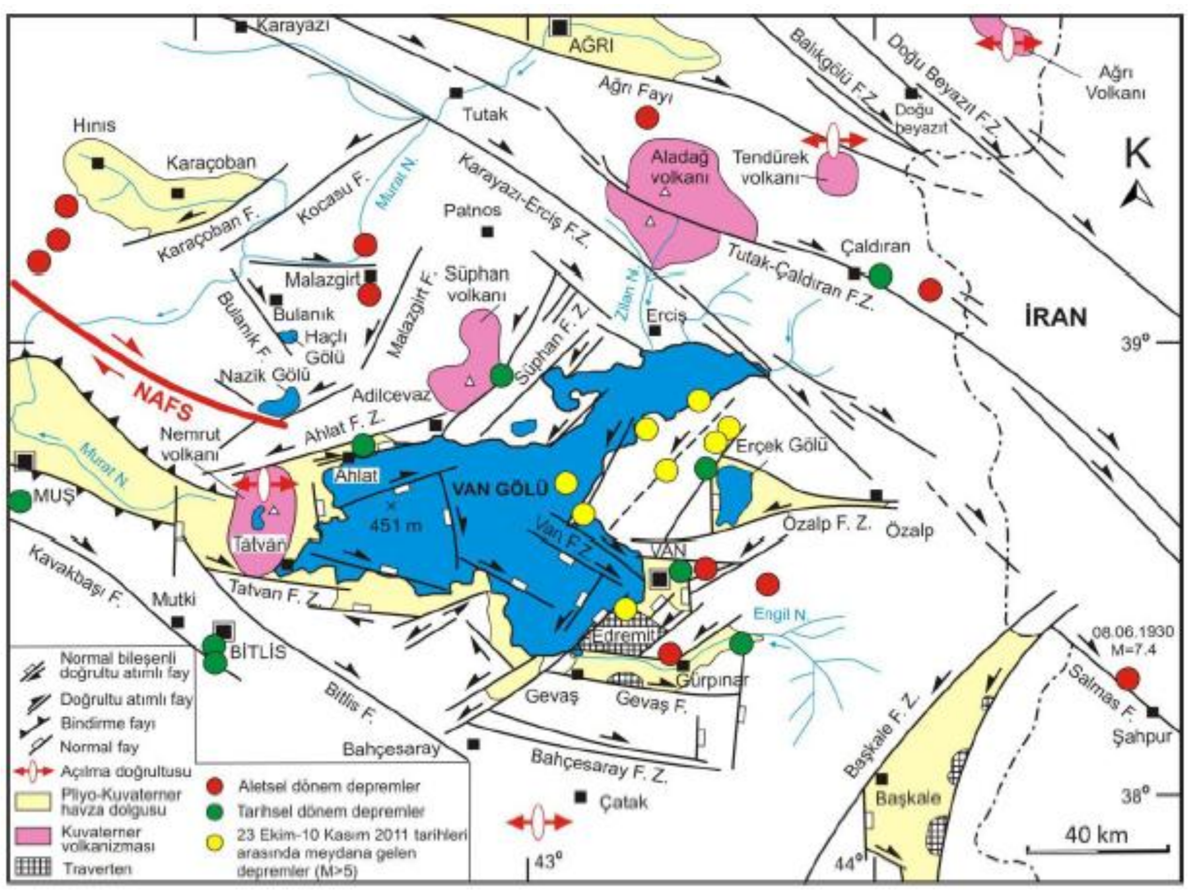
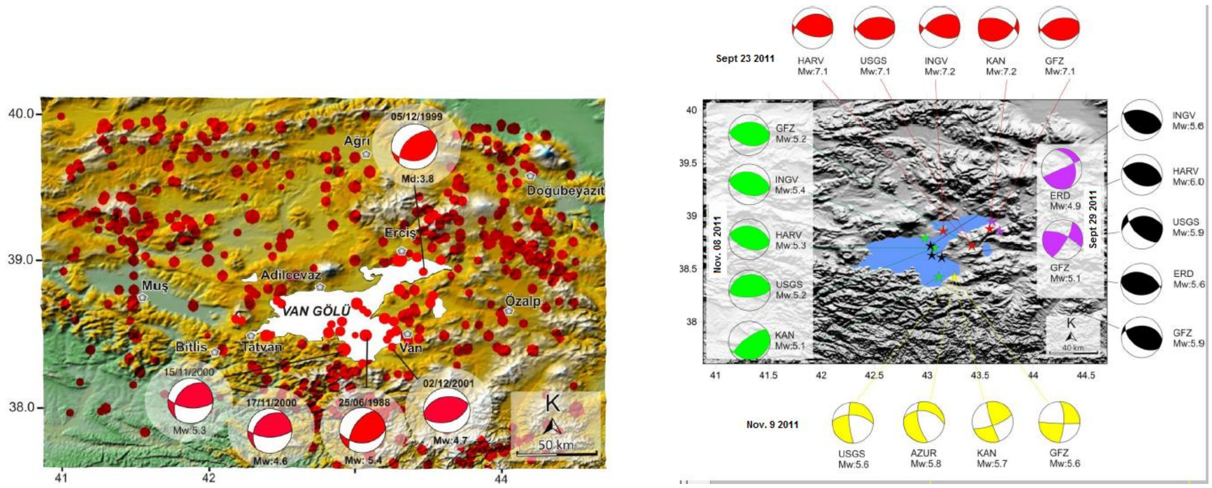


Figure 2. Seismo-tectonic map of Lake Van (Modified by TMMOB, 2011 after Koçyiğit et al., 2001 and Koçyiğit 2002)



a) b)

Figure 3. (a) Locations and magnitudes of historical earthquakes in Lake Van basin between 1990 and 2011; (b) Locations and magnitudes October 2011 Van earthquake (main shock) and aftershocks according to various sources (after TMMOB-JMO, 2011)

2.2. Geologic Conditions

The areal geology of the Lake Van basin is described in great detail in (TMMOB-JMO, 2011). The geologic setup of Lake Van basin comprises the rock masses and alluvial sedimentations formed during Paleozoic Era. Metamorphic rocks belonging to the Bitlis Massif can be observed south of the basin. The volcanic rocks that are produced by Nemrut and Suphan volcanoes are encountered to the west and east. The east of the basin comprises the volcanic rocks and ophiolite compositions belonging to Yuksekova complex. Figure 4 depicts the geologic map of the general area around Lake Van. The Late Paleocene Toprakkale Formation and Early Eocene Tekmal Formation that overlies the Toprakkale Formation are located to the east of basin. The Eocene–Early Miocene Kirkgecit Formation is located at the S-E of the basin. The late Eocene – Oligocene debris can be seen in the North of City of Van. The late Oligocene – early Miocene Van formation is located to the east of Lake Van (Aksoy, 1988).

Cakar (2010) indicates that the residential areas of the City of Van are located on the lake and river sediment deposits that are composed of clay, sand and aggregates. The rivers that pass through the city center towards Lake Van, formed young alluvial deposits. The old city is situated on Eocene period Marls near Van Castle and Quaternary period uncemented lake and river deposits near plain areas. These alluvial deposits can be as deep as 150 m (Acarlar et al., 1991). The ground water table is reported to be shallow, ranging between 0 m to 5 m.

The town of Ercis, which is located 100 km north of City of Van is located on loose quaterner units. The high ground water levels are observed in this area and quick spread of residential areas without proper engineering input raised concerns regarding a possible liquefaction hazard in case of an earthquake (Ozvan, et al, 2008).

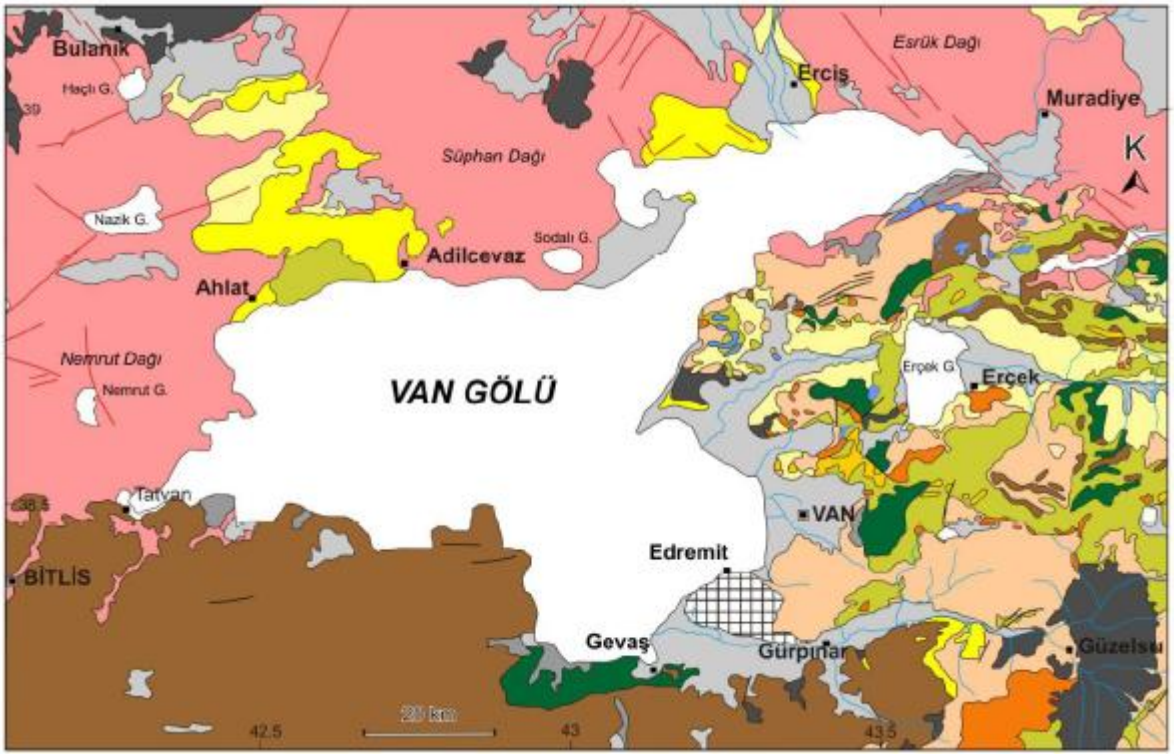


Figure 4. The geologic map of Van area (after MTA, 2002).

2.3. Recorded Strong Ground Motions

A detailed evaluation of strong ground motions measured during Van Earthquake and aftershocks were presented in Ceken et al. (2011). The strong ground motions of Van Earthquake were obtained from Disaster and Emergency Management Presidency (AFAD), who owns and operates a strong ground motion network that comprises 372 stations strategically located throughout the country. The Van Earthquake occurred on October 23rd 2011 were recorded by 22 AFAD stations located at distances ranging from 42 to 590 km from the epicenter. Table 1 gives a summary of measured records. Figure 5 depicts the locations of the stations in the area and maximum accelerations measured by them during October 23th 2011 Van Earthquake. Due to the proximity to Ercis Plain, Muradiye record was used in liquefaction assessment. Figure 6 depicts the acceleration time histories in N-S, E-W and U-D directions. The peak accelerations were 0.176g, 0.173g and 0.08g for N-S, E-W and U-D components, respectively.

Table 1. Measured accelerations during October 23th Van Earthquake (Main Shock).

STATION			Type of Equipment	Measured Accelerations (gal)			Distance to Epicenter	Vs_{30} at the station (m/s)
No	City	Town		N-S	E-W	Vertical		
1	Van	Muradiye	SMACH	178.5	168.5	75.5	42	293
2	Mus	Malazgirt	SMACH	44.5	56.0	25.5	95	311
3	Bitlis	City Center	CMG-5TD	89.66	102.24	35.51	116	Alluvium
4	Agri	City Center	CMG-5TD	18.45	15.08	7.21	121	295
5	Siirt	City Center	CMG-5TD	9.90	9.16	7.04	158	Alluvium
6	Mus	City Center	CMG-5TD	10.3	6.86	4.64	170	315
7	Bingol	Solhan	CMG-5TD	4.58	4.19	2.46	211	463
8	Bingol	Karliova	CMG-5TD	7.52	11.08	4.65	222	Hard
9	Batman	City Center	CMG-5TD	8.29	8.58	3.74	223	450

10	Mardin	City Center	CMG-5TD	2.00	1.90	1.58	284	Hard
11	Elazig	Beyhan	CMG-5TD	1.22	1.19	0.99	289	Hard
12	Elazig	Palu	CMG-5TD	2.11	1.64	1.72	307	329
13	Elazig	Kovancilar	CMG-5TD	1.45	1.66	1.20	313	Alluvium
14	Erzincan	Tercan	CMG-5TD	2.37	3.43	2.26	289	320
15	Erzincan	City Center	CMG-5TD	1.53	1.29	0.71	358	314
16	Bayburt	City Center	CMG-5TD	1.35	1.14	1.27	327	Hard
17	Gumushane	Kelkit	CMG-5TD	1.05	0.88	1.25	378	Alluvium
18	Sanliurfa	Siverek	CMG-5TD	2.00	3.06	0.96	378	Alluvium
19	Malatya	Poturge	CMG-5TD	0.99	0.99	0.94	405	Hard
20	Adiyaman	Kahta	CMG-5TD	2.96	2.70	1.64	437	Alluvium
21	Adiyaman	Golbasi	CMG-5TD	1.12	0.74	0.35	521	469
22	K. Maras	City Center	CMG-5TD	1.74	2.18	0.96	590	317

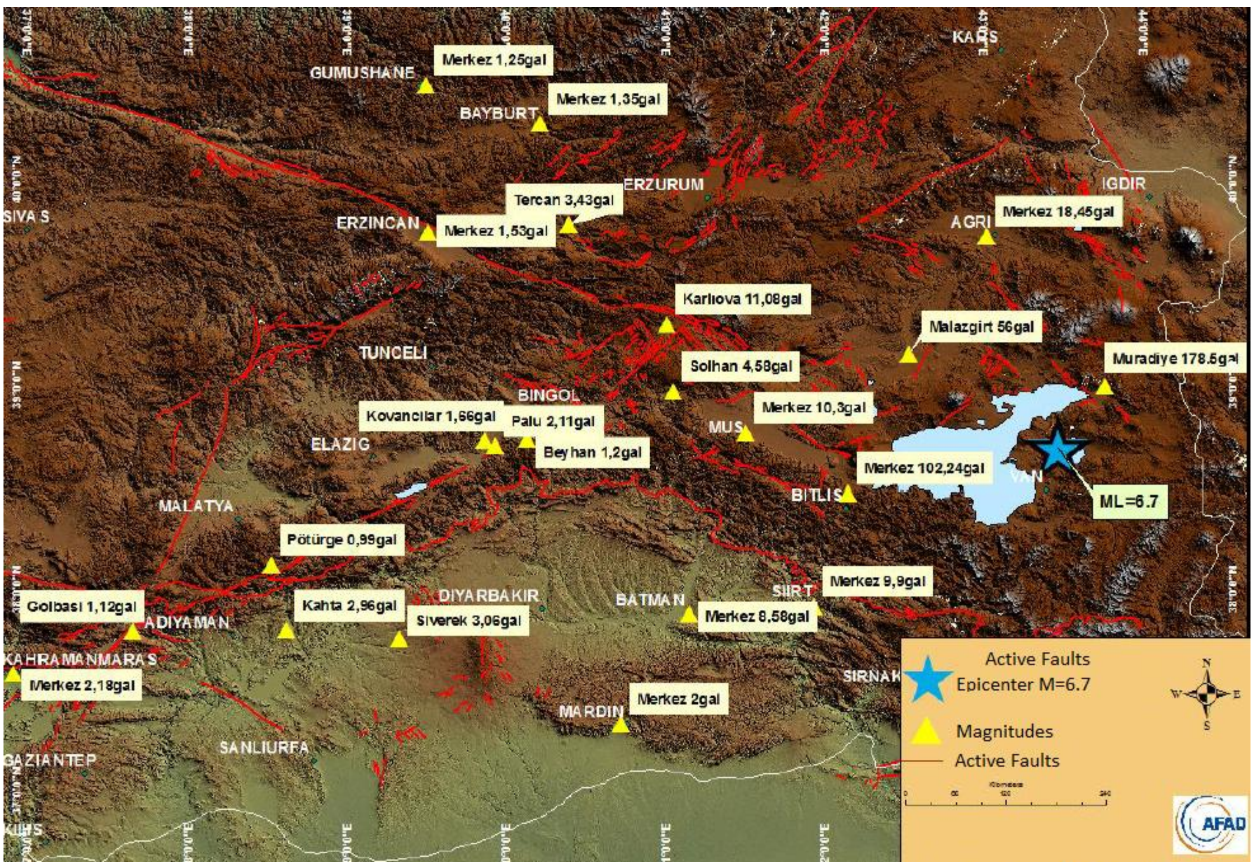
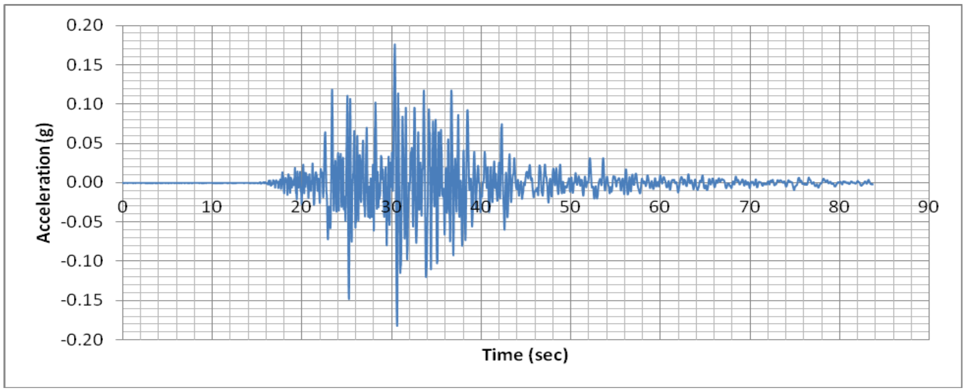
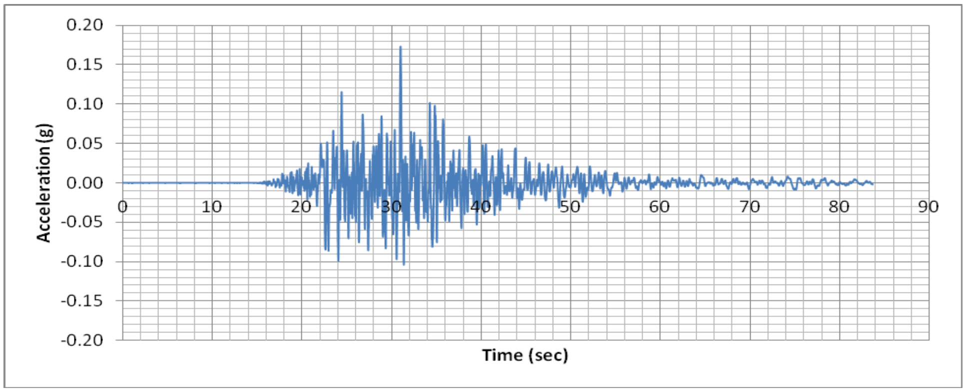


Figure 5. Locations and maximum accelerations measured by various stations during October 23th 2011 Van Earthquake (after Ceken et al., 2011).



(a)



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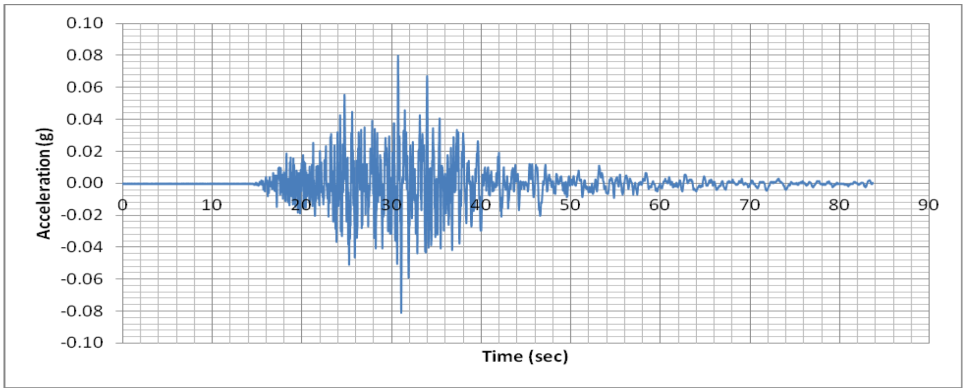

(c)

Figure 6. Acceleration time histories recorded in Muradiye Station. (a) North-South component (Peak=0.176g) (b) East-West component (Peak=0.173g) (c) Vertical component (Peak=0.08g).

2.4. Hydrogeologic Conditions

There are a number of rivers flowing to Lake Van, including Zilan and İrşat Stream in the vicinity of Ercis, which create a large delta at the north of Van Lake. These two streams form the main drainage system of the Erciş Plain. Özvan et al. (2008) indicated that the depths of groundwater table were ranging between 1 and 12 m in the town of Erciş. The direction of groundwater flow was reported to be towards SE and SW and the depth of groundwater table becomes considerably shallower near to the lake. Ulusay et al. (2012) indicated that the groundwater table was generally close to the ground surface near the lake. Figure 7 depicts the hydrogeologic features of Ercis Plain.

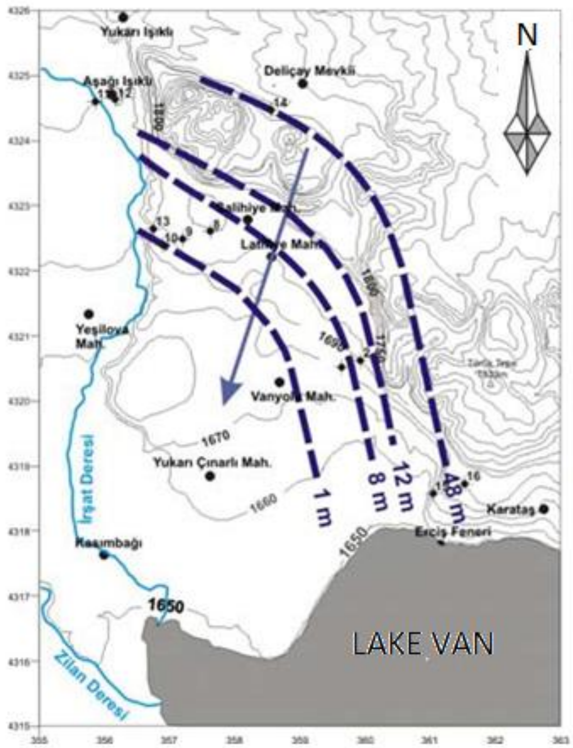

Figure 7. Hydrogeologic features of Ercis Plain (After Özvan et al., 2008).

2.5. Geotechnical Conditions

A detailed description of the geotechnical conditions of Ercis Plain, along with a liquefaction triggering assessment was presented in Özvan et al. (2008). Özvan et al. (2008) reported 18 boreholes, whose their locations are shown in Figure 8.

The grain size distributions of soil samples obtained in the study area were reported by various researchers (Özvan et al., 2008; METU/EERC, 2011; Ulusay, 2012; ITU, 2011). Figure 9 summarizes the grain size distributions of the soils that liquefied in Van Earthquake and the ones that were reported by various researchers. The grain size distributions shown in Figure 9 indicate that the most of the data falls within the ranges, where liquefaction hazard are typically expected. Figure 9 also compares the data specific to Ercis plain to the ranges observed in other areas in Turkey, where liquefaction hazards were observed. The average SPT $(N_1)_{60}$ values presented in Ozvan (2008) was summarized in Table 2 for top 9 m of depth. The SPT $(N_1)_{60}$ value for top 9m depth averaged from 18 boreholes was 15. The average $(N_1)_{60}$ value beyond this depth was 30. Table 3 gives a summary of geotechnical parameters used in the analyses. D_{50} values were reported to range between 0.12mm and 1.8mm. Thus, an average D_{50} value of 1 mm was considered in analyses. An average fine content for top 9 m was assumed as 20% based on the data shown in Figure 9.

Table 2. The average SPT (N1)60 data and ground water levels in the study area.

Borehole	(N1)60	Ground Water Level (m)
SK-1	11	8
SK-2	8	8
SK-3	14	3
SK-4	10	3
SK-5	19	1
SK-6	18	3
SK-7	19	1
SK-8	16	6
SK-9	17	6.5
SK-10	19	4
SK-11	16	2
SK-12	12	4
SK-13	14	7
SK-14	10	1
SK-15	10	2
SK-16	16	1
SK-17	10	1
SK-18	26	5.5

Table 3. Soil layers considered in the analyses

Layer	Unit Weight (kN/m^3)	Fine Content (%)	Thickness (m)	Average $(N_1)_{60}$	Average Vs (m/s)[2]
Layer1	16	20	9	15	220
Layer2[1]	17	N/A	21	30	350

[1]Layer2 was not considered in liquefaction assessment

[2]SPT correlation proposed by Bellana (2009) was used in Vs estimates.

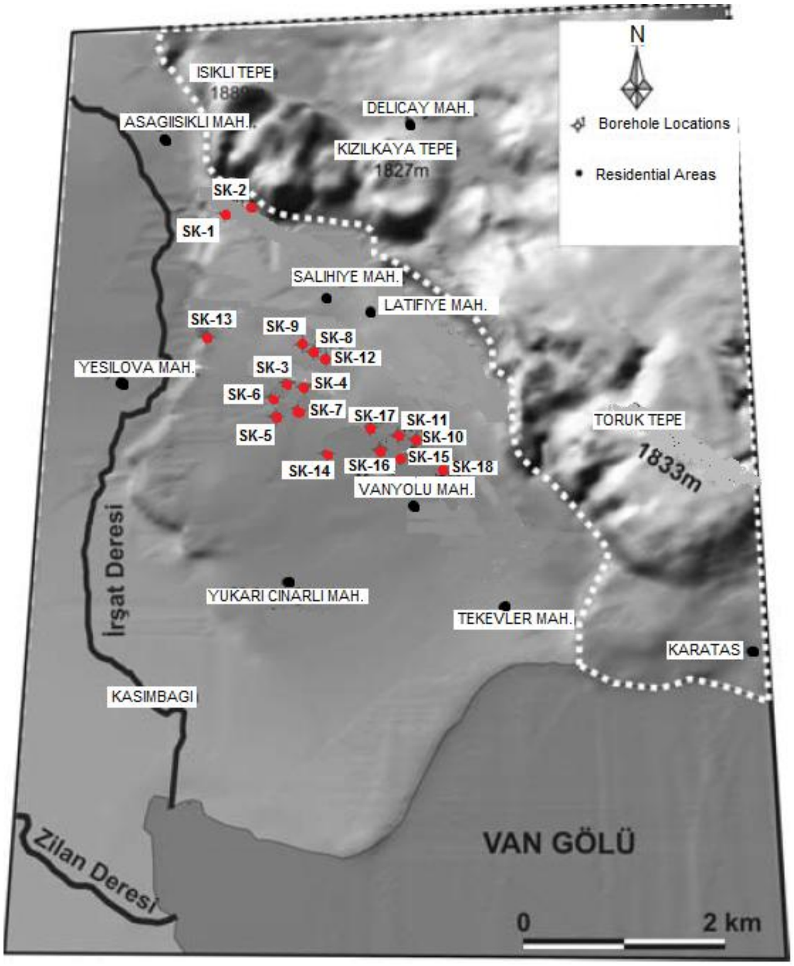

Figure 8. The location of boreholes (After Özvan et al., 2008).

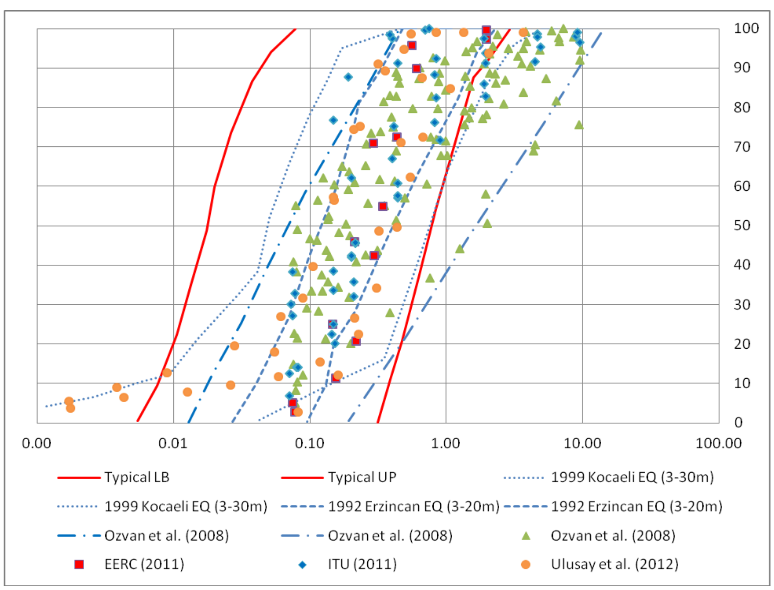

Figure 9. Grain size distribution of the liquefiable materials of Ercis Plane.

2.6. Details of Analytical Solutions

The safety factors against liquefaction triggering and soil lateral spreading were evaluated using various methodologies as outlined below. The site specific ground response analyses were conducted using 1D wave propagation analysis software DEEPSOIL. A frequency domain analysis procedure was adopted. Cyclic Stress Ratio (CSR) values were calculated using site specific ground response analyses and compared to the soil Cyclic Resistance Ratio (CRR) to calculate the safety factor against liquefaction.

The liquefaction potential was performed using Cyclic Stress Ratio (CSR) values obtained from the site specific ground response analyses as well as simplified approach proposed by Seed and Idriss (1971). Equations 1 to 3 provide the calculation procedure for the factor of safety (FoS), i.e.

[1] $$FoS = \frac{CRR}{CSR} * K_\sigma * K_\alpha$$

[2] $$CRR_{7.5} = CRR * MSF$$

[3] $$MSF = (\frac{7.5}{\mathrm{M}})^{2.56}$$

where, K_σ overburden stress correction factor, K_α sloping ground correction factor, M is earthquake magnitude and MSF is a magnitude correction factor.

CRR values used in the assessment were determined using various methods. The simplified stratigraphy used in the assessment was depicted in Table 3.

Cyclic Stress Ratio (CSR):

Maximum cyclic shear stresses ratios obtained from the free-field response analyses as well as simplified approach proposed by Seed and Idriss (1971) were used for the assessment.

Cyclic Resistance Ratio (CRR):

The CRR values were evaluated using various SPT based methods, as summarized in Table 4. The average CRR values were utilized for the calculation of FoS against liquefaction triggering. Only the top layer (9m) was considered in the liquefaction evaluation was limited to the top 9 m. Layer 2 was deemed unlikely to liquefy due to its high stiffness (Vs = 350 m/s)and was not considered in the assessment.

Table 4. CRR evaluation methods.

Method of Analysis
Vancouver Task Force Report (2007) Method
NCEER Workshop (1997) Method
Boulanger and Idriss (2004) Method
Japanese Highway Bridge Code Method
Chinese Code Method

Post-liquefaction Evaluation:

The method proposed by Faris et al. (2006) was used to evaluate the liquefaction induced lateral soil spreading that would take place during the design earthquake. Faris et al. (2006) method is based on Displacement Potential Index (DPI) that is calculated using CSR values. Liquefaction induced soil settlements were calculated using the method proposed by Ishihara and Yoshimi (1992).

3. Results and Discussions

3.1. Site Specific Ground Response Analyses

The results of site specific ground response analyses are summarized in Table 5. The analyses showed that applied input ground motion (N-S component of Muradiye record) was amplified. The maximum amplification factor was calculated as 2.1. Figure 10 shows the acceleration time history of the ground response at the ground surface. The Cyclic Stress Ratio for the liquefiable layer (Layer 1) was calculated as 0.5. This value was used in liquefaction assessments.

Table 5. Results of site specific ground response analyses.

Max. Acceleration (g)	Amplification Factor	CSR
0.38	2.1	0.5

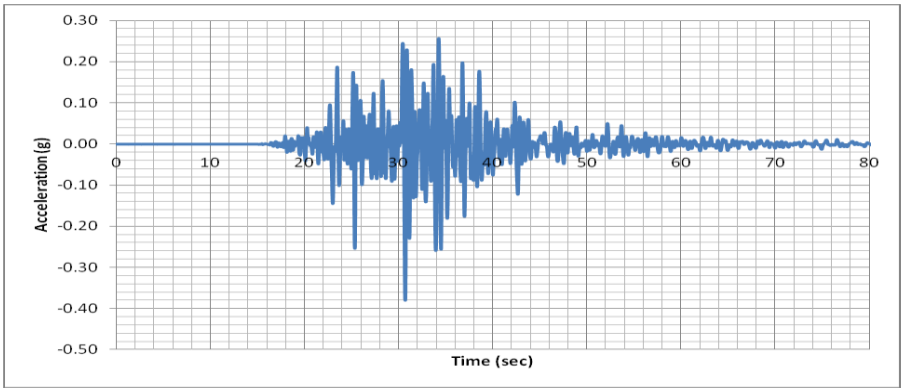

Figure 10. Acceleration time history at the ground surface.

3.2. Analytical Liquefaction Assessment

The CRR values were calculated and depicted in Figure 11 using the five different methods listed in Table 4. The FoS against liquefaction triggering was calculated using the average values of the CRR and CSR calculated from site specific ground response analyses and from simplified method of Seed and Idriss (1971). A FoS of 0.55 was calculated against liquefaction triggering using the CSR values obtained from site specific ground response analyses, which indicates occurrence of liquefaction. The liquefaction induced ground settlement was calculated as 100mm in accordance with Ishihara and Yoshimi (1992). Using the approach proposed by Faris et al. (2006), lateral spreading of 600mm was estimated.

Post earthquake field observations indicated that pockets of the area investigated have experienced liquefaction. Despite the difficulty of quantifying the liquefaction induced ground movement (the area was a constructed zone), signs of lateral soil movement as well as foundation settlements in some buildings were observed. Since the liquefaction assessment presented in this study was based on an average SPT profile that was considered to be representative of the area, it is expected that some locations with higher SPT profiles did not liquefy. This explains the localized nature of observed liquefaction. Namely, only the locations with low SPT values were thought to have liquefied during the earthquake. Figure 12 shows the complete collapse of residential condominiums and sand boiling that occurred near Zilan River.

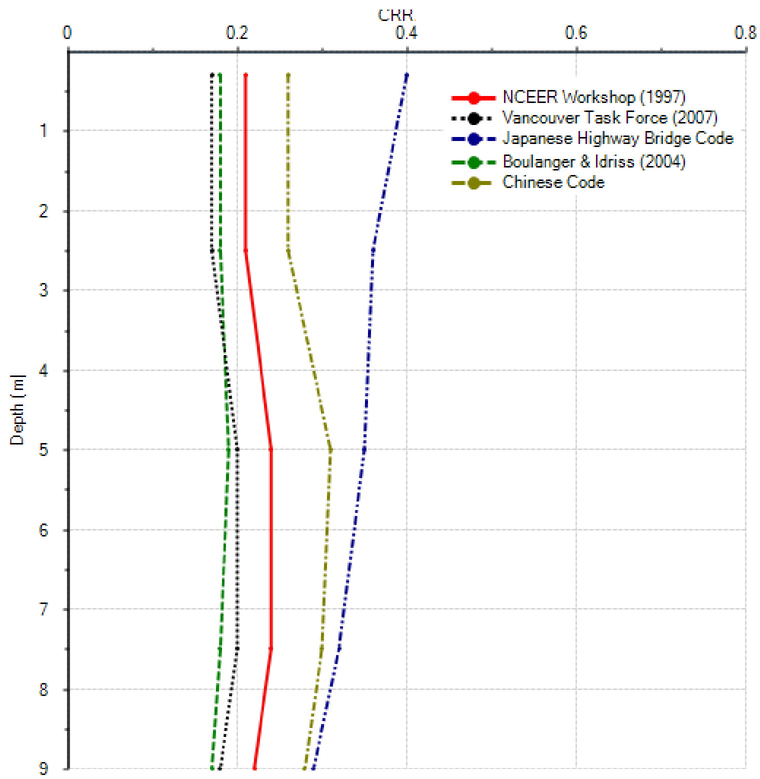

Figure 11. CRR profiles calculated using various analytical approaches.

(a)

(b)

Figure 12. (a) Structural Collapse at Vanyolu district, (b) sand boiling in Zilan River (after Cetin et al., 2011)

4. Summary and Conclusions

The analysis of seismic induced liquefactions that took place in and around the township of Ercis Plain, where Irsat and Zilan streams are discharged to Lake Van, was performed using various analytical methods. The dynamic soil properties were estimated using correlations with available SPT profiles and incorporated into site specific ground response analyses to establish the cyclic stress ratios. The results of these analyses were used in the liquefaction assessment and estimation of seismic induced settlement as well as lateral spreading that were observed in Ercis Plane. The results were compared to field observations, and the following conclusions are derived:

- The predictions of liquefaction using the simple analytical approach in Ercis Plain were supported by field observations.
- The one dimensional seismic ground response analyses performed on simplified ground stratigraphy indicated that the input ground motion (Muradiye Record N-S component) used at the bottom of soil column was amplified 2.1 times, and a maximum CSR = 0.5 at the mid-height of the liquefiable layer (Layer1).
- The liquefaction-induced settlement and lateral soil spreading were estimated as 100mm and 600mm, respectively. Signs of settlement and lateral soil spreading were observed in the field but their magnitudes could not be verified with field measurements.

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