Bull Eng Geol Environ (2018) 77:1145–1154
https://doi.org/10.1007/s10064-017-1020-9

ORIGINAL PAPER

An approach for determining the relationship between the parameters of pressuremeter and SPT in different consistency clays in Eastern Turkey

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Received: 19 September 2016 / Accepted: 10 February 2017 / Published online: 22 February 2017

Abstract The pressuremeter test is one of the borehole loading tests that determines the deformation characteristics of subsurface soil. The main idea of the pressuremeter test is to inflate the cylindrical hole drilled in order to measure the pressure-deformation relations of the soil. Another in situ test by which soil properties are determined is the well-known standard penetration test (SPT). The consistency and firmness of soils can be determined using the test results of these in situ tests. In order to determine the relationship between the results of these two tests in clayey soils with low and high plasticity characteristics, a total of 20 boreholes with 1.5–4.5 m depths were drilled, and both tests were performed at varying depths. Following the pressuremeter test, pure limit pressure (P_L) values and pressuremeter deformation modulus (E_M) were calculated for 31 different levels, respectively. These values were compared to SPT (N_{60}) values, and high determination coefficients (R^2) were attained. Therefore, for clayey soils, it is possible to determine E_M and P_L values from SPT results, and consequently SPT test results can be used to calculate settlement and bearing capacity as well as the undrained shear strength values (c_u) of low and high plasticity clayey soils.

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Keywords Pressuremeter · Standard penetration test · Clay · Correlation

Introduction

Many methods and approaches are used to determine the bearing capacity and settlement properties of the foundation soils on which structures are placed. The most commonly used methods are the menard pressuremeter test (PMT), standard penetration test (SPT), cone penetrometer test (CPT) and plate loading test. Apart from these tests, some other laboratory tests are conducted. Due to possible degradation of the samples taken for the laboratory tests, and the inability of the sample to represent the general characteristics of the soil completely, the accuracy of parameters used in calculations is likely to decrease. The greatest advantage of in situ tests is that they reveal more realistic and reliable results as they are carried out without disturbing the soil. In our country (Turkey), the SPT and PMT tests are the most commonly used in situ tests performed in various soils. Although PMT is more complex to carry out compared to SPT, it is applicable to both soils and fissured rocks. In this test, various variables can be measured directly. However, the greatest drawback of this test is the likelihood that it can be misinterpreted. In recent years, along with widespread use of drilling works, PMT tests are increasingly being conducted in our country, too. In field studies, generally the Menard type pressuremeter is preferred. PMT can be applied to a wider range of soils, from very soft soils to rocks with a uniaxial compressive strength of 20 MPa, in which the SPT test cannot be conducted. PMT can be carried out far into the weak rock class identified in the ISRM (2007) rock characterization method using ground identifications and the uniaxial compressive strength of discontinuity surfaces (Kayabaşı 2012).

Only a limited number of studies between SPT and PMT have been conducted by individual researchers (Chiang and Ho 1980; Ohya et al. 1982; Gonin et al. 1992; Yagiz et al. 2008; Bozbey and Togrol 2010; Kayabaşı 2012; Kayabaşı and Gökceoğlu 2012; Aladağ et al. 2013; Cheshomi and Ghodrati 2015; Anwar 2016). The first studies were revealed by Chiang and Ho (1980) and Ohya et al. (1982). The linear relationship between SPT(N) and E_{PMT} and P_L was presented by Chiang and Ho in weathered granite in Hong Kong in 1980, whereas Ohya et al. (1982) presented the correlation between SPT(N) and E_{PMT} for clay soils. Also, Yagiz et al. (2008) studied the relationship between N_{cor} and E_{PMT} and P_L, and found that a linear relationship exists between the corrected N_{cor} and E_{PMT} and P_L in Denizli (Turkey) for shallow sandy silty clays. Bozbey and Togrol (2010) presented the relationship between N_{60} and E_{PMT} and P_L based on a study conducted in Istanbul (Turkey). Their results were based on 182 tests carried out on sand and clay soils, and present a distinctive linear correlation for each soil type. Gonin et al. (1992) correlated SPT results with E_{PMT} and P_L for nine different French soils.

In some of these studies, high determination coefficients (R^2) between the SPT N, and pure limit pressure (P_L) and Menard pressuremeter (elasticity) modulus (E_M) values were obtained for different soil classes. However, it has been particularly emphasized by the above-mentioned researchers that the empirical formula obtained may be misleading unless the pressuremeter test is applied precisely, the results for different soil classes are included, and different empirical equations for different soil groups by taking the geological characteristics of the study area into consideration are offered (Phoon and Kulhawy 1999; Yagiz et al. 2008; Kayabaşı 2012; Cheshomi and Ghodrati 2015; Bozbey and Togrol 2010).

In this study, the SPT and PMT tests were conducted at low and high plasticity (CL–CH) clay levels of soils with varying SPT N values from soft to firm clay, and at optimum levels in lithological units that can be classified as excessively stiffened or generally soft-supersoft rocks (e.g., marl). While measuring N blow counts via SPT tests, P_L and E_M values were determined via pressuremeter method. The results were then used to determine the relationship between the results of these two tests, and consequently compared with the results of previously conducted researches at similar soils.

Methods

Among a great number of test methods that determine in situ properties of soils, SPT and pressuremeter tests are primarily the most commonly used ones. The SPT test, which was developed in the 1920s with the intent of measuring penetration resistance of the soil, is known to be the most preferred field test of soil studies due to the ease of use it offers. After recording the number of blows that penetrate the tube into the ground as SPT-N_{30} value, an N_{60} value is calculated by revising it in accordance with the specifications in the literature (Bowles 1997; ASTM D1586 1999; Aggour and Radding 2001; British Standards Institution 2007; Sivrikaya and Togrol 2007).

The first study to determine the characteristics of lateral deformation in the soil was conducted in 1930s by Koegler. This was followed by contribution of Dr. Louis Menard in 1950s, who developed the device named Menard Pressuremeter (Menard 1957). Since the development of this device, the number of studies on this subject has increased, and the Menard Pressuremeter has led researchers to develop new approaches and the empirical formulas currently in use.

Menard type pressuremeter equipment consists of two main parts: the read-out unit, which rests on the ground surface, and the probe that is inserted into the borehole. The pressuremeter was lowered into the pre-formed hole and a uniform pressure is applied to the borehole walls by means of an inflatable flexible membrane. The pressure applied to the borehole walls is increased every 60 s in order to deform the borehole walls.

The pressure is held constant for 30 s and 60 s, and the increase in volume required to maintain constant pressure is recorded. A load-deformation diagram was determined to calculate P_L and E_M values (Shields and Bauer 1975; Baguelin et al. 1978; Mair and Wood 1987; Clarke 1995; Coduto 1999; ASTM D4719 2000).

The data used in this study were obtained from 20 exploration boreholes drilled as a part of a soil investigation program. The study area consists of two main layers. The upper levels, between 1.0 and 5.0 m, consist of silty clays and clay. The deeper levels consist of marl/claystone. The depths of the borings range between 1.5 m and 4.5 m. Groundwater was encountered at depths ranging from 2 m to 14 m. SPT and PMT tests were performed in those boreholes at clay levels having different consistencies. The pressuremeter test was performed in accordance with ASTM D4719-00. Soil characteristics were also determined by conducting laboratory tests on disturbed samples taken from these levels where SPT and PMT tests were performed.

Laboratory tests (e.g., soil gradation, Atterberg limits) were carried out to determine the index properties of soil, which were used in soil classifications. In the present study, the results of in situ tests and laboratory test results were evaluated together to determine the relationship between the SPT N, and E_M and P_L values at low and high plasticity (CL–CH) clayey soils in the Kurubaş district of Van, Turkey, and, finally, empirical formulas showing this relationship were developed through regression analyses.

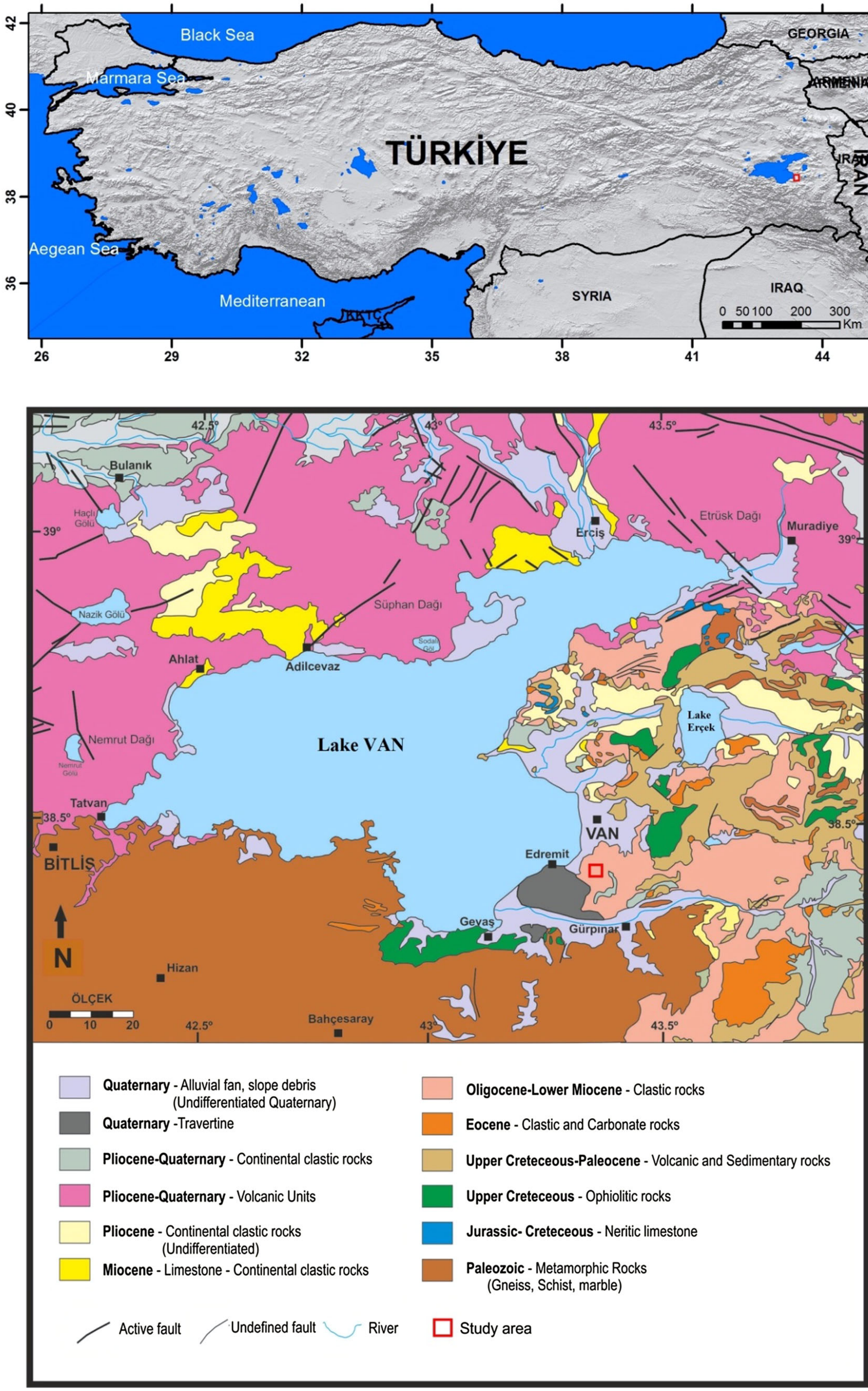


Fig. 1 Site location and geology map of the study area (modified from MTA 2007)

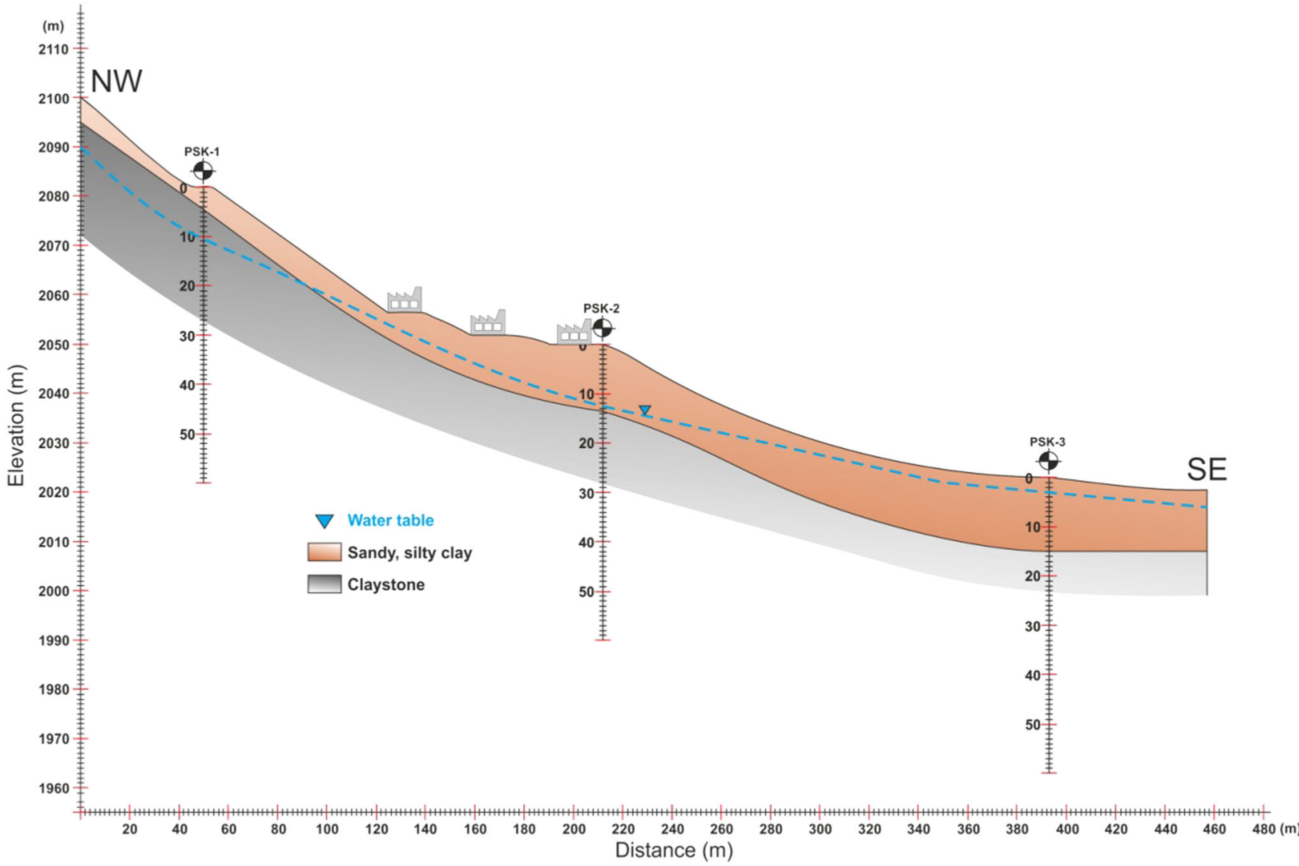
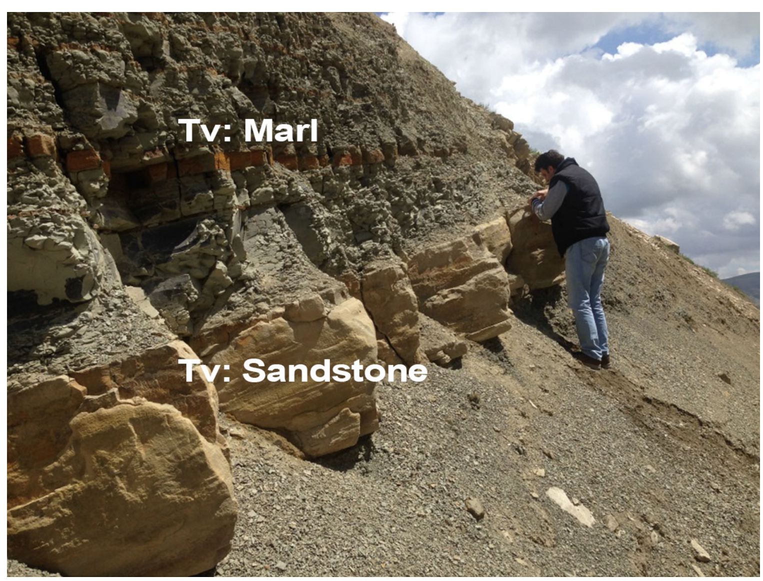


Fig. 2 NW-SE cross section of the study area

Fig. 3 Marl and sandstone layers from the eastern parts of the study area



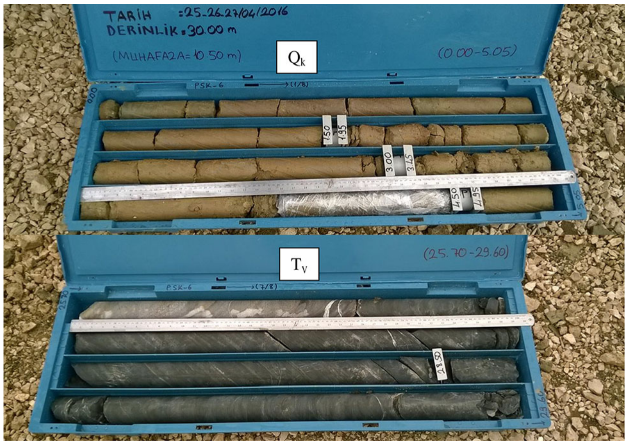


Fig. 4 A view from the cores indicating lower and upper levels of a borehole

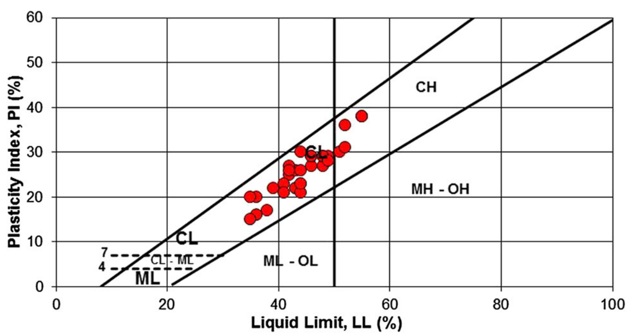


Fig. 5 Soil classification of fine-grained units in the investigated area in accordance with TS 1500 (2000)

Results

Geology

Two different geological units are exposed in the study area (Fig. 1). The basement rocks are Oligocene-Lower Miocene Van formation and consist of alternation of marl/clay and sandstones. Loose sandy-silty clay units cover the Van formation with an approximate maximum thickness of 15 m (Fig. 2).

Van formation

Van formation (Tv) is the most widespread sedimentary unit in the studied area, and is characterized by alternation of sandstones and marls. Sandstones are relatively thin and firmer than the marl layers (Fig. 3).

Clay and fill

Van formation is overlain by a loose sandy-silty clay unit (Qk—Qd) (Fig. 4) which is possibly a result of the weathering of the Van formation. The approximate thickness of the unit is about 3–5 m, but, it sometimes reaches a maximum of 15 m. Plasticity is dominantly low within this unit; however, higher levels also exist.

Index properties of clay levels

Based on the grain size distribution tests, the particle size of soil differs from very fine to fine. Soil characteristics of the upper levels within the study area are classified as low (CL) and high (CH) plasticity clay-silty clay (Fig. 5). The water content of test samples was determined at between 11% and 33%. Depending on the water content, the physical state of a clayey soil may change.

Statistical evaluation

SPT and PMT tests were performed at 34 various levels of clay soils with different consistencies at varying depths between 1.50 and 4.50 m. E_M and P_L values were calculated from the pressuremeter curve determined after pressuremeter tests whereas SPT (N_{60}) values were calculated using SPT (N_{30}) values (Table 1). A statistical study was performed to determine the relationship between SPT (N_{60}) values and E_M and P_L values in CL and CH type of clayey soils.

The coefficient of correlation determines the linear dependency between two variables. When the coefficient of correlation ρ_{xy} is equal to zero, there is no linear dependency between x and y; however, when the absolute value of ρ_{xy} approaches 1, the dependency between variables becomes increasingly stronger, and turns into a deterministic relation. But, this relation does not always indicate a cause and effect relationship between two variables. It may lead to a greater correlation coefficient where both variables have a relationship with another variable as well. On the other hand, it is important to assess whether the distribution is suited for the data set obtained in this study. Otherwise, this may result in a great difference between measured and calculated values using proposed empirical formulas. The t test and the F test were used to assess the validity of the proposed equations together with the coefficient of regression (the r value). Since the t test could not be applied for a limited number of data, the data in this study were evaluated initially in terms of concordance with the commonly used F test analysis. The computed F test value was found to be greater than the tabulated F value (Table 2), supporting a reliable correlation between measured and predicted values.

Statistical compatibility analysis was performed for the measured E_M, P_L and SPT (N_{30}) values, and finally for the SPT (N_{60}) values calculated using SPT (N_{30}) values (Table 1). The results of this analysis are given in Tables 2

Table 1 The measured soil parameters

Number (N)	Depth (m)	SPT (N_{30})	SPT (N_{60})	Measured EM (MPa)	Measured PL (MPa)
1	1.50[a]	5	5	0.29	0.13
2	1.50	12	12	2.26	0.43
3	1.50	14	14	14.82	0.61
4	1.50	17	18	11.62	0.67
5	1.50	22	23	48.73	2.21
6	3.00	11	9	1.89	0.18
7	3.00	14	10	0.94	0.24
8	3.00	12	12	2.84	0.41
9	3.00	14	13	5.14	0.64
10	3.00	14	13	6.92	0.64
11	3.00	16	15	10.40	0.78
12	3.00	20	15	23.81	1.12
13	3.00	18	16	10.83	1.37
14	3.00	19	17	17.00	1.36
15	3.00	19	17	16.82	1.13
16	3.00	22	19	25.58	1.58
17	3.00	26	19	33.15	1.09
18	3.00	25	20	33.50	3.00
19	3.00	21	20	18.80	0.93
20	3.00	24	21	26.63	1.81
21	3.00	25	22	25.66	1.93
22	3.00	27	23	35.63	2.16
23	3.00	28	24	34.59	2.01
24	3.00	29	25	31.54	2.59
25	3.00	35	29	48.42	2.69
26	3.00	37	31	52.36	3.12
27	3.00[a]	50	49	190.17	2.82
28	4.50	17	13	10.62	1.36
29	4.50	33	28	42.46	2.73
30	4.50	37	31	50.37	3.32
31	4.50	38	32	62.98	3.57
32	4.50	38	32	50.37	3.31
33	4.50[a]	50	37	187	5.21
34	4.50	47	38	83.97	4.32

SPT Standard penetration test, *EM* pressuremeter deformation modulus, *PL* pure limit pressure

[a] Levels of rock and saturated clay soil

Table 2 Analysis of variance for the significance of the regressions and r values

Model	Sum of squares	*df*	Mean square	*F* value	*F* table	*F*
E_M						
Regression	11,461.3	1	11,461.3	308.217	4.17	0.000[a]
Residual	1078.4	29	37.2			
Total	12,539.6	30				
P_L						
Regression	33.7977	1	33.7977	246.091	4.17	0.000[a]
Residual	3.9828	29	0.1373			
Total	37.7805	30				

Dependent variables: E_M and P_L

[a] Predictors: (constant), SPT

Table 3 Results from *F* tests of proposed equations and the significances of the *r* values

	E_M	SPT (N_{60})	P_L
N	31		
Mean	27.1	20.35	1.72
SD	20.4	7.49	1.12
SE mean	3.7	1.3	0.2
df	60		
Estimate for difference		18.64	
	−6.76		
95% CI for difference		(15.92; 21.35)	
	(−14.58; 1.06)		

and 3. After determining the compatibility of the data set that will be used in statistical analysis, regression analysis using a commercial software package (SPSS v23; SPSS 2002) was performed.

The regression coefficients (R^2) between E_M and SPT (N_{60}) and P_L and SPT (N_{60}) were calculated as 0.75 and 0.76, respectively when the correlation was performed for 34 different levels having different types of clayey soils (Fig. 6a, b). The sub foundation soils at three points where SPT and PMT had been conducted were found to be marl and saturated clay. Since, the scope of this study was to determine the relationship between SPT and PMT test results in CL–CH class soils; the values obtained for marl and saturated clay were not taken into consideration in the analyses. Therefore, regression analysis was repeated using the values gathered from 31 different levels of CL and CH soils, and the determination coefficients (R^2) between E_M and SPT (N_{60}) as well as P_L and SPT (N_{60}) were found to be 0.91 and 0.89, respectively (Fig. 6c, d; Table 4).

The values of E_M and P_L obtained from PMT tests in this study were compared with the values calculated using the proposed equations, in Bozbey and Togrol (2010), Kayabaşı (2012) and Cheshomi and Ghodrati (2015). The results are given in Tables 5 and 6. A similar linear relationship exists between E_M and SPT (N_{60}) and P_L and SPT (N_{60}) in all proposed equations (Fig. 7a, b). It is important to note that the empirical equations developed for calculating E_M and P_L values in this study reveals more accurate results than those developed by other researchers.

In all proposed equations, it was determined that the coefficient of determination between SPT (N_{60}) and E_M was lower than SPT (N_{60}) and P_L (Fig. 8). This may be attributed to the fact that P_L values are read through pressuremeter curve directly, while E_M is calculated from the below equation proposed by Baguelin et al. (1978), which is dependent on the Poisson ratio of the soil, which, in many cases, is hard to determine.

$$E_M = k\frac{P}{V}$$

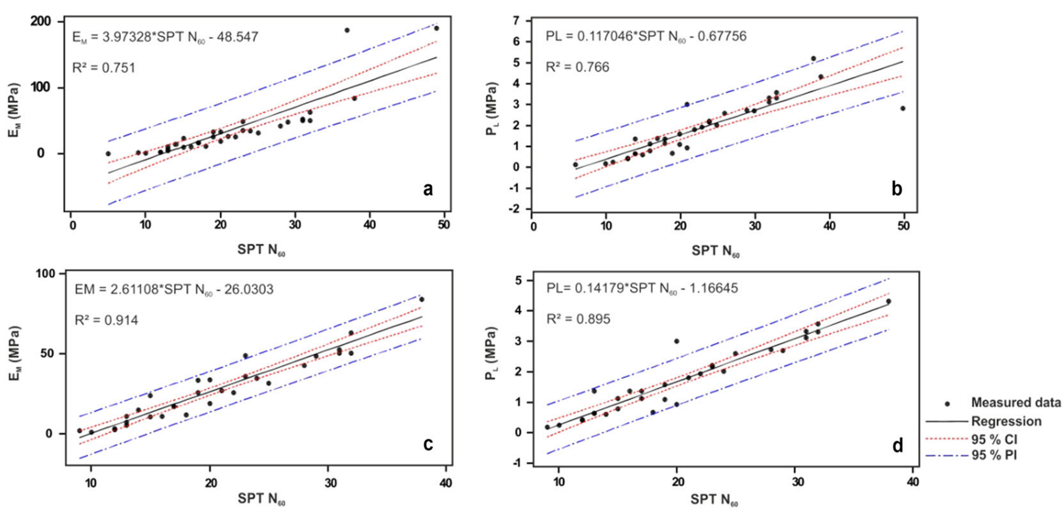


Fig. 6 Regression and confidence intervals between E_M–SPT (N_{60}) and P_L–SPT (N_{60}) of all samples (34 samples) (**a**, **b**) and (**c**, **d**) CL and CH soils samples (31 samples) in the study area

Table 4 Summary of the developed model

Model	*N*	Equation	R^2	Adjusted R^2	Standard error of the estimate
E_M	31	E_M (MPa) = 2.611 (N_{60})—26.03	0.914[a]	0.911	6.09801
P_L		P_L (MPa) = 0.142 (N_{60})—1.166	0.895[a]	0.891	0.370592

[a] Predictors: (constant), SPT

Table 5 Comparison between measured E_M and P_L with estimated E_M and P_L

Number (N)	Depth (m)	SPT N_{60}	SPT N_{30}	E_M (MPa)			P_L (MPa)		
				Measured	Predicted	Residual	Measured	Predicted	Residual
1	1.5	12	12	2.26	5.3026	−3.0426	0.43	0.53504	−0.10504
2	1.5	14	14	14.82	10.5248	4.2952	0.61	0.81862	−0.20862
3	1.5	18	17	11.62	20.9691	−9.3491	0.67	1.38578	−0.71578
4	1.5	23	22	48.73	34.0245	14.7055	2.21	2.09474	0.11526
5	3	9	11	1.89	−2.5306	4.4206	0.18	0.10967	0.07033
6	3	10	14	0.94	0.0805	0.8595	0.24	0.25146	−0.01146
7	3	12	12	2.84	5.3026	−2.4626	0.41	0.53504	−0.12504
8	3	13	14	5.14	7.9137	−2.7737	0.64	0.67683	−0.03683
9	3	13	14	6.92	7.9137	−0.9937	0.64	0.67683	−0.03683
10	3	15	16	10.4	13.1358	−2.7358	0.78	0.96041	−0.18041
11	3	15	20	23.81	13.1358	10.6742	1.12	0.96041	0.15959
12	3	16	18	10.83	15.7469	−4.9169	1.37	1.1022	0.2678
13	3	17	19	17	18.358	−1.358	1.36	1.24399	0.11601
14	3	17	19	16.82	18.358	−1.538	1.13	1.24399	−0.11399
15	3	19	22	25.58	23.5802	1.9998	1.58	1.52757	0.05243
16	3	19	26	33.15	23.5802	9.5698	1.09	1.52757	−0.43757
17	3	20	25	33.5	26.1912	7.3088	3	1.66936	1.33064
18	3	20	21	18.8	26.1912	−7.3912	0.93	1.66936	−0.73936
19	3	21	24	26.63	28.8023	−2.1723	1.81	1.81116	−0.00116
20	3	22	25	25.66	31.4134	−5.7534	1.93	1.95295	−0.02295
21	3	23	27	35.63	34.0245	1.6055	2.16	2.09474	0.06526
22	3	24	28	34.59	36.6355	−2.0455	2.01	2.23653	−0.22653
23	3	25	29	31.54	39.2466	−7.7066	2.59	2.37832	0.21168
24	3	29	35	48.42	49.6909	−1.2709	2.69	2.94548	−0.25548
25	3	31	37	52.36	54.9131	−2.5531	3.12	3.22906	−0.10906
26	4.5	13	17	10.62	7.9137	2.7063	1.36	0.67683	0.68317
27	4.5	28	33	42.46	47.0799	−4.6199	2.73	2.80369	−0.07369
28	4.5	31	37	50.37	54.9131	−4.5431	3.32	3.22906	0.09094
29	4.5	32	38	62.98	57.5242	5.4558	3.57	3.37085	0.19915
30	4.5	32	38	50.37	57.5242	−7.1542	3.31	3.37085	−0.06085
31	4.5	38	47	83.97	73.1906	10.7794	4.32	4.22159	0.09841

Table 6 Empirical relationships among E_M, P_L and SPT (N_{60}) by several studies

Soil type	E_M/P_L	E_M	P_L	Researchers
Silty clay	12–21	E_M (kPa) = 388.67 (N_{60}) + 4554 $r = 0.91$	P_L (kPa) = 29.45 (N_{60}) + 219.7 $r = 0.97$	Yagiz et al. (2008)
Silty clay	– –	E_M (MPa) = N_{60}-2.67 $R^2 = 0.85$	P_L (MPa) = 0.05 × N_{60} + 0.42 $R^2 = 0.78$	Cheshomi and Ghodrati (2015)
Clayey soil	7–19	E_M (MPa) = 1.61 $(N_{60})^{0.71}$ $R^2 = 0.72$	P_L (MPa) = 0.26 $(N_{60})^{0.57}$ $R^2 = 0.67$	Bozbey and Togrol (2010)
Clayey soil	– –	E_M/Pa = 19.3 $(N_{60})^{0.63}$ $R^2 = 0.39$	–	Ohya et al. (1982)
Clayey soil	– –	E_M (MPa) = 0.29 $(N_{60})^{0.71}$ $R^2 = 0.74$	P_L (MPa) = 0.043 $(N_{60})^{1.2}$ $R^2 = 0.74$	Kayabaşı (2012)
Clayey soil	– –	E_M (MPa) = 2.611 (N_{60})−26.03 $R^2 = 0.914$	P_L (MPa) = 0.142 (N_{60})−1.166 $R^2 = 0.895$	This study

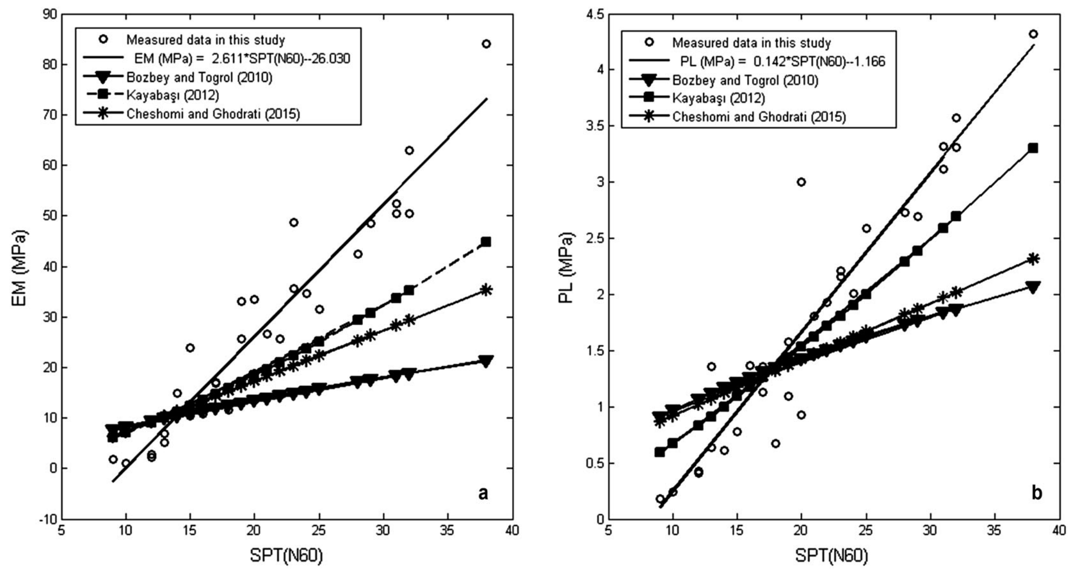


Fig. 7 Comparison of measured and calculated E_M and P_L value for clayey soils

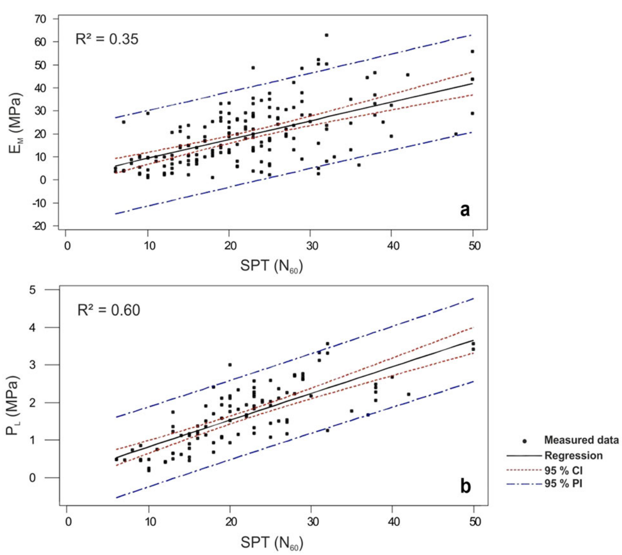


Fig. 8 Regression and confidence interval curves between **a** SPT (N_{60}) and E_M and **b** SPT (N_{60}) and P_L generated from the data regarding four studies

where; $k = 2(1 + \upsilon)(V_c + V_m)$.

In this equation, V_c and V_m values are the volume of the probe used in the pressuremeter, and the mean value of volume of the probe determined from the linear side of the pressuremeter curve, respectively.

Conclusion

In this study, the results of in situ tests (SPT and PMT) and laboratory tests were evaluated together in order to determine the relationship between SPT and PMT tests, which are commonly being used to determine the characteristics of clayey soils. High determination coefficients (R^2) showing the relationship between SPT and PMT test results suggest the use of SPT (N_{60}) values higher than ten for calculating E_M and P_L values.

The values of E_M and P_L obtained from PMT tests were compared with the values calculated using the developed formulas in this study and previously developed formulas by other researchers. Although all equations yield similar linear relationship between E_M and SPT (N_{60}) and P_L and SPT (N_{60}), the variation in the results suggests an increased number of the data set used. Since, the calculation of E_M depends on the Poisson ratio of soils, the determination coefficient calculated for the relationship between SPT (N_{60}) and E_M values was found to be lower than that calculated for SPT (N_{60}) and P_L values. Therefore, it is recommended to determine the Poisson ratio for each level separately when conducting PMT tests, for more accurate results. It is also recommended to establish multiple regression analysis among the SPT, PMT and the results of laboratory tests for determining the physical and mechanical characteristics of clayey soils.

Acknowledgements The authors thank Elif Özvan and Kemal Gezici for their support during different stages of this study. The authors also thank Dr. M. Nuri Almalı for his valuable help for evaluating the results of the statistical analysis.

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