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ORIGINAL ARTICLE

A study of the relationship between the pressuremeter modulus and the preconsolidation pressure around a thrust fault

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Abstract

The study area is in a zone under the influence of the Lake Van water changes and the Van fault, which caused a destructive earthquake in 2011. Due to the level changes of Lake Van, sediments with different thicknesses as well as grain sizes were deposited in this region and the characteristics of these sediments were significantly affected by the morphology and lake water fluctuations in the past. A total of six boreholes were drilled along a 3-km line within the study area to determine the preconsolidation pressure (σ_{pc}) and the pressuremeter test values of the clayey levels of old lake deposits—which are known to have different physical and mechanical properties—with hopes to gain an insight on how they influence the mechanical tests performed in the field and in laboratory conditions. The relationship between these values was also statistically evaluated. When both datasets were evaluated together, it was determined that the stresses in the area close to the Van Thrust Fault plane caused deformations in the soil, which in turn affected the hanging-wall block of the thrust fault in particular. The inspection of E_M and σ_{pc} values for the area within the primary compression zone of the Van Fault revealed that both values of the boreholes on the footwall block were higher compared to other boreholes close to the lake (southwest). This finding indicates that the fault stresses at the footwall block of the fault plane enhance the mechanical characteristics of the soil. The data obtained were also evaluated using regression analysis. Relationships between all available data were investigated and a high coefficient of determination was derived between the Menard deformation modulus (E_M) and the preconsolidation (σ_{pc}) pressure.

Keywords Clay soil · Menard deformation modulus · Preconsolidation pressure · Thrust fault

Introduction

One of the most important geotechnical problems that negatively affect a reinforced structure on clayey soil in long term is the phenomena known as the “consolidation settlement”. Long-term settlements may cause deformations in the bearing elements of the structure, which is especially valid for the structures located on top of highly plastic soils. The damage on the bearing elements may lead to foundational weaknesses, which in turn increase the loss of life and property in case of destructive earthquakes, as was experienced in numerous cases. For this reason, the consolidation parameters of clayey soil layers should be determined and a structural design should be performed according to the determined parameters. One of the most significant consolidation parameters is the preconsolidation pressure (σ_{pc}), which represents the existence of past stresses that affected the ground, along with the maximum effective stress.

There are numerous methods and approaches used for determining the maximum effective stress in the memory of the soil. One of these methods is the consolidation experiment, which is performed in laboratory conditions. In general, the determination of σ_{pc} is known to be prone to errors that may occur in the disturbed samples taken for the test. In such a case, the experimental specimen cannot fully reflect

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the in situ properties of the soil. Therefore, it is possible to overcome these errors by performing in situ experiments. The primary advantage of in situ tests is that the overall stress conditions of the soil are better reflected in the field. In addition, in the in situ tests, the parameters from the desired levels along the vertical profile of the soil can be retrieved easily and quickly. One of these in situ tests is the widely used Menard pressuremeter (PMT) that can be executed at the desired level of a borehole without the disturbance of soil.

Geologic deposits contain data in their histories, which are sometimes called the "memory" of the soil. An undisturbed soil sample has within it a record of the conditions under which it was formed, whether it happened underwater or on land, within in a volcano or deep in the Earth's crust. Furthermore, it commonly "records" certain events that affected its features since its formation, such as bending, breaking, squeezing, partial recrystallization (Nagaraj 1993). Casagrande (1932) was the first researcher who stated that soils have such a "memory". In addition, Casagrande indicated that the stress and other changes are preserved or recorded in the soil structure that has occurred during the soil's history. Casagrande (1932, 1936) was also the first to suggest the σ_{pc} value of clayey soils. Following these studies, Ward et al. (1959), Simons (1965), Tchalenko (1967), and Esu and Calabresi (1969) calculated the maximum past horizontal effective stresses that influenced the soil by applying consolidation experiments on the samples taken from the ground in horizontal directions as per the Casagrande method. Then, Voight (1974) stated that the dissipation of pore pressures "locks in" orogenic stresses in superjacent rocks. In the studies, Ingles and Lafeber (1966) and Holtz and Kovacs (1981) showed that the primary texture of the ground changes as a response to the stresses that are imposed on the ground.

Stress mechanics is commonly most effective in areas close to a fault plane. Fener (2006) stated that the grain size distribution is effective in σ_{pc} and that the recording of the ground memory gets shorter as the sand content increases. Günaydın (2007) excavated a number of trenches in different sections on a segment of the Gerede fault (Bolu, Turkey) along with some undisturbed blocks, from which samples were collected to evaluate the theoretical principal stress causes that the fault has enforced its load on its direction. This loading in practice can be in any direction, and it can be the result of numerous types of activities, such as active folding, faulting and creeping, all of which tend to deform the soil deposit by stressing it (Voight 1966; Feda 1978; Hobbs et al. 1976). Even if the loading is transient (sudden), it still tends to consolidate the soil (Bishop and Henkel 1953).

In the researches regarding the PMT test itself, efforts were mostly directed towards determining the relationship between Standard Penetration Test (SPT) and PMT results. There are some studies carried out by different researchers that compare the SPT and PMT results (Chiang and Ho 1980; Yağız et al. 2008; Bozbey and Togrol 2010; Kayabaşı 2012; Aladağ et al. 2013; Cheshomi and Ghodrati 2015; Anwar 2016; Özvan et al. 2018). Some of these studies revealed a high coefficient of determination (R^2) between SPT-N_{60} values and Menard modulus of elasticity (E_M), and between SPT-N_{60} and limit pressure (P_L) values for different soil classes. None of these studies, however, has investigated a possible statistical relationship between σ_{pc} and E_M or P_L values obtained from PMT. Similarly, no study in the literature has investigated the correlation between σ_{pc} and E_M values at different levels of clay. On the contrary, numerous studies in the literature exist regarding the change of σ_{pc} values in the stress zones. Thus, the aim of this study is set as to establish a statistical comparison of σ_{pc} values with the deformation modulus (E_M) value obtained by PMT. In this context, a region with clayey soil levels under different stress conditions was chosen as the study area. The clay soil levels of the deposits in the study were formed with water level changes in the Lake Van. These clay materials have different thicknesses and characteristics (Fig. 1). The soils in this study area under different stress rates, consequently, the σ_{pc} values were affected by a thrust type fault as well as vertical stresses caused by hydrostatic and overburden pressures.

Materials and methods

In this study, Bardakçı (Van, Turkey) region was chosen to investigate the soil conditions discussed in the first chapter. The soils in this area are composed of old lacustrine deposits with varying soil classes and thicknesses caused by the water level fluctuations of the Lake Van. The soil layers of the area were exposed to different stress conditions during their history. It is quite logical to assume that these deposits were affected by the stresses caused by Van Thrust Fault as well, which also caused a recent damaging earthquake on 23 October 2011 ($M_w = 7.1$), and they were almost assuredly affected by the vertical pressures exerted by the hydrostatic lake level and sediment loads during the formation process.

Geotechnical studies as a main part of this study were carried out both in the field and in the laboratory. During the field studies, undisturbed (UD) soil samples were retrieved by Shelby tubes. In addition, a pressuremeter device (Apageo trademark GA model) and equipment were used for the PMT tests. In laboratory, a number of experiments were performed on clay soil samples. The Casagrande device was used to test the liquid limit. Moreover, consolidation tests were performed using an odometer device. ASTM standards were practiced in all tests.

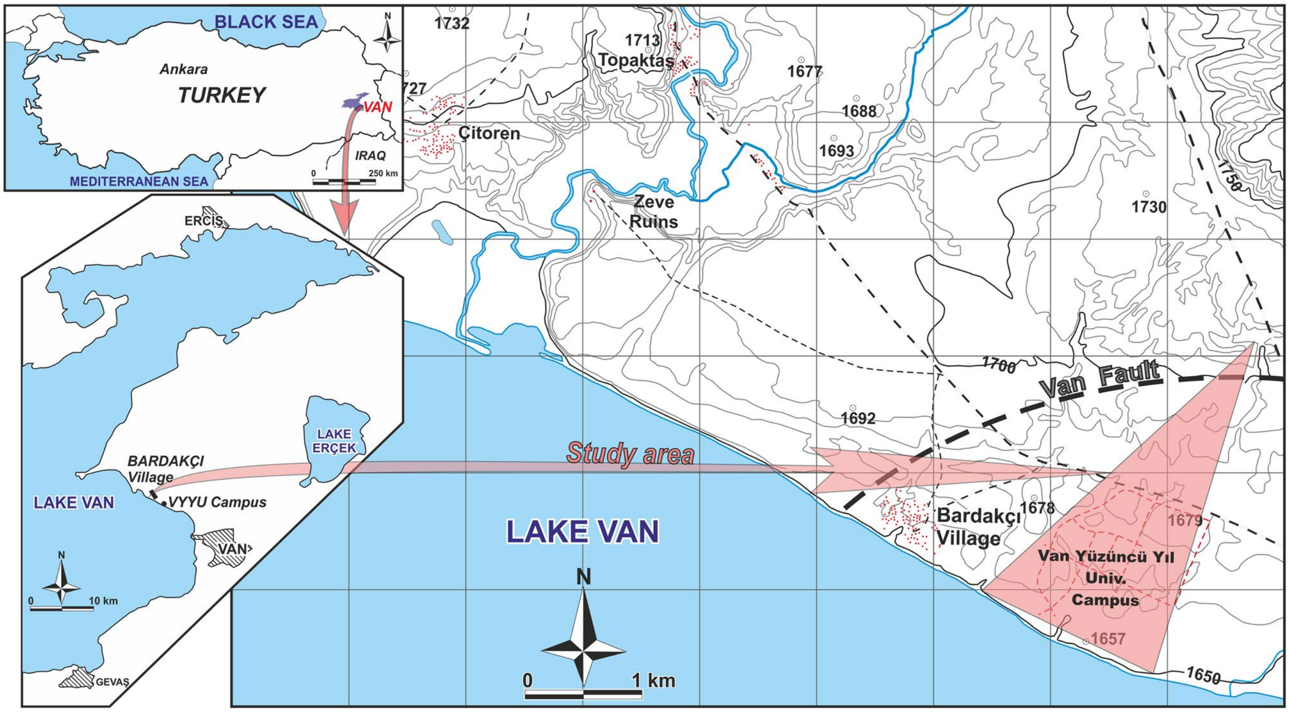

Fig. 1 Location map of the study area

Method

Geotechnical boreholes were drilled at six different locations on the clay soil levels determined in previous studies (Selçuk 2003; Akın et al. 2015). A couple of borehole machines were used simultaneously at each location (Fig. 2). The pressuremeter test was performed in one of these boreholes while the UD sample from the same soil level was taken from the other one. The clay soil samples taken with Shelby tubes were covered with paraffin and wrapped in the stretch film to prevent contact with air before the laboratory tests.

Pressuremeter (PMT) test

This test technique includes the operation for drilling of the borehole and insertion of the probe, and then performing the pressuremeter tests in both granular and cohesive soils (ASTM D4719-00 2000). The pressuremeter is a cylindrical probe that has an expandable, flexible membrane designed to implement equal pressure to the walls of a borehole (Fig. 3a). The pressuremeter test originally consists of placing an inflatable cylindrical probe in a predrilled hole and expanding this probe while measuring the changes in volume and pressure in the probe. Two main parameters, namely the limit pressure (P_L) and pressuremeter deformation modulus (E_M) are obtained with this test method. P_L is the pressure at which the probe volume reaches twice the original soil cavity volume. Pressuremeter modulus is the modulus calculated from the slope of the pseudo-elastic portion of the corrected pressure–volume curve experiencing little to no creep (ASTM D4719-00 2000). These parameters are then used in the geotechnical analysis and foundation design.

Fig. 2 A general view of drilling in the study area

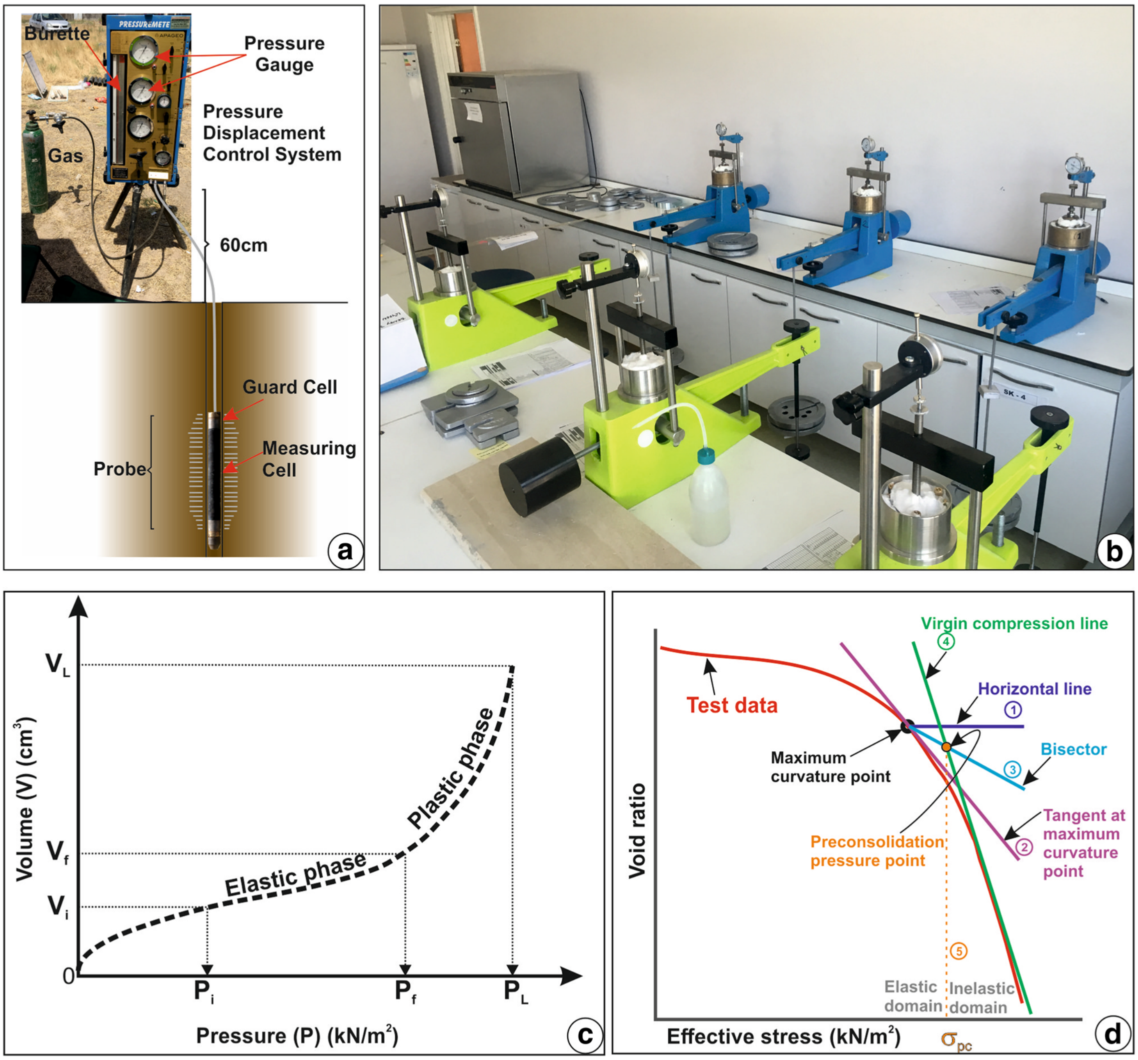

Fig. 3 A view of the PMT and consolidation tests

The required calibrations specified in the standards were performed before each experiment. The test depth was measured as 60 cm, which is the distance from the center of the pressure gage to the center of the probe. The standard pressure was exerted and this pressure was added to the pressure readings obtained on the readout apparatus after the experimental phase. The PMT was continued approximately for 10–15 min, and the experiments were carried out immediately after the drilling of the well. 30-s and 1-min readings were performed after pressure or volume increases were applied. Once the test reached the maximum predetermined step, the procedure was terminated by deflating the probe to its original volume and removing it from the hole. E_M and P_L values were determined and calculated using pressure and volume value that obtained from PMT test according to standard (ASTM D4719-00 2000).

One-dimensional consolidation test

This test process is generally performed on undisturbed samples of fine-grained soils. The changes in specimen height that take place during the consolidation process are measured, and these data are then used to determine the relationship between the effective stress and the void ratio or the strain (ASTM D 2435-09 2009). The experiment was performed on undisturbed samples extracted from Shelby tubes. The standard loading schedule was determined using the load increment ratio to one, which was obtained by doubling the pressure on the soil to obtain values of approximately 12, 25, 50, 100, 200 kPa, etc. (Fig. 3b). If the slope and shape of a virgin compression curve or determination of the preconsolidation pressure are required, the final pressure was assumed equal to or greater than four times the preconsolidation pressure (ASTM 2435-09 2009).

50-mm-diameter and 20-mm-high samples were used in this study. If the experiment was carried out for the bottom part of groundwater table or the saturated soil, water was added to the consolidation cell shortly after applying the load. If the sample was taken from the top of the groundwater level, the consolidation cell was wrapped with moist cotton to prevent the variation in sample volume due to evaporation (Fig. 3b).

Determination of preconsolidation pressure (σ_{pc})

The accurate determination of preconsolidation pressure (σ_{pc}) is crucially significant for settlement analysis in clay sediments. In this method, the maximum effective stress that the soil is under the influence of and that gives the final shape of the soil texture is defined as preconsolidation pressure. Many methods represent the findings as graphical outputs that were invented by researchers to determine the preconsolidation pressure history of soil samples (Casagrande 1936; Burmister 1951; Schmertmann 1955). Casagrande (1936) method is the most commonly used technique and was used in this study as well. The preconsolidation pressure value was calculated from the graph of the plotted ratio of the void (e) to effective stress (σ').

In the final stage of this study, correlation analysis between E_M and σ_{pc} values was performed and the variations in σ_{pc} values over time in the hanging-wall and footwall blocks near the thrust fault plane were interpreted.

Geology

The East Anatolian High Plateau was shaped as a result of the collision between the Arabian and Eurasian plates in the eastern Mediterranean region (Şengör and Yılmaz

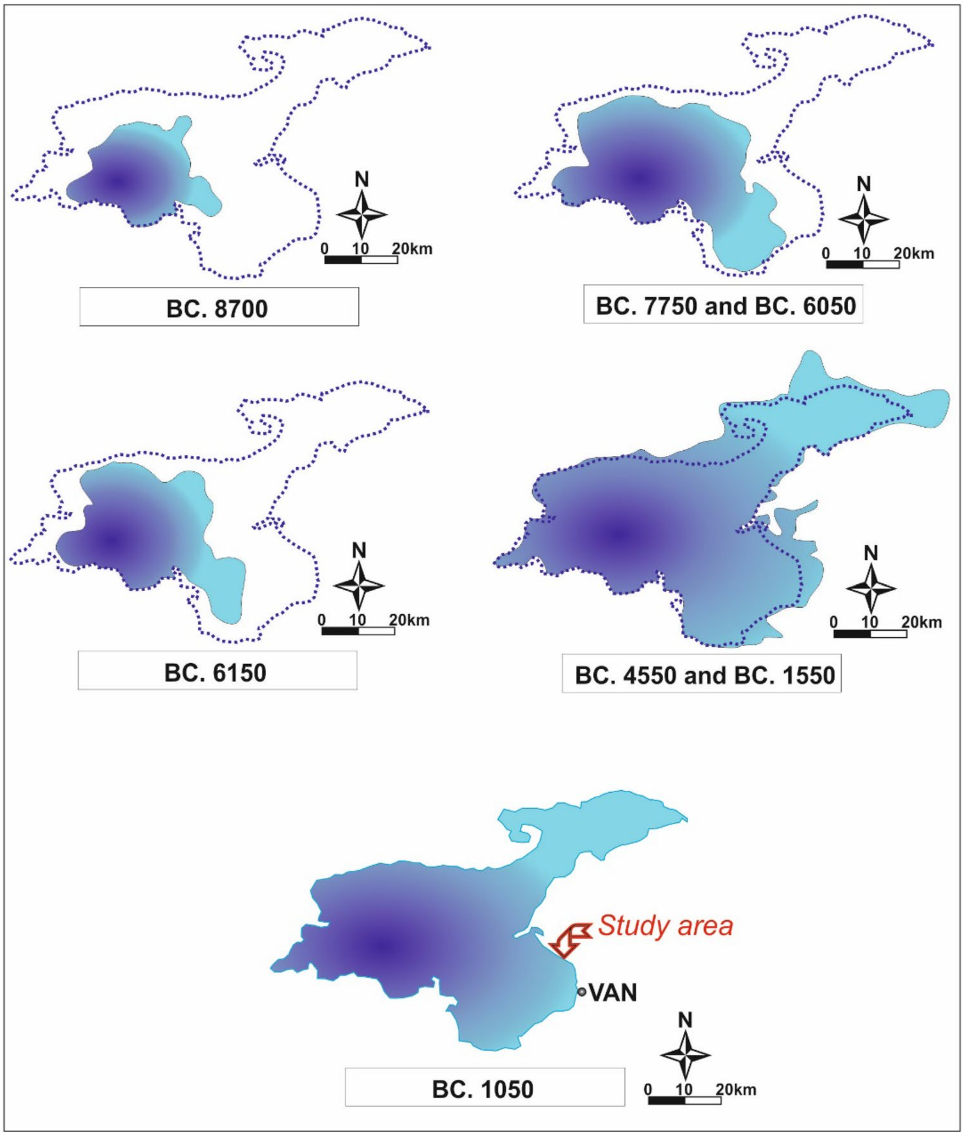

Fig. 4 Lake Van water level fluctuations in different periods (modified from Landmann et al. 1996a, b)

1981; Sengul et al. 2019). The study area is located at the southeastern part of this plateau, which is also known as the Lake Van Basin. Mesozoic metamorphic rocks, Triassic limestones, Upper Cretaceous ophiolites, and Miocene turbidities constitute the basement rocks of the basin. These rocks are unconformably overlain by Quaternary units that are of volcanic, travertine and lacustrine sediments. The Late Quaternary aged lacustrine deposits are represented by a thick sequence, which is composed of consolidated or over-consolidated clay, medium to fine-bedded sand, and silt (Valeton 1978; Acarlar et al. 1991; Özvan et al. 2005; Erdoğan and Özvan 2015; Özvan and Erdoğan 2016; Üner 2018).

Most of the researchers that performed studies on the region tried to quantify previous lake levels in lacustrine sediments in the basin (Landmann et al. 1996a, b; Kempe et al. 2002; Kuzucuoğlu et al. 2010; Litt et al. 2009). Fluctuations of the lake water levels were based on the data of onshore terraces. According to these data, previous lake levels were elevated above the present water surface level of Lake Van, and reached up to a peak of 110 m (Fig. 4). Lake Van water levels have changed numerous times in the last century. The water level of the lake was measured to be at an average of 1646.5 m between 1944 and 1967. Later on, the lake level elevated to 1648.5 m in 1988, and 1650.5 m in 1996, after which it dropped back to 1647 m between 1997 and 2006 (Kuzucuoğlu et al. 2010). The present lake level is 1648 m above sea level (Görür et al. 2015).

The geology of the study area consists of old lake and stream sediments, which were deposited due to water level changes of Lake Van in different time periods. Lacustrine sediments can provide significant insights into a lake's past water levels. The lacustrine sediments in the basin with different thicknesses and different soil properties are commonly observed in the study area and its vicinity (Acarlar et al. 1991; Selçuk 2003; Özkaymak 2003; Özvan 2004; Akın et al. 2013, 2015; Akkaya et al. 2015, 2018; Akkaya and Özvan 2019). The units originating from old lake and stream sediments in the study area are defined as Pliocene–Quaternary aged units (Acarlar et al. 1991).

Many boreholes were drilled in previous years that went as deep as 15–20 m, and certain properties of geological units have been determined by previous studies (Selçuk 2003; Akın et al. 2015). These studies commonly report that the units in the study area consist of clay, silt, sand and gravel with different thicknesses. In addition, it has been revealed that these lacustrine sediments have different spreads in lateral and vertical directions.

The units in the study area are cut by the Van Thrust Fault to the north of the study area, which ruptured during the 2011 Van Earthquake ($M_w = 7.1$). The fault plane is

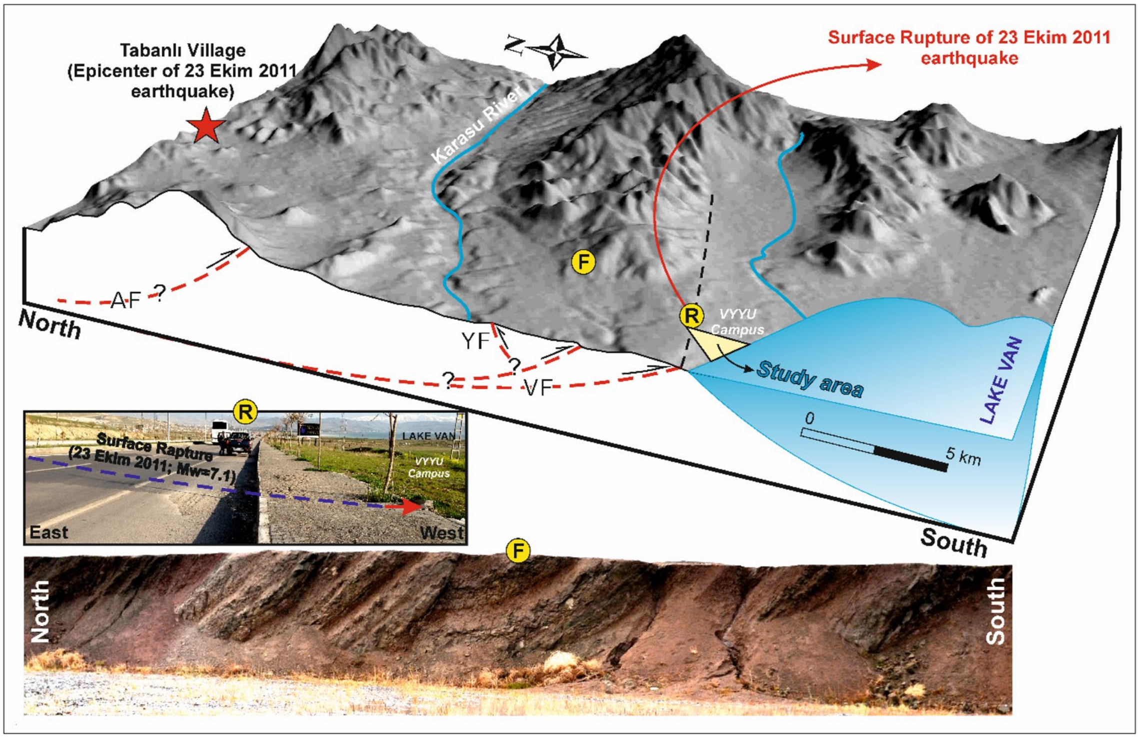

Fig. 5 An image of the fault planes at the north of the study area (modified from Akkaya et al. 2015) (*YK* Yeni Köşk Thrust Fault, *AF* Alaköy Thrust Fault, *VF* Van Thrust Fault)

dipping north. The surface rupture of the fault was traced along from the northeast region of the study area towards the Lake Van (Fig. 5) and the southwest hanging-wall block of the fault exerts pressure on the old lacustrine sediments. The eastern part of the fault, on the other hand, constitutes a tectonic boundary between these sediments and the Upper Pliocene unit.

Undisturbed soil samples (UD) were taken by drilling at six different locations, while the PMT tests were performed at every 1.5 m in the old lake deposits that are of the Pleistocene–Holocene age (Fig. 6). In general, fine-grained soils were observed in these drillings, while at some levels, fine-grained sandy layers exist as well. According to previous studies, these clay layers reveal dissimilar physical and mechanical (Selçuk 2003; Akın et al. 2015) as well as mineralogical properties (Kılıçer 2009). The major reason of the mineralogical and physical variations is associated with the transgression and regression sequences of the Lake Van, while the mechanical differences are due to vertical (hydraulic and/or overburden) and horizontal stresses originating from the stress zone of the fault.

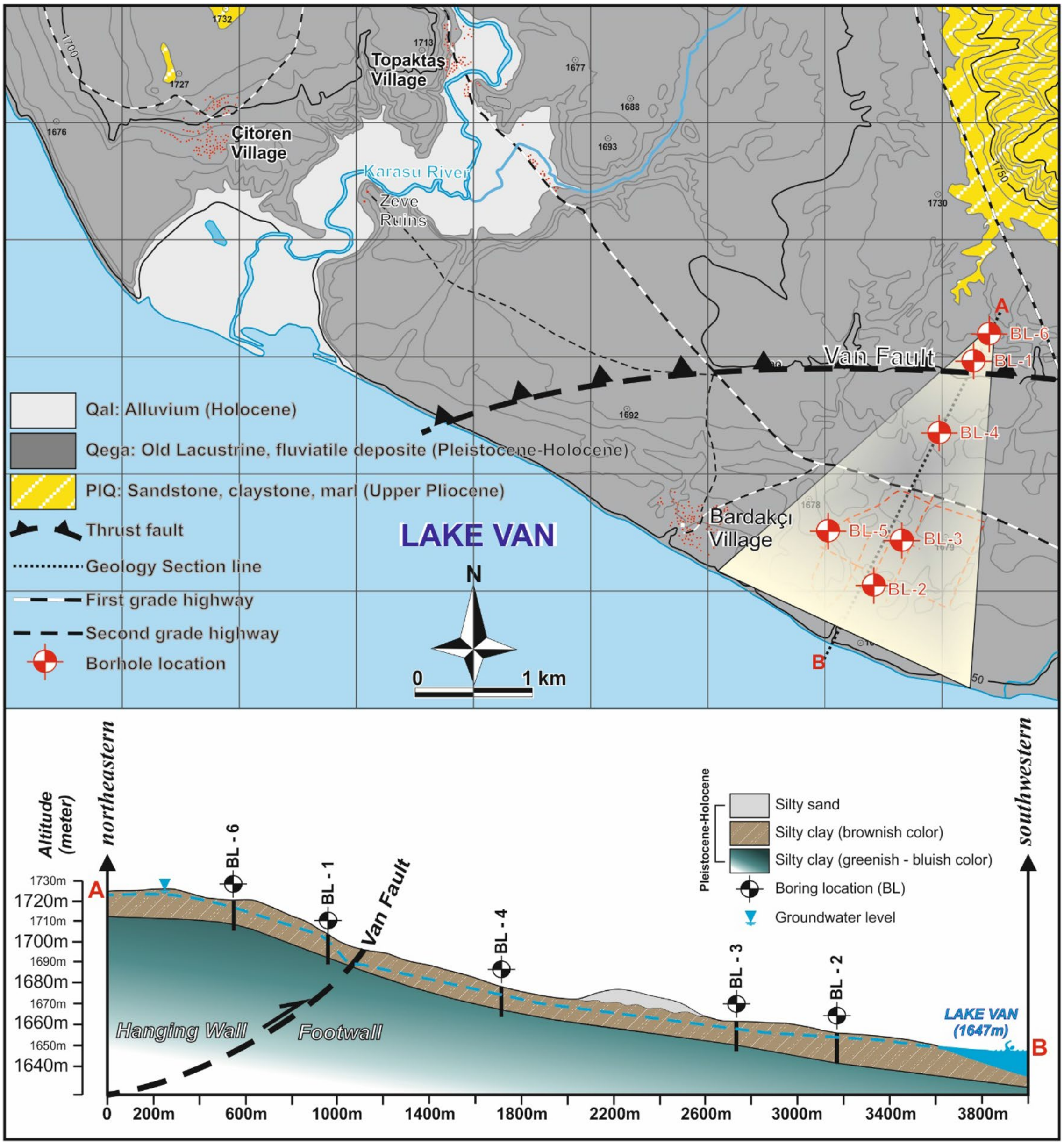

Fig. 6 General geology map and a geological cross-section of the study area

Table 1 Some physical properties of clays used in the study

BL no.	Depth (m)	Atterberg limits			Water content (%)	Specific gravity	Sand %	Silt %	Clay %	Density (g/cm^3)	Soil class	Liquidity index (LI) (Holtz and Kovacs, 1981)		Activity (Skempton, 1953)		Swelling potential (Seed et al. 1962)	
		LL	PL	PI													
1	1.00	66	27	39	16.4	2.70	22.5	38.6	39	2.11	CH	− 0.27	Solid	1.00	Normal	10.69	High
1	2.00	66	27	39	24.4	2.81	22.5	38.6	38.9	2.03	CH	− 0.07	Solid	1.00	Normal	10.69	High
1	2.75	45	20	24	16	2.79					CL	− 0.17	Solid				
1	4.50	44	20	24	20.2	2.80	17.4	42.3	40.3	2.13	CL	0.01	Plastic	0.59	Passive	3.39	Medium
1	5.50	44	18	26	12.7	2.76	18.3	36.6	44.9	2.10	CL	− 0.21	Solid	0.58	Passive	4.58	Medium
1	6.50				23.5	2.79	9.4	49	41.6	1.98	CL						
1	7.25	88	28	60	22.3	2.87					CH	− 0.1	Solid				
1	8.75	56	26	30	16.3	2.78	17.9	56.3	25.8	2.03	CH	− 0.32	Solid	1.16	Normal	3.73	Medium
1	9.75	60	25	35	21.2	2.84	24.3	56.4	19.3	2.03	CH	− 0.11	Solid	1.81	Active	4.08	Medium
1	10.5	36	17	19	12.4	2.72					CL	− 0.24	Solid				
1	11.25	25	19	6	20.7	2.79					CL	0.28	Plastic				
1	12.5	46	19	28	20.0	2.70					CL	0.04	Plastic				
2	1.00	46	18	29	17.1	2.60	24.9	47.9	26.9	1.93	CL	− 0.03	Solid	1.08	Normal	3.58	Medium
2	3.50	58	20	39	31.2	2.78	11.2	49.7	39.1	1.97	CH	0.29	Plastic	1.00	Normal	10.73	High
2	4.50	72	22	49	29.3	2.78	10.5	52.4	37.1	1.82	CH	0.15	Plastic	1.32	Active	17.76	High
2	5.50	72	22	49	30.7						CH	0.18	Plastic				
2	6.50	63	22	41	31.1	2.78	1.1	60.7	38.2	1.92	CH	0.22	Plastic	1.07	Normal	11.83	High
2	9.00	54	21	33	30.2						CH	0.28	Plastic				
2	14.00	76	22	54	28.9						CH	0.13	Plastic				
3	1.00	76	26	50	23.3	2.77	18.1	46.3	35.3	1.85	CH	− 0.05	Solid	1.42	Active	17.75	High
3	2.50	80	28	52	23.9	2.74	17.5	44.5	38	1.92	CH	− 0.08	Solid	1.37	Active	21.03	High
3	4.25	52	21	31	21.6	2.76	26.6	37.6	35.9	2.07	CH	0.02	Plastic	0.86	Normal	5.62	High
3	5.50	50	20	30	22.3	2.76	27.4	39.7	32.9	2.01	CH	0.08	Plastic	0.91	Normal	4.76	Medium
3	6.75	51	23	28	22.8	2.73	2.9	62.2	34.9	2.02	CL–CH	− 0.01	Solid	0.80	Normal	4.27	Medium
3	7.25	51	23	28	21.4	2.76	4.3	38.7	57	2.09	CL–CH	− 0.06	Solid	0.49	Passive	6.97	High
3	8.25	51	23	28	27.5	2.76	0.2	64.1	35.8	2.00	CL–CH	0.16	Plastic	0.78	Normal	4.38	Medium
3	9.00	81	29	52	25.6	2.76	0.3	43.3	56.4	2.03	CH	− 0.07	Solid	0.92	Normal	31.25	High
3	9.75	64	32	32	27.6	2.76	0.7	40.6	58.8	1.97	CH	− 0.14	Solid	0.54	Passive	9.96	High
3	10.75	65	20	44	32.0	2.76	0.4	46.4	53.2	1.97	CH	0.27	Plastic	0.83	Normal	19.61	High
3	12.25	49	19	30	21.1	2.74	11.2	47.9	41	2.10	CH	0.07	Plastic	0.73	Passive	5.93	High
3	13.75	41	18	23	24.0	2.76	9.3	57.3	33.4	2.02	CL	0.26	Plastic	0.69	Passive	2.53	Medium
4	2.50	65	23	42	22.0						CH	− 0.02	Solid				
4	3.50	65	23	42	17.4	2.76	9.2	57	33.8	2.14	CH	− 0.13	Solid	1.24	Normal	11.1	High
4	4.50	62	22	39	22.2						CH	0.01	Plastic				
4	5.75	62	22	40	20.9	2.75	6.34	56.9	36.8	2.10	CH	− 0.03	Solid	1.09	Normal	10.74	High
4	7.00	56	21	34	20.9	2.76	9.79	50.9	39.3	2.09	CH	0	Solid	0.86	Normal	7.72	High

Table 1 (continued)

BL no.	Depth (m)	Atterberg limits			Water content (%)	Specific gravity	Sand %	Silt %	Clay %	Density (g/cm^3)	Soil class	Liquidity index (LI) (Holtz and Kovacs, 1981)		Activity (Skempton, 1953)		Swelling potential (Seed et al. 1962)	
		LL	PL	PI													
4	8.25	74	26	48	19.8	2.76	12.01	49.8	38.2	2.08	CH	− 0.13	Solid	1.26	Active	17.41	High
4	9.50	49	18	31	19.4	2.74	10.9	36.3	52.8	2.08	CL	0.05	Plastic	0.59	Passive	8.28	High
4	11.75	36	16	20	12.1						CL	− 0.2	Solid				
5	2.50	26	15	11	19.0	2.70	43.97	36.79	16.82		CL	0.36	Plastic	0.65	Passive	0.21	Low
5	5.50	34	20	14	15.9	2.76	38.21	44.47	17.33		CL	− 0.29	Solid	0.81	Normal	0.39	Low
5	6.25	34	18	16	11.6	2.70	40.54	40.37	18.85	2.06	CL	− 0.4	Solid	0.85	Normal	0.59	Low
5	7.25	34	21	13	18.0	2.74	27.35	52.72	19.03		CL	− 0.23	Solid	0.68	Passive	0.36	Low
6	2.25	48	18	30	26.1	2.69	19.5	3.5	42.6	2.06	CL	0.27	Plastic	0.70	Passive	6.17	High
6	3.25	48	18	30						1.99	CL	− 0.6	Solid				
6	5.50	46	20	26	23.6	2.76	2.6	45	52.3	2.01	CL	0.14	Plastic	0.50	Passive	5.35	High
6	6.50	53	24	29	27.2	2.73	3.8	62.4	33.8	1.96	CH	0.11	Plastic	0.86	Normal	4.5	Medium
6	8.00	54	23	31	18.7						CH	− 0.14	Solid				
6	9.00	45	20	25	22.6	2.75	5.3	49.1	45.5	2.04	CL	0.11	Plastic	0.55	Passive	4.22	Medium
6	10.25	61	21	39	20.6	2.77	5.4	42	52.3	2.09	CH	− 0.01	Solid	0.75	Passive	14.35	High

Physical properties of clay units in the study area

In the first stage of the laboratory studies, the physical properties of clay levels were determined (Table 1). It is determined that more than 80% of all the soil samples are represented by silt and clay size with respect to sieve and hydrometer analyses (ASTM D7928-17 2017). The water content of the same samples were subsequently examined, revealing the highest water content as 32.0% and the lowest water content as 11.6%. The water content of most of these samples is between 20 and 24%, and the average water content is calculated as 21.9%. Specific gravities of the same specimens are found to be between 2.60 and 2.87, while their densities are between 1.82 and 2.14 g/cm^3.

Clay samples were tested to determine their liquid limits, plastic limits, and the plasticity indexes according to ASTM D4318-17e1 (2017). The consistency limits (i.e., the liquid, plastic, and shrinkage limits) are water contents that define the soil behavior. The liquid limit (LL) values of these samples are determined between 25 and 88%, while the plastic limit (P_L) ranges from 15 to 32%. When these values are plotted on the plasticity chart, it is concluded that the soils in the study area consist of low (CL) and high (CH) plasticity clay (Fig. 7).

According to the results of field and laboratory tests, the clay samples have different plasticities and water contents (Table 1). In addition, it was determined that these clays present different liquidity indexes (LI), consistency indexes (Ic), activities (A) and swelling potentials (Table 1). Based on the liquidity index (LI) and consistency index (Ic) values, it is evident that the clays close to the lake (BL-2) and at the northern (BL-6) section of the study area are generally plastic, while the clays are generally classified as firm at locations close to the fault scarp (BL-1, BL-4, and BL-5). Consistent with the study of Skempton (1953), clays in this study can be considered to be at "normal activity" levels. Furthermore, with respect to the study of Seed et al. (1962), the swelling potential of these clays can be considered as high (Table 1).

Results and discussion

The soil layers in the study area consist of soils with different plasticities and swelling potentials, as well as varying water contents. The major aim of this study is to correlate the elasticity modulus of the soil obtained by the PMT test with the preconsolidation pressure of the clayey soils. For this purpose, σ_{pc} and PMT values of clayey units at the corresponding levels of a couple of boreholes were investigated,

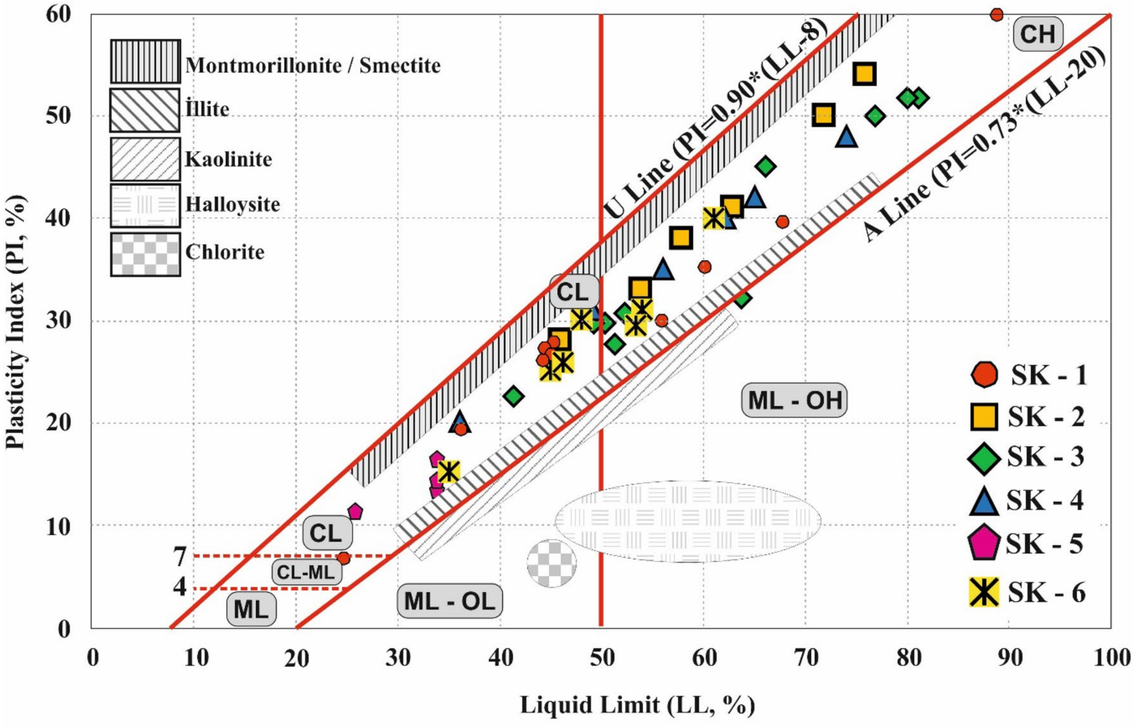

Fig. 7 The distribution of samples on the plasticity chart (modified from Cassagrande 1948; Howard 1977)

after which the statistical relations between these values were interpreted (Table 2).

The PMT tests in boreholes were performed at every 1.5 m. The results of PMT tests can be influenced by many factors such as borehole yield and the groundwater. Thus, the Menard deformation modulus (E_M) and net limit pressure (P_L) values could not be calculated at some levels. On the other hand, E_M and P_L values were obtained for a total of 33 different subsurface levels in the study area. When the calculated values are examined, it is determined that E_M and P_L values range between 5.76 and 64.62 MPa, and 0.85 and 6.58 MPa, respectively. When these values are compared with the typical E_M and P_L value ranges given by Menard (1975), it is determined that the investigated soils are classified as “very hard–hard clay”. Furthermore, the highest E_M values are assigned to the locations close to the Van Fault zone. On the contrary, the lowest E_M values are obtained from the spots nearby the lake, which is in the southwestern part of the study area (Fig. 8).

A total of 80 undisturbed soil samples (UD) were collected from the boreholes at harmonious PMT levels. Some levels of UD samples were used in consolidation experiments. In total, 35 samples suitable for the consolidation test were investigated in terms of their σ_{pc} values (Table 2). Overconsolidation ratio (OCR) of these samples was calculated from the ratio of current vertical effective stress (σ_v) to the σ_{pc} values.

Considering the σ_{pc} values obtained from the investigated soil levels, it is determined that the highest and lowest σ_{pc} values are 312 kPa and 88.3 kPa. For the OCR values, the maximum value is 7.80 whereas the minimum OCR value is 1.20. These OCR values indicate that the clayey soils in the study area are mostly over-consolidated (OC) (Table 2).

The inspection of variations of σ_{pc} values reveals that the σ_{pc} increases as the depth escalates in all boreholes, except for the borehole BL-1, which is the closest spot to the Van Thrust Fault (Fig. 8). The assessment of E_M values reveal that the peak values are obtained from the samples taken from the borehole BL-4, which is on the footwall of the Van Thrust Fault (Fig. 8). Since the undisturbed samples could not be taken from the borehole BL-5, only a single consolidation test could be performed in this borehole. Therefore, it is difficult to declare any idea for the borehole BL-5.

Considering the earthquake data available for the region, no earthquake record exists for the instrumental period until the 23 October 2011 earthquake. The long period of the compression in the fault could have been the source of this relatively large-magnitude earthquake, and no study in Turkey has reported compression due to thrust faults in that manner. This thrust fault exerts a noteworthy stress on the lacustrine sediments in the study area. These lacustrine sediments contain various deformational structures as an indicator of the effect of thrust fault on these soil layers. As a result of this stress, particularly due to the horizontal component, the sediments

Table 2 PMT test results in the study area and the obtained preconsolidation (σ_{pc}) pressure and over-consolidation ratio (OCR)

BL	Ground water level (m)	Depth	Soil class	Pressuremeter modulus		Effective stress (kPa)	Preconsolidation (σ_{pc}) (kPa)	OCR	
				E_M (MPa)	P_L (MPa)				
1	3.4	1.0	CH	18.94	0.85	20.70	125.60	6.10	Over-consolidated
1		2.0	CH	30.97	3.19	39.76	127.50	3.20	Over-consolidated
1		4.5	CL	34.74	2.49	83.10	147.20	1.80	Over-consolidated
1		5.5	CL	40.69	3.77	92.70	138.30	1.50	Over-consolidated
1		6.5	CL	38.02	3.76	95.60	137.30	1.40	Over-consolidated
1		8.8	CH	38.30	3.07	121.71	196.20	1.60	Over-consolidated
2	2.3	1.0	CL	14.66	1.75	18.89	147.20	7.80	Over-consolidated
2		3.5	CH	12.40	1.63	56.69	167.80	3.00	Over-consolidated
2		4.5	CH	25.40	3.46	59.44	177.60	3.00	Over-consolidated
2		6.5	CH	22.65	2.63	82.08	186.40	2.30	Over-consolidated
3	6.0	1.0	CH	19.71	2.10	18.15	135.40	7.50	Over-consolidated
3		2.5	CH	22.73	2.01	47.14	137.30	2.90	Over-consolidated
3		4.3	CH	32.21	4.14	86.25	206.00	2.40	Over-consolidated
3		5.5	CH	33.89	3.13	108.64	233.50	2.10	Over-consolidated
3		6.8	CL–CH	42.98	3.78	126.61	197.20	1.60	Over-consolidated
3		7.3	CL–CH	–	–	136.12	196.20	1.40	Over-consolidated
3		8.0	CH	–	–	139.26	212.90	1.50	Over-consolidated
3		8.3	CH	38.96	5.16	139.53	206.00	1.50	Over-consolidated
3		8.8	CH	–	–	147.10	215.80	1.50	Over-consolidated
3		9.8	CH	–	–	151.49	226.60	1.50	Over-consolidated
3		12.3	CH	40.29	3.61	190.45	230.50	1.20	Over-consolidated
3		13.8	CL	49.00	3.81	196.94	279.60	1.40	Over-consolidated
4	5.5	3.5	CH	28.22	3.04	73.38	225.60	3.10	Over-consolidated
4		5.8	CH	39.87	3.38	116.04	230.50	2.00	Over-consolidated
4		7.0	CH	46.98	3.99	128.74	269.80	2.10	Over-consolidated
4		8.3	CH	57.93	3.08	141.14	294.30	2.10	Over-consolidated
4		9.5	CH	64.62	3.79	154.44	312.00	2.00	Over-consolidated
5	2.5	2.5	CL	13.01	1.64				
5		6.3	CL	50.49	5.42	89.50	124.60	1.40	Over-consolidated
5		7.3	CL	60.80	5.05				
6	2.1	2.3	CL	5.76	0.97	43.96	88.30	2.00	Over-consolidated
6		3.3	CL	9.25	1.05	52.19	112.80	2.20	Over-consolidated
6		5.5	CL	9.48	1.00	75.27	145.20	1.90	Over-consolidated
6		6.5	CL	17.03	2.31	81.94	196.20	2.40	Over-consolidated
6		9.0	CH	48.35	6.58	112.54	233.50	2.10	Over-consolidated
6		10.3	CL	54.14	5.30	130.44	235.40	1.80	Over-consolidated
	Min			5.76	0.85	18.15	88.30	1.20	
	Max			64.62	6.58	196.94	312.00	7.80	
	Average			33.20	3.15	98.76	191.07	2.45	

present different engineering properties (Fig. 9). Stresses along the fault zone and orientation on the soil occur during the compression period. The soil texture in some of the UD samples taken from the boreholes at the hanging-wall of this fault reveals significant variation (Fig. 9). In addition, the mechanical test results are influenced by this variation as well. For this reason, it can be stated that the tectonic stresses are more effective on σ_{pc} and E_M values compared to the effect of σ_v in locations close to fault plane (Figs. 10, 11).

The relationship between σ_{pc} and E_M values of clay levels

It is determined that the physical and mechanical properties of the examined specimens depict dissimilarities in the

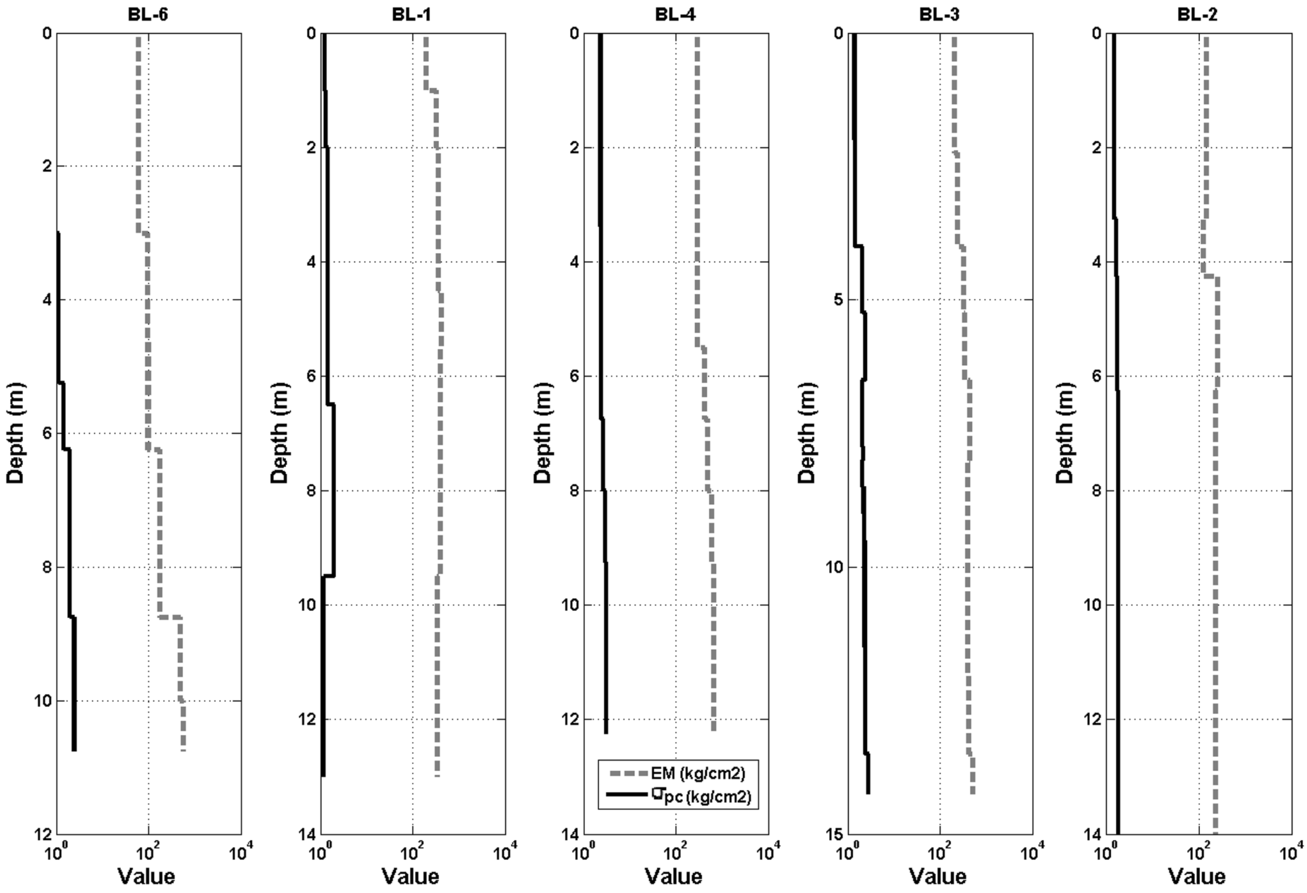

Fig. 8 Variation of E_M and σ_{pc} values with depth in the study area

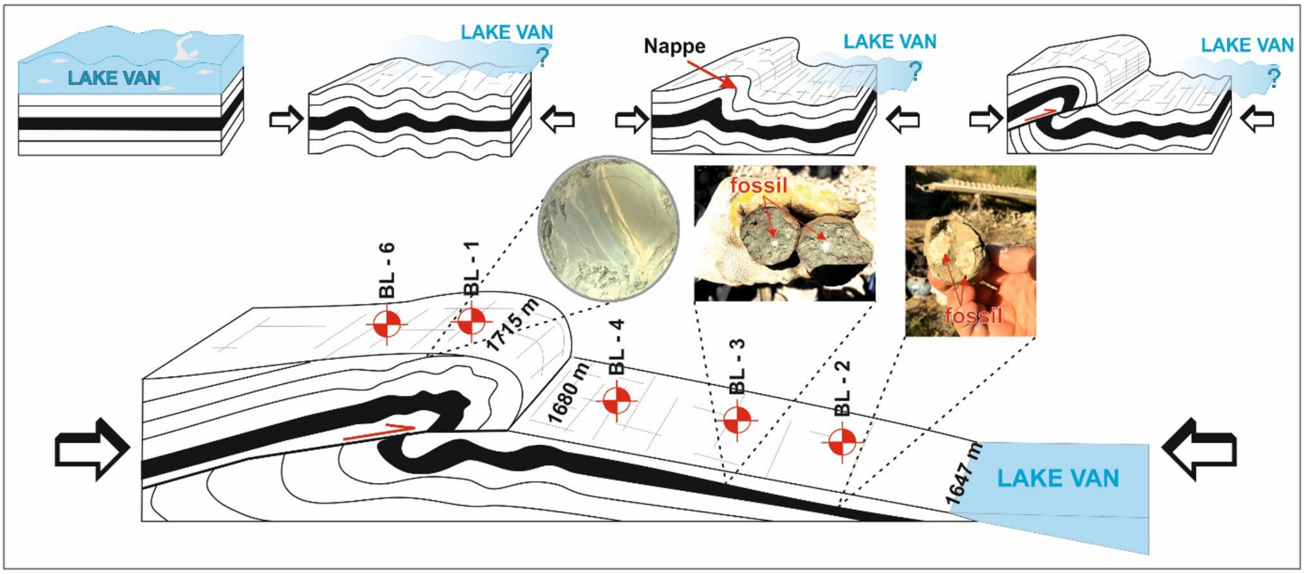

Fig. 9 An image of geological evolution in the study area

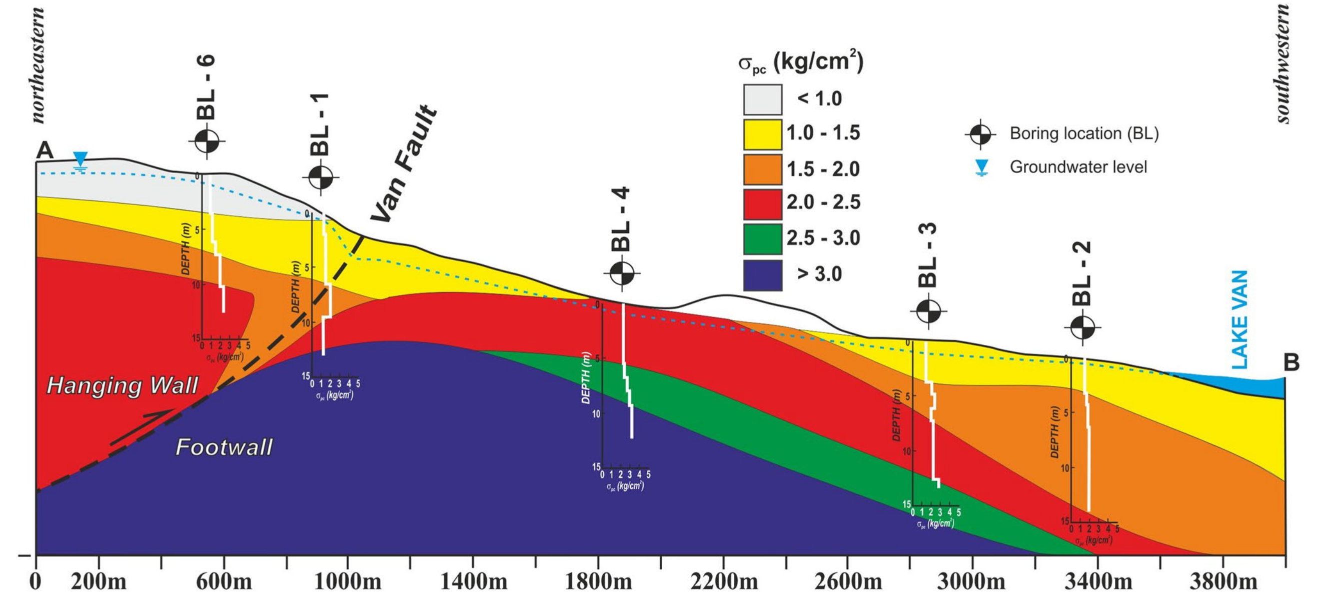

Fig. 10 Cross-section of the σ_{pc} values in the direction of NE–SW in the study area

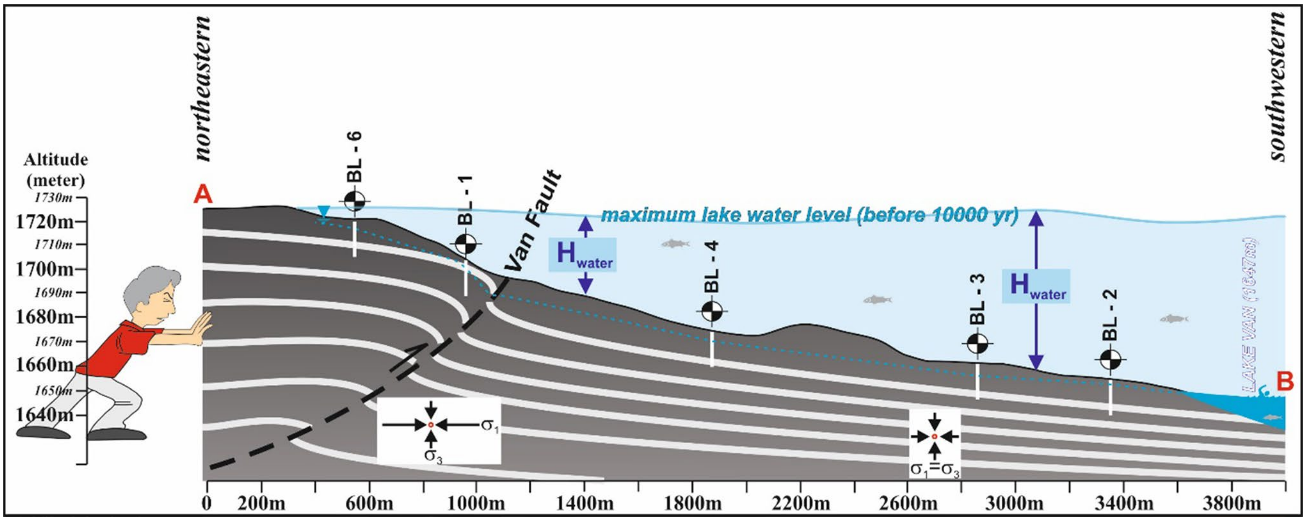

Fig. 11 A drawing of effects of the stress conditions on soils in the study area

laboratory and in situ tests. These differences are also recognized in the relationships between these parameters. Firstly, the data obtained from each borehole are correlated separately and the suitability of the data is evaluated. When the relationship between E_M and σ_{pc} is statistically examined for each borehole location, it is determined that there is a high determination coefficient for all locations, except for the BL-1 ($R^2=0.19$) data (Fig. 12a). According to all data, the coefficient of determination is obtained as $R^2=0.52$ for the relationship between E_M and σ_{pc} (Eq. 1) (Fig. 12b):

$$\sigma_{pc} = 0.2053\left(E_M\right)^{0.3863} \quad R^2 = 0.52. \tag{1}$$

When the correctness between these values is evaluated, it can be realized that the σ_{pc} data nearest to the fault (BL-1) affect the relationship using all data due to deformation structures in the soil at that particular location. The values of BL-1 are believed to be affected by the Van Thrust Fault. In the statistical regression analysis performed after

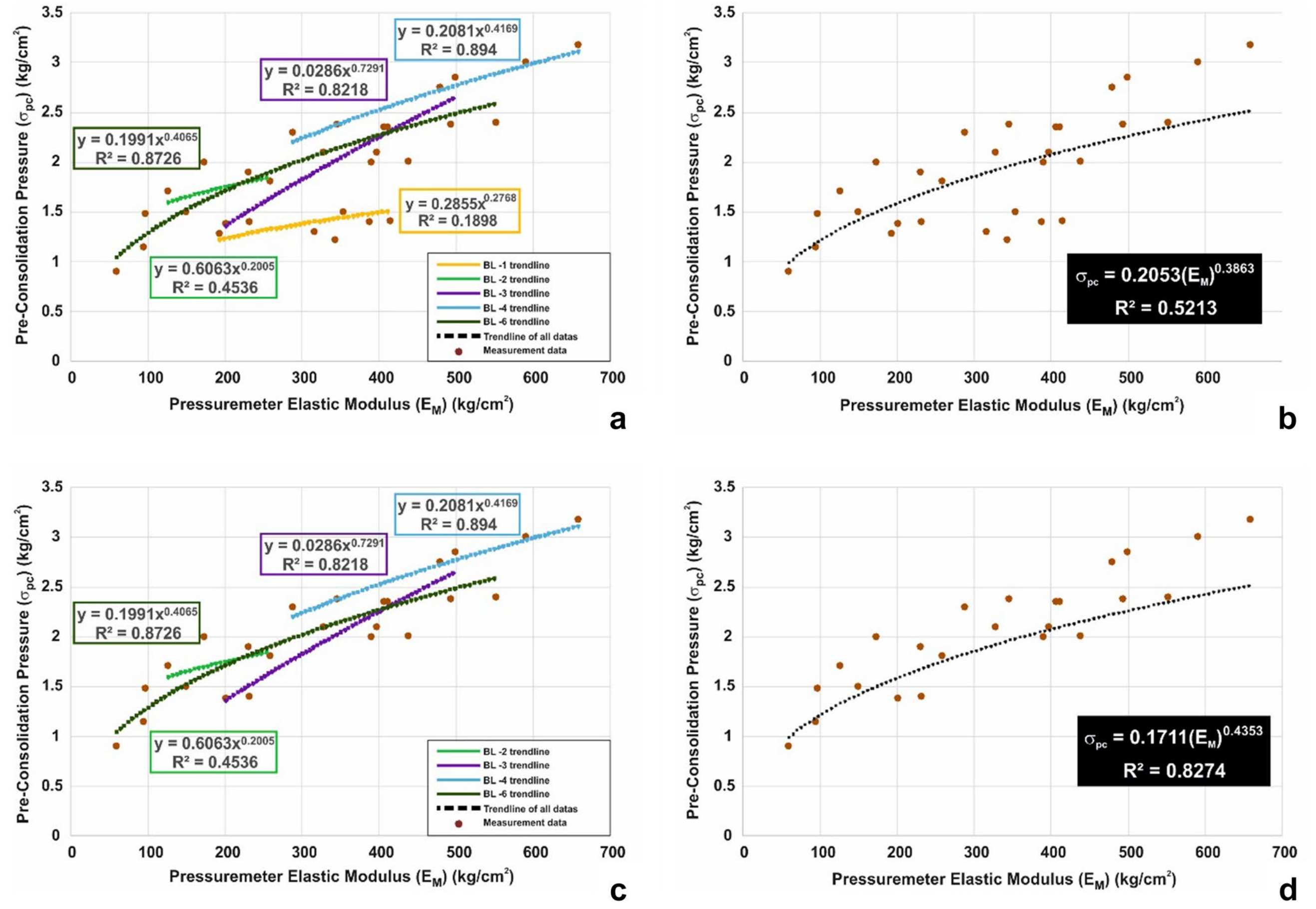

Fig. 12 Relationships between E_M and σ_{pc} data in each borehole (**a**), $E_M - \sigma_{pc}$ relation of all data (**b**), $E_M - \sigma_{pc}$ relationship after removing the data of BL-1 (**c**), $E_M - \sigma_{pc}$ relation of all data except for BL-1 (**d**)

removing the data of the borehole BL-1, the R^2 value escalates from 0.52 to 0.83 (Fig. 12c, d). The modified equation (2) is obtained without the data of BL-1:

$$\sigma_{pc} = 0.1711\left(E_M\right)^{0.4353} \quad R^2 = 0.83. \tag{2}$$

The increase observed in the R^2 value after omitting the BL-1 data indicates that the clayey soil at that particular location is different from other spots. This outcome points out that the deformation close to the fault plane in the hanging wall is capable of influencing the test results and may cause errors.

Conclusions

When the liquidity index (LI) and consistency index (Ic) values of the clay levels are assessed, the clay layers near the Lake Van are in plastic character, while the clay levels are generally very stiff in the areas close to the Van Thrust Fault.

When the OCR values are calculated, these clay deposits are found to be over-consolidated. The overconsolidation values of these clay levels indicate that these units were subjected to considerable stress rates in the past compared to the current vertical effective stresses. Supposing the fact that the overconsolidation is due to the fluctuations in the water level of the Lake Van, the highest overconsolidation ratio should have been derived from the locations close to the lake, while the current results are the opposite. Therefore, it is concluded that the difference in preconsolidation pressure values of clay soils in the study area is mostly affected by the stresses derived from the Van Thrust Fault. The mechanical soil properties of clay levels in and around the surface rupture have increased due to fault stresses.

When σ_{pc} and E_M values are evaluated, it is determined that σ_{pc} and E_M values increase as the elevation gets deeper. In this study, the outcomes of in situ (σ_{pc} and E_M) and laboratory tests are assessed together to determine the relationship between σ_{pc} and E_M, which are commonly being used to determine the characteristics of consolidated clayey soils. High determination coefficients (R^2) are obtained for the relationship between σ_{pc} and E_M (Eq. 2).

Equation (2) can be used especially for the over-consolidated clayey soils. However, it is recommended to increase the experimental data for clays with different consistency and preconsolidation values.

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References

Acarlar M, Bilgin ZA, Erkal T, Güner E, Şen AM, Umut M, Elibol E, Gedik İ, Hakyemez Y, Uğuz MF (1991) Van Gölü Doğu ve Kuzeyinin Jeolojisi MTA Raporu, Ankara, No: 9469, 94s **(in Turkish)**

Akın M, Özvan A, Akın MK, Topal T (2013) Evaluation of liquefaction in Karasu River floodplain after the October 23, 2011, Van (Turkey) earthquake. Nat Hazards 69:1551–1575

Akın MK, Akın M, Akkaya İ, Özvan A, Üner S, Selçuk L, Tapan M (2015) Mikrobölgeleme Çalışmasına Altlık Oluşturmak Üzere Van Yüzüncü Yıl Üniversitesi Kampüs Zemininin Dinamik Özelliklerinin Belirlenmesi. Jeoloji Mühendisliği Dergisi 39(1):1–26 **(in Turkish)**

Akkaya İ, Özvan A (2019) Site characterization in the Van settlement (Eastern Turkey) using surface waves and HVSR microtremor methods. J Appl Geophys 160:157–170

Akkaya İ, Özvan A, Tapan M, Şengül MA (2015) Determining the site effects of 23 October 2011 earthquake (Van province, Turkey) on the rural areas using HVSR microtremor method. J Earth Syst Sci 124(7):1429–1443

Akkaya İ, Özvan A, Akın M, Akın MK, Övün U (2018) Comparison of SPT and Vs-based liquefaction analyses: a case study in Erciş (Van, Turkey). Acta Geophys 66(1):21–38

Aladağ CH, Kayabası A, Gokçeoğlu C (2013) Estimation of pressuremeter modulus and limit pressure of clayey soils by various artificial neural network models. Neural Comput Appl 23:333–339

Anwar MB (2016) Correlation between PMT and SPT results for calcareous soil. HBRC J 14(1):50–55

ASTM D2435-09 (2009) Standard test method for one-dimensional consolidation properties of soils. In: Annual book of ASTM standards, vol 0408, West Conshohocken, pp 238–247

ASTM D4318-17e1 (2017) Standard test methods for liquid limit, plastic limit, and plasticity index of soils. ASTM International, West Conshohocken, PA. http://www.astm.org. Accessed 10 May 2018

ASTM D4719-00 (2000) Standard test method for prebored pressuremeter testing in soils. ASTM International, West Conshohocken, PA. http://www.astm.org. Accessed 10 Feb 2018

ASTM D7928-17 (2017) Standard test method for particle-size distribution (gradation) of fine-grained soils using the sedimentation (hydrometer)analysis. ASTM International, West Conshohocken, PA. http://www.astm.org. Accessed 10 May 2018

Bishop AW, Henkel DJ (1953) Pore pressure changes during shear in two undisturbed clays. In: Proceedings of 3rd international conference on soil mechanics and foundation engineering, Zurich, Switzerland, pp 94–99

Bozbey I, Togrol E (2010) Correlation of standard penetration test and pressuremeter data a case study from Estunbol Turkey. Bull Eng Geol Environ 69:505–515

Burmister DM (1951) The application of controlled test methods in consolidation testing. Proc Symp Cons Test Soils ASTM Spec Tech Publ 126:83

Casagrande A (1932) The structure of clay and Its Importance in Foundation Engineering. J Borton Soc Civ Eng 1932:72–113 **(reprinted in Contributions to Soil Mechanics 1925–1940, BSCE)**

Casagrande A (1936) The determination of the pre-consolidation load and its practical significance discussion D-34. In: Proceeding of the first international conference on soil mechanics and foundation engineering, Cambridge, Massachusetts, vol 3, pp 60–64

Cassagrande A (1948) Classification and identification of soils. Trans ASCE 113:901–930

Cheshomi A, Ghodrati M (2015) Estimating Menard pressuremeter modulus and limit pressure from SPT in silty sand and silty clay soils, a case study in Mashhad, Iran. Geomech Geoeng Int J 10(3):194–202

Chiang YC, Ho YM (1980) Pressuremeter method for foundation design in Hong Hong. Proc Sixth Southeast Asian Conf Soil Eng 1:31–42

Erdoğan O, Özvan A (2015) Evaluation of strength parameters and quality assessment of different lithotype levels of Edremit (Van) Travertine (Eastern Turkey). J Afr Earth Sci 106:108–117

Esu F, Calabresi G (1969) Slope stability in an overconsolidated clay. In: Proceedings of 7th international conference on soil mechanics and foundation engineering, Mexico City, Mexico, vol 2, pp 555–563

Feda J (1978) Stress in subsoil and methods of final settlement calculation. Elsevier, Amsterdam

Fener M (2006) Zemin Granülometrisinin Ön Konsolidasyon Basıncı ve Zemin Hafızasına Etkisi. Doktora Tezi, ÇÜ Fen Bilm Enst, Adana, s107 **(in Turkish)**

Görür N, Çağatay MN, Zabcı C, Sakınç M, Akkök R, Şile H, Örçen S (2015) The late quaternary tectono-stratigraphic evolution of the Lake Van, Turkey. MTA Dergisi 151:1–47

Günaydın O (2007) Aktif Faylar Üzerinde Stres Dağılımının Casagrande Yöntemiyle Belirlenmesi; Kuzey Anadolu Fay Sistemi Gerede (Bolu) Segmenti. Doktora Tezi, ÇÜ Fen Bilm Enst, Adana, s100 **(in Turkish)**

Hobbs BE, Means WD, Williams PF (1976) An outline of structural geology. Wiley, New York

Holtz RD, Kovacs WD (1981) An introduction to geotechnical engineering. Prentice-Hall, Inc., New York, p 733

Howard AK (1977) Laboratory classification of soils-unified soil classification system. Earth Sciences Training Manual No4, US Bureau of Reclamation, Denver, p 56

Ingles OG, Lafeber D (1966) The influence of volume defects on the strength and strength isotropy of stabilized clays. Eng Geol 1:305–310

Kayabaşı A (2012) Prediction of pressuremeter modulus and limit pressure of clayey soils by simple and non-linear multiple regression techniques: a case study from Mersin, Turkey. Environ Earth Sci 66:2171–2183

Kempe S, Landmann G, Müller G (2002) A floating varve chronology from the last glacial maximum terrace of Lake Van/Turkey. Res Deserts Mt Afr Central Asia 126:97–114

Kılıçer A (2009) Yüzüncü Yıl Üniversitesi Kampus Alanı Karot Örneklerinin Kil Mineralojisi. Yüzüncü Yıl Üniversitesi, Fen Bilimleri Enstitüsü, Van, s89 **(in Turkish)**

Kuzucuoğlu C, Christol A, Mouralis D, Doğu AF, Akköprü E, Fort M, Brunstein D, Zorer H, Fontugne M, Karabıyıkoğlu M, Scaillet S, Reyss J, Guillou H (2010) Formation of the Upper Pleistocene terraces of Lake Van (Turkey). J Quat Sci 25(7):1124–1137

Landmann G, Reimer A, Kempe S (1996a) Climatically induced lake level changes at Lake Van, Turkey, during the Pleistocene/Holocene transition. Glob Biogeochem Cycles 10:797–808

Landmann G, Reimer A, Lemcke G, Kempe S (1996b) Dating Late Glacial abrupt climate changes in the 14,570 years long continuous varve record of Lake Van/Turkey. Paleogeogr Paleocl Paleoecol 122:107–118

Litt T, Krastel S, Sturm M, Kipfer R, Örçen S, Heumann G, Franz SO, Ulgen UB, Niessen F (2009) ‘PALEOVAN’, International Continental Scientific Drilling Program (ICDP): site survey results and perspectives. Quat Sci Rev 28:1555–1567

Menard LF (1975) The Menard pressuremeter: interpretation and application of pressuremeter test results to foundation design. D60AN Sols Soils 26:5–43

Nagaraj TS (1993) Principles of testing soils, rocks and concrete. Elsevier, Amsterdam

Özkaymak Ç (2003) Van Şehri Yakın Çevresinin Aktif Tektonik Özellikleri. Yüzüncü Yıl Üniversitesi, Fen Bilimleri Enstitüsü, Van, s84 **(in Turkish)**

Özvan A (2004) Van Ili Yerleşim Alanının Mühendislik Jeolojisi. Yüzüncü Yıl Üniversitesi, Fen Bilimleri Enstitüsü, Van, s89 **(in Turkish)**

Özvan A, Erdoğan O (2016) Geotechnical handicap of travertine with different lithotype levels as foundation material. J Geol Soc India 88:799–807

Özvan A, Akkaya İ, Tapan M, Şengül MA (2005) Van yerleşkesinin deprem tehlikesi ve olası bir depremin sonuçları. Kocaeli Deprem Sempozyumu Kocaeli 2005, 23–25 Mart 2005 Kocaeli **(in Turkish)**

Özvan A, Akkaya İ, Tapan M (2018) An approach for determining the relationship between the parameters of pressuremeter and SPT in different consistency clays in Eastern Turkey. Bull Eng Geol Environ 77:1145–1154

Schmertmann JH (1955) The undisturbed consolidation behavior of clay. Am Soc Civ Eng Trans 120:1201–1233

Seed HB, Woodward RJ, Lundgren R (1962) Prediction of swelling potential for compacted clays. J Soil Mech Found Div ASCE 88:53–87

Selçuk L (2003) Yüzüncü Yıl Üniversitesi Zeve Kampüsü Yerleşim Alanının Mühendislik Jeolojisi. Yüzüncü Yıl Üniversitesi, Fen Bilimleri Enstitüsü, Van, s118 **(in Turkish)**

Şengör AMC, Yılmaz Y (1981) Tethyan evolution of Turkey: a plate tectonic approach. Tectonophysics 75:181–241

Sengul MA, Gürboğa Ş, Akkaya İ, Özvan A (2019) Deformation patterns in the Van region (Eastern Turkey) and their significance for the tectonic framework. Geol Carpath 70:193–208

Simons NE (1965) Consolidation investigation on undisturbed Fornebu clay. Nor Geotech Inst 62:1–9

Skempton AW (1953) The colloidal activity of clays. Proc Third Int Conf Soil Mech Found Eng 1:57–61

Tchalenko JS (1967) The influence of shear and consolidation on the microscopic structure of some clays. Ph D Thesis, University of London, London, UK

Üner S (2018) Late Quaternary lacustrine storm deposits: sedimentological properties and regional significance (Lake Van Basin-Eastern Turkey). Arab J Geosci 11:582. https://doi.org/10.1007/s12517-018-3946-z

Valeton I (1978) A morphological and petrological study the terraces around Lake Van, Turkey. In: Degens ET, Kurtman F (eds) Geology of Lake Van, vol 169. MTA Publications, London, pp 64–80

Voight B (1966) Interpretation of in situ measurements. Proc Int Soc Rock Mech Lisbon Portugal 3:332–348

Voight B (1974) A mechanism for “locking-in” orogenic stress. Am J Sci 274:662–665

Ward WH, Samuels SG, Butler ME (1959) Further studies of the properties of London clay. Geotechnique 9:33–58

Yağız S, Akyol E, Sen G (2008) Relationship between the standard penetration test and the pressuremeter test on sandy silty clays: a case study from Denizli. Bull Eng Geol Environ 67:405–410