Periodica Polytechnica
Civil Engineering

62(3), pp. 825–839, 2018
https://doi.org/10.3311/PPci.12063

TECHNICAL NOTES

Simple and Non-Linear Regression Techniques Used in Sandy-Clayey Soils to Predict the Pressuremeter Modulus and Limit Pressure: A Case Study of Tabriz Subway

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Received 30 January 2018; Revised 13 February 2018; Accepted 22 February 2018

Abstract

Nowadays, some common field tests consist of SPT test and pressuremeter test are performed in investigating the geotechnical parameters of projects such as tunneling. Due to the high cost of pressuremter test performance and its time-consuming procedure, using some empirical relations between SPT and Pressuremeter tests are recommended for primarily study of the project. The purpose of this study is to perform regression analyses between the N_{SPT} and the uniaxial compression strength test and the pressuremeter test parameters obtained from a geotechnical investigation performed in route of 2nd line of Tabriz metro. Correlations were carried out for sandy and clayey soils separately. A series of simple and nonlinear multiple regression analyses are performed and as a result of analyses, several empirical equations are developed. It is shown that the empirical equations developed in this study are statistically acceptable.

Keywords

pressuremeter modulus (E_M), SPT blow count (N_{SPT}), modulus of uniaxial compression strength (E_{UCS}), Tabriz subway

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1 Introduction

Prior to constructing engineering structures, it is essential to study their technical and economical situations. Studying generally includes ground and underground measurements. Stress-strain modulus of soil could be estimated by experimental methods such as uniaxial compression strength test (UCS) and triaxial compression test. Also, it is measured by in situ tests consist of standard penetration test (SPT), flat jack test, cone penetration test (CPT), dilatometer test, pressuremeter test and in situ plate loading test [35].

The pre-bored pressuremeter is an in place test procedure consists of positioning a cylindrical probe at depth into a pre-bored hole and then inflating the probe with either air or fluid while measuring the amount of fluid (assumed incompressible) introduced to the system and the resulting pressure in the probe [9,10]. These two measurements along with the probe geometry provide the information required to develop an in place stress-strain relationship for the soil at the location of the test (see Figure1). It was Kogler in the 1930s that developed the idea of installing equipment to the desired depth and measuring the deformation properties. However, difficulties arose in using and interpreting the results of the equipment developed by Kogler. The equipment was later developed by Menard in 1957 as the ‘‘Menard Pressuremeter’’ [39].

Standard penetration test (SPT) was first introduced in early 1900’s by driving an open end pipe into soil during wash boring process and it has become the most extensively used in situ test in site investigation practice. Originally, the test was used to determine the relative density of granular soils. The idea of the SPT at the beginning was the comparison of blows required to penetrate the tested soil. If the number of blows for a tested location was larger than another location, it was concluded that the denser soil is the one with the largest blow count. Although SPT had been performed only for granular soils in the past, it is executed in almost all kinds of soil today including weak rocks. In accordance with ASTM D1586 [4], a standard sampler is driven into the soil by the energy delivered from a 63.5 kg weight hammer having a free fall of 760 mm. For every 150 mm penetration of the sampler from the bottom of borehole, number of blow counts are recorded until a total distance of 450 mm is penetrated [4]. Number of blow counts required for the penetration of last 300 mm is added and it is referred as SPT N value. The number of blow counts recorded during the first 150 mm is ignored in order to prevent the adverse effects of disturbances during boring process on the test results. Test is usually stopped on the following conditions: 50 or more blows are required for a 150 mm penetration; 100 blows are obtained to drive the required 300 mm; and 10 successive blows produce no advance. SPT data have been used in correlations for unit weight, relative density, angle of internal friction and unconfined compressive strength (Figure 1a). However, it is recommended the measured N value is standardized by multiplying it by the ratio between the measured energy transferred to the rod and 60% of the theoretical free-fall energy of the hammer [7, 35].

The Unconfined Compression Test is a laboratory test method that is used to assess the mechanical properties of rocks and fine-grained soils. It provides a measure of the undrained, unconfined compressive strength as well as the stress-strain characteristics of rock, soil or other material specimen. This test provides the most direct means of determining a material's strength and is often included in the laboratory testing program of geotechnical investigations, especially when dealing with rocks. In general, the test can be conducted on rock samples or on undisturbed, reconstituted or compacted cohesive soil samples. In this test, cylindrical specimens are tested in compression without lateral confinement. The sample is loaded axially at a constant axial strain rate of about 0.5 to 2% per minute. The applied load and resulting deformation are measured with data acquisition system to generate load-deformation curves. The sample is loaded until it either (1) exceeds its unconfined compression strength (brittle failure) or (2) reaches 15% axial strain. At either state the sample is considered to be at failure. The axial stress at failure is the unconfined compressive strength (UCS) (Figure 1b). The load-deformation curves, typically plotted as axial strain vs. axial stress, can be used to define elastic properties of the material (elastic (Young's) modulus and Poisson's ratio [7, 21, 45, 51, 53].

The pressuremeter test measures the strength and deformation properties in terms of the relationship between the radial applied pressure and the resulting deformation. The test uses a cylindrical probe placed at the desired depth in a pre-bored hole. The pressuremeter dimensions have not been standardized, which may lead to errors when attempting to compare test data from different probes. Commonly a 76 mm diameter probe is used [9]. Figure 1c shows a diagram depicting the principles of the Menard pressuremeter test. Calibrations in the pressuremeter test is essential for obtaining accurate results from the test and if the calibrations are not carried out properly, then the data obtained from the test can be considered as useless. After the tests, volume changes recorded during the test are plotted against the pressure with considering the necessary corrections based on calibrations. A typical pressuremeter graph is shown as given in Figure 1d.The modulus of pressuremeter test utilized to compute the settlement of the soils was calculated using the theory of expansion of an infinitely thick cylinder as Equation (1). At the beginning of the test, probe expands rapidly inside the borehole without any resistance until the pressure reaches p_{0h} value. At the pressure p_{0h}, it is assumed that the membrane is in full contact with the sides of the borehole. p_{0h} value is often interpreted as total horizontal in situ stress. With further increase in the pressure, the slope of the pressure and volume curve becomes almost constant which is the result of elastic behaviour of soil and it is described as elastic range on the graph. After the pressure pf, permanent deformations and creep occur in the soil and the volumetric expansion increases significantly with the pressure. General ranges of the net limit pressure and pressuremeter modulus for sands and clays are summarized in Tables 1 and 2 [9, 13, 14, 15, 28, 29, 37, 38].

$$E_M = 2.(1+\mu).(V_0+V_m).(\Delta P/\Delta V) \quad (1)$$

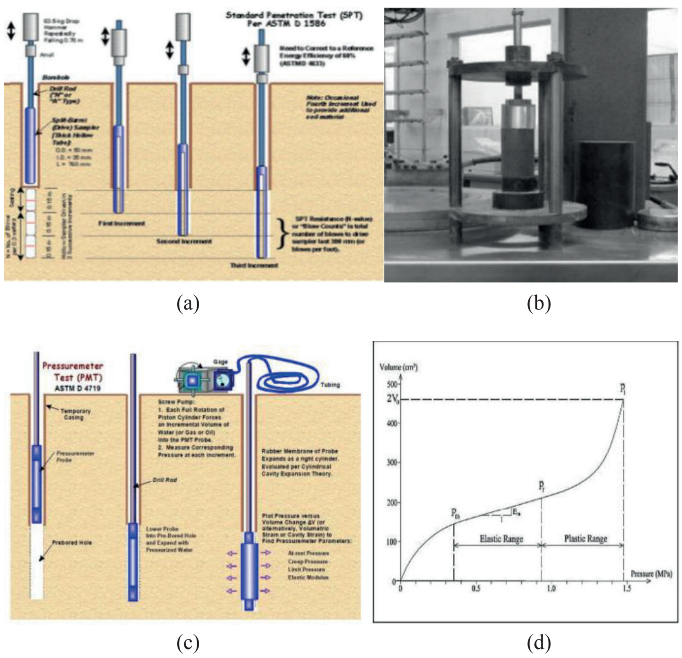


Fig. 1 Diagrams depicting the principles of the (a) SPT test, (b) UCS test, (c) Pressuremeter test and (d) a typical pressuremeter graph.

Table 1 Approximate common values of the pressuremeter parameters for sands

Soil Type	Loose	Compact	Dense	Very Dense
P_M (KPa)	0–500	500–1500	1500–2500	> 2500
E_M (KPa)	0–3500	3500–12000	12000–22500	>22500

Table 2 Approximate common values of the pressuremeter parameters for clays

Soil Type	Soft	Medium	Stiff	Very Stiff	Hard
P_M (KPa)	0–200	200–400	400–800	800–1600	>1600
E_M (KPa)	0–2500	2500–5000	5000–12000	12000–25000	>25000

Pressuremeter test equipment is sophisticated and expensive. However, SPT is a practical test and is used widely. Both tests have an important intersection in application area. Tough uniaxial compression test performed on undisturbed specimens in laboratory, the estimation of the pressuremeter modulus and the limit pressure from SPT blow counts and uniaxial compression test is useful to investigators. The application direction does not create a problem for isotropic soil conditions [44]. Also Lee and Rowe determined that anisotropy has little influence on the settlement of vertical loading to the ground surface. Considering the results of these studies, it is possible to say that the vertical loading condition of the SPT and uniaxial test results and the horizontal loading condition of the pressuremeter test may have little effect on the results [33].

Correlations between various soil parameters and the results obtained from the pressuremeter test and SPT have been reported by [1, 5, 6, 26, 32, 41]. Baguelin et al. [5, 6] proposed a relationship between shear strength and the pressuremeter parameters of soils, while Ohya et al. [41] investigated the relationship between the values obtained by SPT tests and the results of pressuremeter tests for various types of soils. Kulhawy and Mayne [32] reported relationships between the SPT blow count and E_M for both sand and clay soils, while Menard [40] conducted pressuremeter tests to integrate the parameters into foundation design. Schnaid et al. [43] stated that the pressuremeter test could be used to investigate the strengths of unsaturated soils in situ, since characterizing the properties of such soils using laboratory tests is complicated due to the effects of suction.

The very recent studies have been conducted by [8, 30, 54, 55]. Yagiz et al. [55] searched for relationships between SPT blow counts and E_{PMT} and P_L from pressuremeter results based on a study conducted in Denizli, Turkey. Their results were based on 15 readings carried out on shallow sandy silty clays (1.5–2 m). They found that linear relationships existed between the corrected SPT number and E_{PMT} and P_L in arithmetic axes. Also Bozbey and Togrol [8] studied the correlations between SPT and pressuremeter parameters. The authors [8] emphasized many difficulties arising from the disturbance of the soil, the drainage conditions and the level of strain during the drilling and testing processes. The proposed empirical equations for sandy and clayish soils have high coefficients of determination. Kayabasi in 2012 [30] investigated for relationships between SPT blow counts and E_{PMT} and P_L from pressuremeter results based on a study conducted in Mersin, Turkey. Their studied area was the foundation area consists of mainly clayey soils. Their regression analyses were carried out in three steps. In the first step, E_M and N_{60} as well as P_L and N60 values were correlated, and a good prediction performance was determined. In the second step of the regression analysis, the moisture contents (w%) were added to the equations as a second variable with N_{60} values, which resulted in a better performance relative to the first step of the statistical analysis. In the third step, the plasticity index (PI %) values were also added in the equations, and empirical equations estimating pressuremeter parameters from N_{60} values, moisture content (w, %) and the plasticity index (PI,%) were developed and non-linear multiple empirical equations with high regression coefficients extracted (Table 3) [11, 49,61–63].

Table 3 Existing empirical equations for E_M versus N Values and P_M versus N values

Reference	Equation	Coefficient of Determination
Cassan [11]	$P_L = 0.028N - 0.0021$ (kPa)	$R^2 = 0.53$
Hobbs and Dixon (1969)	$P_L = 0.021N - 0.33$ (kPa)	$R^2 = 0.90$
Wasachkowski(1976)	$P_L = 0.056N - 0.092$ (kPa)	$R^2 = 0.92$
Yagiz et al. [57]	$E_M = 388.67N_{cor} + 4554$(kPa) (sandy silty clayish soils)	$R^2 = 0.91$
	$P_L = 29.45N_{cor} + 219.7$(kPa) (sandy silty clayish soils)	$R^2 = 0.94$
Bozbey and Togrol [8]	$E_M = 1.33(N_{60})^{0.77}$ (MPa) (Sandy soils)	$R^2 = 0.82$
	$P_L = 0.33(N_{60})^{0.51}$ (MPa) (Sandy soils)	$R^2 = 0.74$
	$E_M = 1.61(N_{60})^{0.71}$ (MPa) (clayey soils)	$R^2 = 0.72$
	$P_L = 0.26(N_{60})^{0.57}$ (MPa) (clayey soils)	$R^2 = 0.67$
Kayabasi [30]	$E_M = 0.68PI - 0.014(N_{60})^{2.067} - 10.44\ln w + 23.82$	$R^2 = 0.79$
	$P_L = 2.7\ln PI - 0.00001(N_{60})^{3.4} + 52.39w^{-0.011} + 58.76$	$R^2 = 0.84$

2 Studied area

Tabriz with 160 Km^2 area and the population about 2 million is one of the most crowded and important cities in the northwest of Iran. According to the city transportation studies, 4 metro lines with total length of 70 Km were considered. The case study of this paper is the 2nd line of Tabriz metro, which consists of a metro system with the length of 22 Km of 9.45 meter diameter tunnel and 20 stations. The line is started from the Qaramalek in the west of the city and ended in Tabriz International Exhibition in the east of Tabriz (Figure 2). Also the line is routed through the downtown of a major metropolitan area and beneath the crowded city streets and adjacent to high raised and important buildings. Previous researches see [59, 60]

Primarily geotechnical study of 2nd line is performed by drilling 53 boreholes and 17 wells. Also to study the complementary geotechnical research of this line, 92 boreholes and 3 wells have been drilled. Due to the route changes of the 2nd line in some parts of the project, among the information of 102 boreholes, 65 boreholes selected to investigate which 40 boreholes were clayey and other 25 boreholes were sandy. Information of these selected boreholes shown in Tables 4 and 5. Drilling of the boreholes is done by OGB and SKB4 rotary drilling equipment. To investigate the layers condition and ground resistance, SPT had been done in all boreholes. In addition, in different depth of the boreholes, other tests had been done such as pressuremeter test, penetration test, shear velocity wave test and permeability test. Also during drilling some samples transported to the laboratory to test physical, mechanical and chemical tests on them. These tests consists of grain size distribution, hydrometry, Atterberg limits, bulk unit weight test, natural moisture content test, G_s, uniaxial compression test, triaxial test and shear test.

The in situ tests showed that the mean value of the pressuremeter modulus (E_M) for sandy soils is determined as 24.77 MPa and a standard deviation of 6.97 MPa, and for clayish soils is 23.93 MPa and a standard deviation of 10.91 MPa, respectively. Also the minimum pressuremeter modulus (E_M) for sandy and clayish soils is 13.5 and 10.6 MPa, respectively, and its maximum value for sandy and clayish soils are 37 and 57.5 MPa, respectively. Limit pressure (P_L) obtained from the pressuremeter tests for sandy soils have the mean, minimum and maximum values of 3.86, 2.2 and 5.4 MPa, respectively.

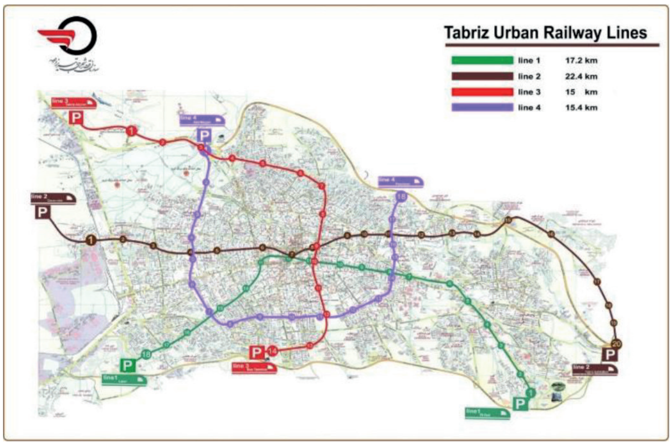
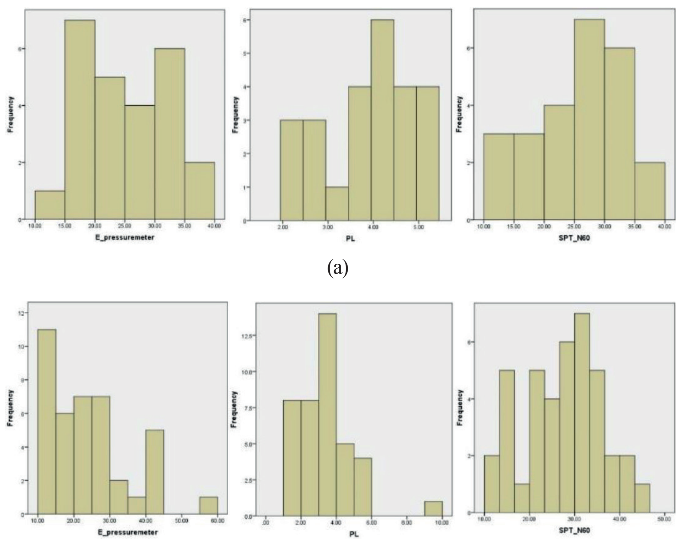


Fig. 2 Tabriz urban railway lines



(a)

(b)

Fig. 3 Histograms of the in situ test data (a) sandy soil and (b) clayey soil (pressuremeter modulus (E_M), limit pressure (P_L) and corrected SPT blow count (N_{60}))

Also the mean, minimum and maximum values of Limit pressure for clayish soils are 3.3, 1.1 and 9 MPa, respectively. The histogram of the E_M, P_L and SPT_N_{60} values for sandy and clayey soils are given in Figure 3. The degree of soil consolidation was described by Baguelin et al in 1978 [5] with the E_M/P_L ratio. The mean value of E_M/P_L obtained in this study for sandy and clayish soils are approximately 10 and 9.5, respectively. So the values show that the 2nd line of the metro is normally consolidated.

Laboratory tests were applied on both disturbed (SPT samples) and undisturbed samples taken from the boreholes. Uniaxial compression strength of the samples for sandy soils ranges between 1.5 and 8.5 and clayish soils between 1.5 and 12 MPa. The plasticity index (PI) for clayish soils ranges between 9 and 37.2%. The results of the natural moisture content tests for clayish soils showed minimum, maximum and mean values of 14, 32 and 21.38 respectively.

3 Analysis

Regression analyses have been used for a long time in environmental geology and geotechnics [12, 23, 27, 30, 36, 46, 48, 56]. To conduct a safe regression analysis, four stages stablished. Regression analysis was performed in two stages for sandy soils

Table 4 The measured soil parameters of sandy boreholes.

Borehole	SPT_ raw	SPT_N_{60}	Measured E_M(Mpa)	EUCS (Mpa)	Measured P_L (Mpa)	PI %	W %
BH3	33	24.7	31.5	3.8	4.6	13	21
BH4	39	37.4	36.5	8.5	5.3	20	18
BH7	48	36.5	37	6.5	5	24	20
BH22	26	18.1	17.5	3.5	2.5	10.5	23
BH26	34	26.3	34.5	4.5	3.8	13	18
D2B2	44	25.2	22.5	3	4	11	22
DH3	36	25	18.5	2	2.3	23	24
DH9	28	20.2	19.5	4	2.7	24	26
DH17	25	21	26	3	4.1	10	18
DH20	50	33	30.5	4.4	4.6	3	27
I2B1	50	30	27.5	3.5	4.6	9	17
J2B2	50	33.1	30.4	8	5.4	20	16
L2E6	38	30	32	5	4.2	22	21
L2E11	19	14.5	22.5	5.5	3.2	28	22
O2B2	16	13	16	1.5	2.5	12	24
NW9	29.5	26.4	23	5.4	4.3	12.3	18
NW1	31	27.3	23.4	4.8	3.7	13	16
NW2	31	27	31	6	4.2	12.5	16
BH21	32	18.5	15.5	3.5	4.1	18	21
BH20	40	25.4	19	3	3.5	15	14
DH16	10	12.5	15.4	2.2	2.4	16	17
K2B2	50	32.5	27	4	4.5	25	17
BH5	37	23.4	21	4.4	3.7	22	19
L2E3	23	17	13.5	3.3	2.2	16	19
L2E14	45	32.7	28	6.2	5	17	12

Table 5 The measured soil parameters of clayey boreholes.

Borehole	SPT_ raw	SPT_N_{60}	Measured E_M (Mpa)	EUCS (Mpa)	Measured P_L(Mpa)	PI %	W %
B2B1	50	27.5	22	1.5	3.66	17	24
BH2	33	23.8	14.5	3.5	2.1	20	17
BH9	49	46.5	57.5	6.3	5.3	28	23
BH14	50	35.5	18.5	3.5	3.5	20	22
BH16	16	13.2	13	1.5	1.5	11	23
BH17	34	27.3	14.7	4	3	21.5	17
BH23	47	30	16.5	2	2.1	14.5	19
BH25	23	16.4	19.6	4.2	3.5	14.4	21
C2B1	25	15	12.5	2.5	1.7	10.5	20
DH2	30	21	13.5	5	1.5	11	17
DH4	20	13	12	1.5	1.4	9	14
DH5	50	29	25.5	3	3.5	16.4	24
DH7	33	19	21	3.3	2.6	16	21
DH8	33	20	14	4	1.8	15	22
DH21	36	21.1	13.8	2	3.6	22	17
DH27	50	33.7	21.5	6	4.4	27.4	23
E2B1	20	15.8	10.6	2.5	1.1	21.5	17
H2B1	41	24.7	16.7	3.5	2.6	16	20
L2E2	38	33.4	25	4.5	2.5	16	18
L2E12	43	32.7	27	6.5	3.3	18	23
L2E13	48	40.6	44	9.5	4.8	37.2	27
L2E21	34	29	23.5	5.5	2.4	26	22
L2E22	50	40.2	40	8	5.7	30.5	32
L2EB4	42	30.5	22	2	3.3	14.7	22
L2EB7	50	33.2	35	9	4.4	33	26
L2W1	25	16.5	12.5	3	1.5	9	17
N2B2	50	33.8	26.5	5	3.6	21	20
NE1	36	25.5	22	6.5	3.2	22	21
NE2	50	29.7	28.4	7.5	3.1	28	23
NE3	50	30.3	19.5	5	3.3	23.4	19
NW7	38	30	20.5	6	2.7	26	24
NW8	25	20.7	18.5	5.5	2.6	24	22
P2B2	50	38.5	43	9	4.4	32.7	25
Q2B1	50	37	43.5	12	9	32	24
R2B2	48	35.5	40	6.5	5	28.5	28
BH18	12	15	13	1.5	1.7	9	18
L2E16	34	28.5	30	3.5	3.7	15.5	19
L2E19	33	24.7	33.5	4.5	5	25	20
S2B1	50	33	25	5	4.4	27	21
NW4	28	23.3	27.5	4.5	3.6	17	23

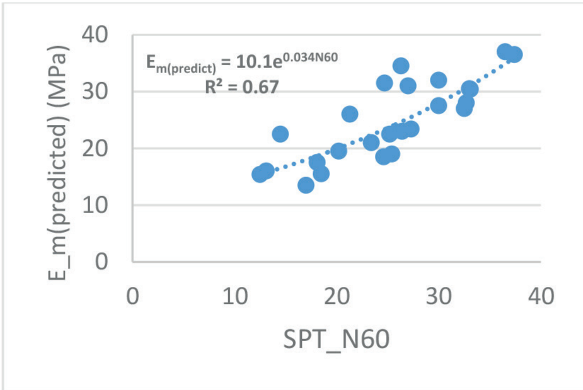
and four stages for clayish soils to obtain the best and most efficient empirical relations. Regression analysis was undertaken using a commercial software package (SPSS 2002) [52].

As a first stage, regression analysis were performed to obtain empirical relations between the pressuremeter modulus (E_M) and the corrected SPT blow counts (N_{60}) for sandy soil which the results of the regression analysis are shown in Table 6. The equation with the highest coefficient of the regression between N_{60} and E_M is represented by an exponential function (Figure 4a, Equation 2). For checking this regression model, residual analysis were applied and the Durbin Watson value for sandy soil was obtained 1.65 (Figure 4b).

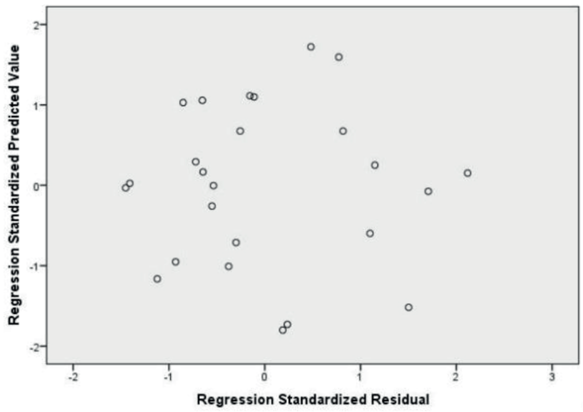
$$E_{M\_(predicted)} = 10.1\exp(0.034N_{60})\ \text{MPa} \quad (R^2 = 0.67) \tag{2}$$

Table 6 Summary of simple regressions between pressuremeter modulus (E_m) and corrected standard penetration test (SPT_N_{60}) for sandy soils

Linear	Power	Exponential	Logarithmic
$E_{M\_(predicted)} = 0.803N_{60} + 4.517$ $R^2 = 0.66$	$E_{M\_(predicted)} = 2.085(N_{60})^{0.764}$ $R^2 = 0.64$	$E_{M\_(predicted)} = 10.1\exp(0.034N_{60})$ $R^2 = 0.67$	$E_{M\_(predicted)} = 17.81\ln(N_{60}) - 31.96$ $R^2 = 0.62$



(a)



(b)

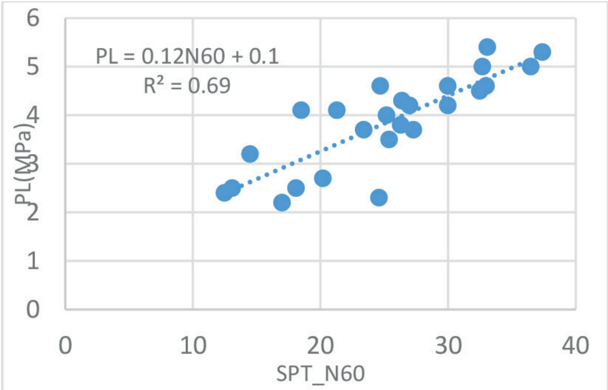
Fig. 4 a) correlation of E_M and N_{60} values in sandy soils, b) Residual analysis result for E_M - N_{60} relationship

The same procedures are applied for SPT (N_{60}) values versus Limit Pressure (P_L) values (Table 7). The highest coefficient of the regression between SPT and PL is represented by a linear function (Figure 5a, Equation 3). Also for checking this regression model, residual analysis were applied and the Durbin Watson value for sandy soil was obtained 2.1 (Figure 5b).

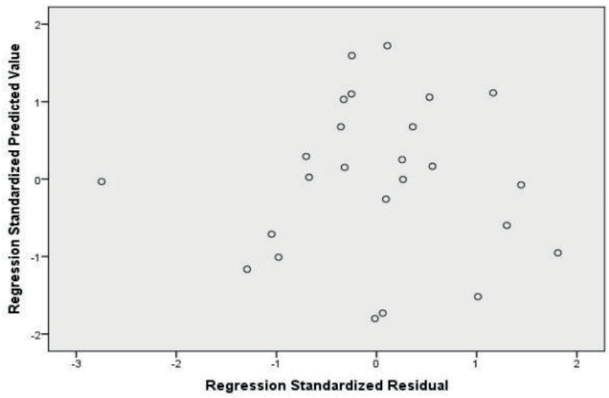
$$P_{L\_(predicted)} = 0.12N60 + 0.1\ \text{MPa} \quad (R^2 = 0.69) \tag{3}$$

Table 7 Summary of simple regressions between pressuremeter modulus (P_L) and corrected standard penetration test (SPT_N_{60}) for sandy soils

Linear	Power	Exponential	Logarithmic
$P_{L\_(predicted)} = 0.12N_{60} + 0.1$ $R^2 = 0.69$	$P_{L\_(predicted)} = 0.38(N_{60})^{0.716}$ $R^2 = 0.64$	$P_{L\_(predicted)} = 1.679\exp(0.031N_{60})$ R2 = 0.65	$P_{L\_(predicted)} = 2.57\ln(N_{60})\text{-}4.319$ $R^2 = 0.66$



(a)

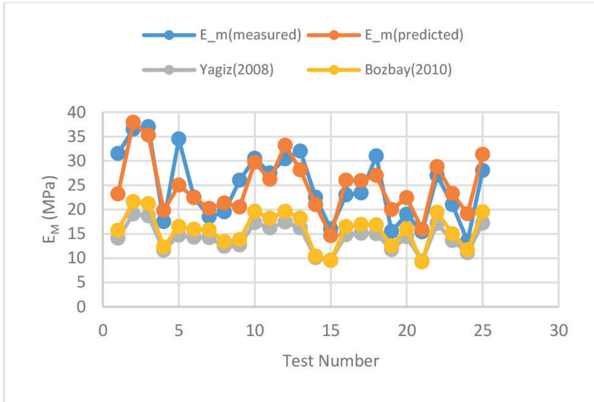


(b)

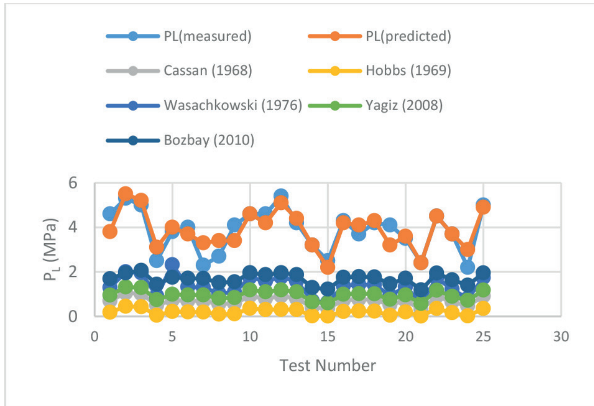
Fig. 5 a) correlation of PL and N60 values in sandy soils, b) Residual analysis result for PL - N60 relationship

The root mean square error (RMSE) indices and values accounted for (VAF) are calculated to qualify the prediction performance of the equations for simple regression analysis, as performed by previous researchers [2, 16, 18, 19, 56, 57]. An excellent prediction is represented with 0 in RMSE values and 100% in VAF values. The equation developed from this study for sandy soils gives a close RMSE value to 0 and VAF value to 100%. So value of RMSE and VAF in sandy soils is 3.9 and 76.4%, respectively. Also using the N_{60} values and the previously proposed equations for P_L, the P_L values are predicted. So RMSE and VAF value for this equation are calculated 0.55 and 71.3%, respectively (Figure 6a and 6b).

Though unconfined compression strength test (UCS) is a laboratory test and performed on disturbed and undisturbed samples which obtained from the boreholes, the values obtained from this test are somewhat representation of soil strength and stiffness and deformation capability characteristics. So results of unconfined compression strength test could be correlated with the pressuremeter parameters and the SPT. The UCS results of the SPT samples, N_{60} values, pressuremeter modulus (E_M) and limit pressure (P_L) values are graphed for sandy soils, and the curves of each parameter are inspected with a trend line (Figure7).



(a)



(b)

Fig. 6 Comparison of the measured and estimated values of a) E_M and b) P_L, estimated from other empirical equations for sandy soils

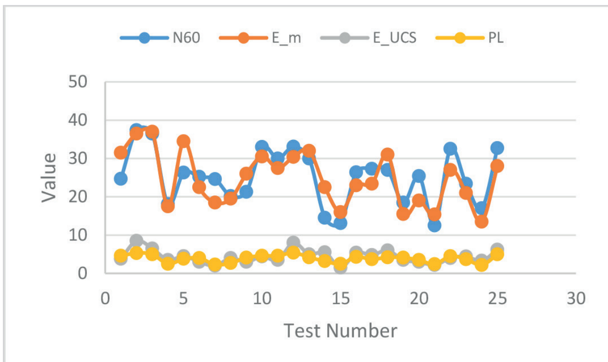


Fig. 7 Trending graph of the correlated parameters in sandy soils

In the second stage of sandy soils statistical studies, the correlations between pressuremeter parameters and the SPT and UCS are evaluated together. At first the SPT and UCS defined as the function of pressuremeter parameters:

$$f(SPT, E_{UCS}) = E_M \tag{4}$$

$$f(SPT, E_{UCS}) = P_L \tag{5}$$

A simple regression analysis between the measured pressure modulus (E_M) with the E_{UCS} gives Eq. (6) with a linear relationship (Figure 8a). So non-linear multiple regression will be more suitable than the linear multiple regression which similar procedures were followed by Yagiz et al. [57]; Dagdelenler et al. [16] and Kayabasi [30] when developing multiple regression equations.

$$E_M = 2.8219E_{UCS} + 12.41 \text{ MPa} \quad (R^2 = 0.49) \tag{6}$$

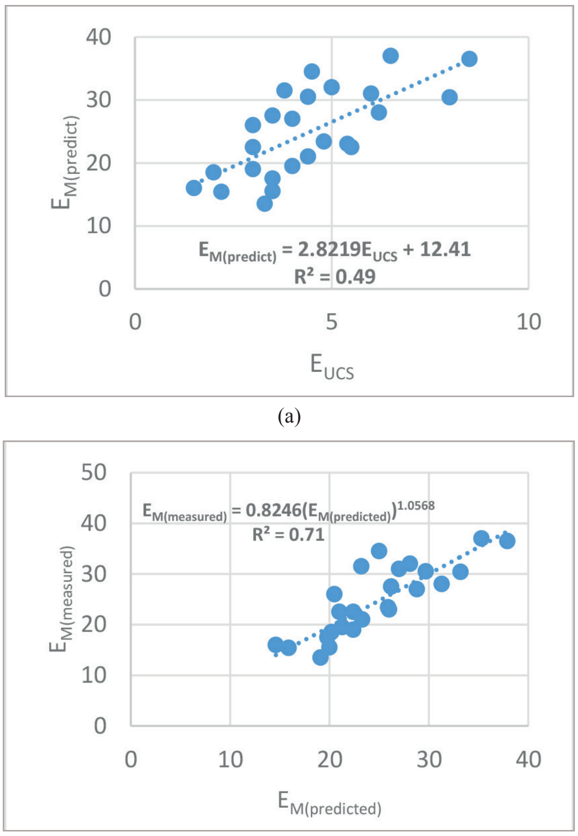
Combination of Equations 2 and 6 can be defined as follows: $E_M = b_1\text{Exp}(b_2 N_{60}) + b_3 \text{ EUCS}^{b4} + b_5$

Where b_i (i = 1,5) are the coefficients of the nonlinear multiple regression equation. The following equation for predicting the pressuremeter modulus is obtained by applying a nonlinear regression analysis using the SPSS:

$$E_{M(predict)} = 2.222\text{Exp}(0.058N_{60}) + 12.252\text{UCS}^{0.281} - 3.898 \text{ MPa} \tag{7}$$

The coefficient of determination (R^2) between $E_{M(measured)}$ and $E_{M(predicted)}$ from Equation (7) is 0.71, which is nearly the same coefficient of determination as Equation (2) (Figure 8b).

$$E_{M(measured)} = 0.8246\, E_{M(predicted)}^{1.0568} \text{ MPa} \quad (R^2 = 0.71) \tag{8}$$



(a)

(b)

Fig. 8 Correlation of a) E_M and E_{UCS} and b) $E_{M(measured)}$ and $E_{M(Predicted)}$ with two variables in sandy soils

Also the correlation of the measured limit pressure (P_L) and the E_{UCS} give Equation (9) (Figure 9a):

$$P_L = 1.71\text{Ln}(E_{UCS}) + 1.5 \text{ MPa} \quad (R^2 = 0.53) \tag{9}$$

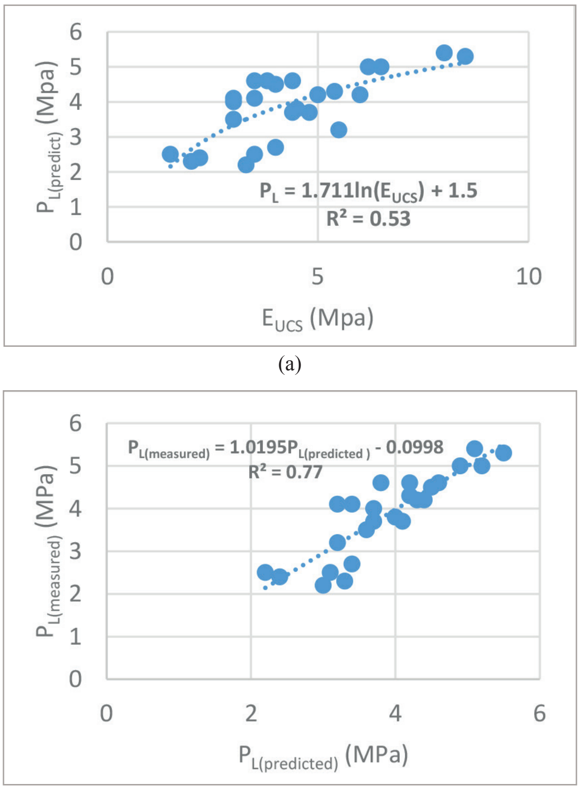
The combination of Equations 3 and 9 can be expressed with the following equation:

$$P_L = b_1\text{Ln}(E_{UCS}) + b_2 N_{60}^{b3} + b_4 \tag{10}$$

Where b_i (i = 1,4) are the coefficients of the equation. Equation (11) is obtained by employing a nonlinear statistical regression analysis:

$$P_{L(predict)} = 0.72\text{Ln}(E_{UCS}) + 0.034N_{60}^{1.23} + 1.06 \text{ MPa} \tag{11}$$

The $P_{L(predict)}$ data derived from Equation (11) and the $P_{L(measured)}$ values correlated with the basic regression analysis results in a regression coefficient (R^2) of 0.77, which is nearly the same as the coefficient of determination of Equation (3) (Figure 9b).



(a)

(b)

Fig. 9 Correlation of a) P_L and E_{UCS} and b) $P_{L\,(measured)}$ and $P_{L\,(Predicted)}$ with two variables in sandy soils

3.1 Development of empirical models for clayish soils

As the procedure of sandy soils, the correlation of pressuremeter parameters are performed with the SPT and UCS results for clayish soils. In addition to the SPT and UCS, two another parameters, moisture content (W%) and plasticity index (PI%), employed to correlate with the pressuemeter parameters. The reason for employing the correlation of these two parameters is related to time dependent of deformation of the clayish soils. As known, the clayish soils have a time for deformation during the pressuremeter test, but could not deform due to the sudden falling of the SPT hammer and the driving of a head in the soil. Therefore, the measured blow counts are of the resistance of the soil, not its deformability and plasticity during the application of the SPT test. A pressuremeter test takes at least 10 min, depending on the increasing pressure on the test materials. The selected pressures are applied on borehole walls with time intervals. Thus, the stress strain and the strength behavior of the material are characterized. The behavior of the test material is much better determined by the pressuremeter test than the SPT. The moisture content and plasticity index results of the SPT samples, UCS values, N_{60} values, pressuremeter modulus (E_M) and limit pressure values are graphed, and the curves of each parameter are inspected with a trend line (Figure 10). Considering the characteristics of pressuremeter test and SPT test, in clayey soils the sensitivity of pressuremeter test is much more than SPT test. The moisture content variation and plasticity index influence the pressuremeter test results more than the SPT blow counts. These differences arise from the test time differences between tests. Also Comparison of the measured and estimated values of E_M and P_L and estimated from other empirical equations for sandy soils are shown in (Figure 11a and 11b).

In clayish soils, a first stage, regression analysis were performed to obtain empirical relations between the pressuremeter modulus (E_M) and the corrected SPT blow counts (N_{60}) which the results of the regression analysis are shown in Table 8. The equation with the highest coefficient of the regression between N_{60} and E_M is represented by an exponential function (Figure 12a, Equation 12). For checking this regression model, residual analysis were applied and the Durbin Watson value for clayey soil was obtained 2.22 (Figure12b).

$$E_{M\_(predict)} = 6.76Exp(0.05N_{60})\ MPa \quad (R^2 = 0.70) \tag{12}$$

Table 8 Summary of simple regressions between pressuremeter modulus (E_m) and corrected standard penetration test (SPT_N_{60}) for clayey soils

Linear	Power	Exponential	Logarithmic
$E_{M\_(predicted)} = 1.066N_{60} + 5.191$ $R^2 = 0.66$	$E_{M\_(predicted)} = 0.733(N_{60})1.042$ $R^2 = 0.65$	$E_{M\_(predicted)} = 6.76exp(0.05N_{60})$ $R^2 = 0.70$	$E_{M\_(predicted)} = 24.92ln(N^{60})–57.26$ $R^2 = 0.57$

The same procedures are applied for SPT (N_{60}) values versus Limit Pressure (P_L) values (Table 9). The highest coefficient of the regression between SPT and PL is represented by a power function (Figure 13, Equation 13). Also for checking this regression model, residual analysis were applied and the Durbin Watson value for sandy soil was obtained 1.9 (Figure 13a).

$$P_{L\_(predict)} = 0.1N_{60}^{1.06}\ MPa\ (R^2 = 0.62) \tag{13}$$

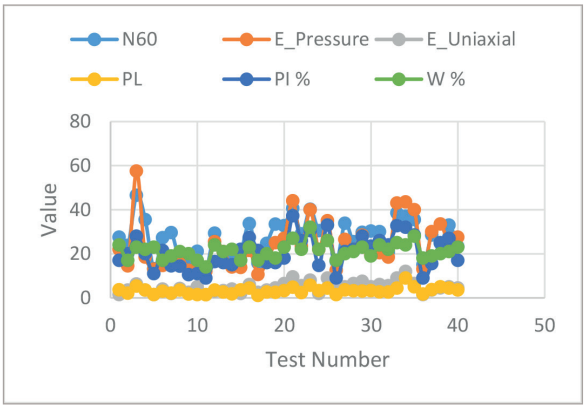
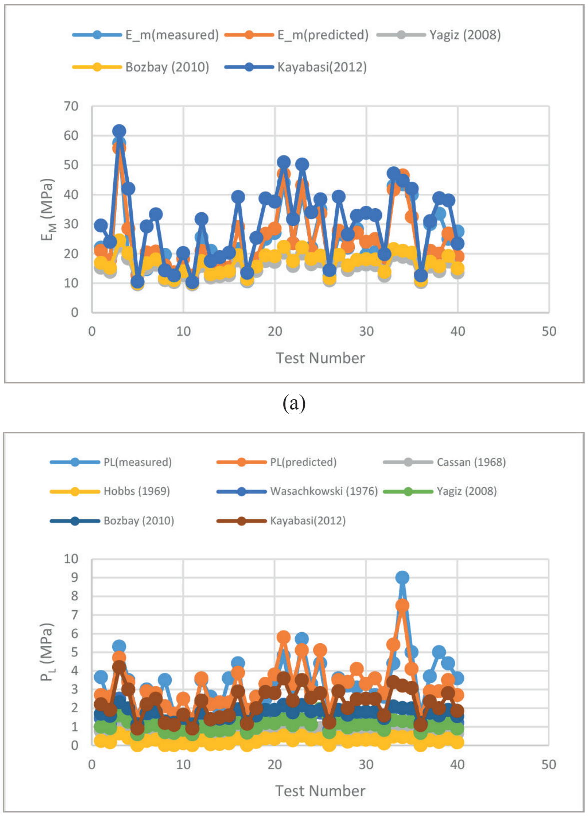


Fig. 10 Trending graph of the correlated parameters in clayey soils



(a)

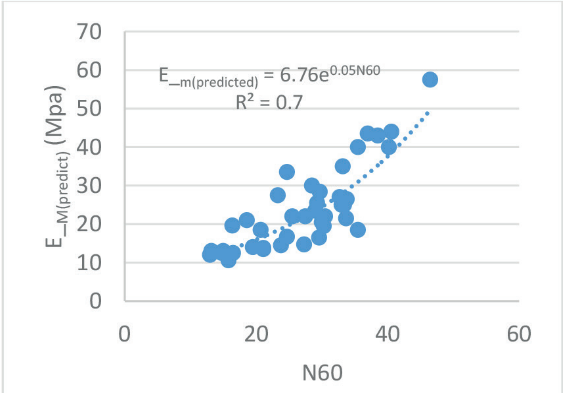
(b)

Fig. 11 Comparison of the measured and estimated values of a) E_M and b) P_L, estimated from other empirical equations for clayey soils

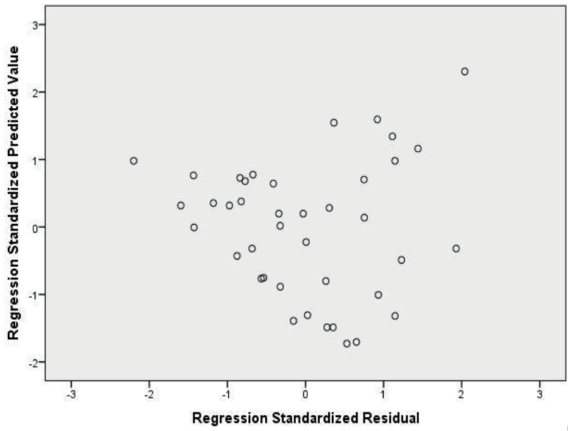
Table 9 Summary of simple regressions between pressuremeter modulus (P_L) and corrected standard penetration test (SPT_N_{60}) for clayey soils

Linear	Power	Exponential	Logarithmic
$P_{L\_(predicted)} = 0.13N_{60} + 0.24$ $R^2 = 0.52$	$P_{L\_(predicted)} = 0.1(N_{60})1.06$ $R^2 = 0.62$	$P_{L\_(predicted)} = 0.949exp(0.042N_{60})$ $R^2 = 0.61$	$P_{L\_(predicted)} = 3.165ln(N_{60})-7.012$ $R^2 = 0.49$

The equation developed from this study for clayey soils gives a close RMSE value to 0 and VAF value to 100%. So value of RMSE and VAF in clayey soils is 5.51 and 68.8%, respectively. Also using the N_{60} values and the previously proposed equations for P_L, the P_L values are predicted. So RMSE and VAF value for this equation are calculated 0.77 and 67.3%, respectively (Figure 13b).

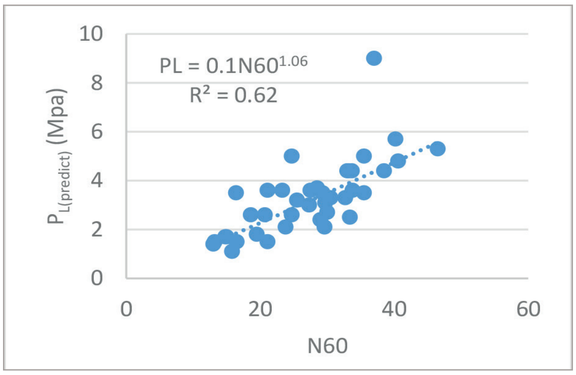


(a)

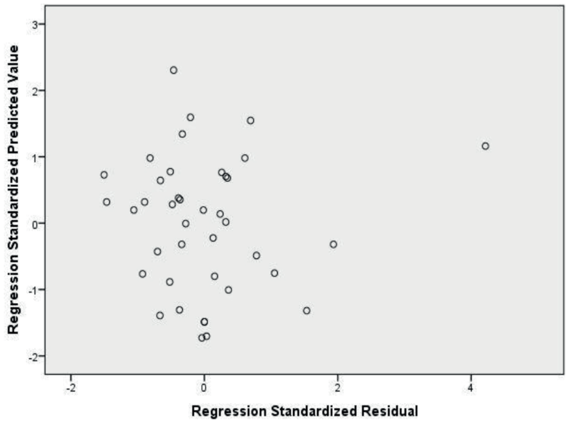


(b)

Fig. 12 a) correlation of E_M and N_{60} values in sandy soils, b) Residual analysis result for E_M - N_{60} relationship

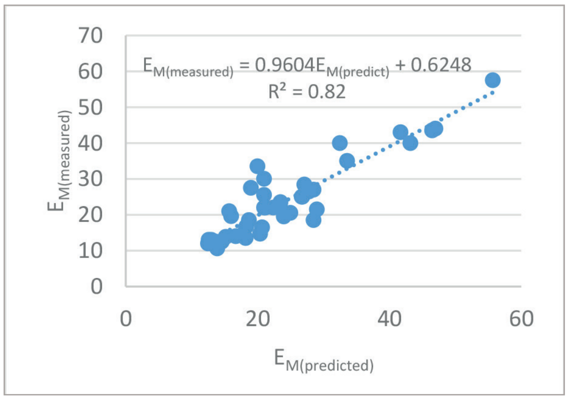


(a)

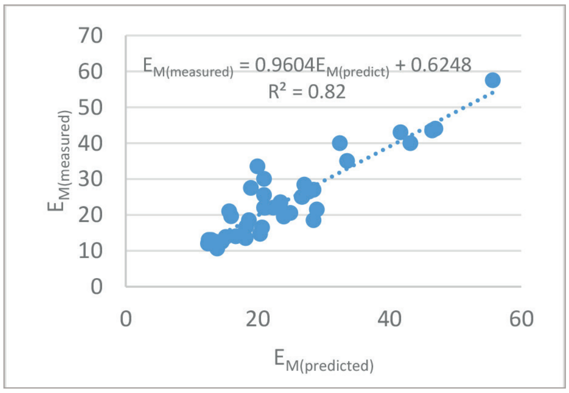


(b)

Fig. 13 a) correlation of P_L and N_{60} values in clayey soils, b) Residual analysis result for P_L - N_{60} relationship



(a)



(b)

Fig. 14 Correlation of a) E_M and E_{UCS} and b) $E_{M(measured)}$ and $E_{M(Predicted)}$ with two variables in clayey soils

In the second stage of clayey soils statistical studies, the correlations between pressuremeter parameters and the SPT and UCS are evaluated together. At first the SPT and UCS defined as the function of pressuremeter parameters:

$$f(SPT,E_{UCS}) = E_M \tag{14}$$

$$f(SPT, E_{UCS}) = P_L \tag{15}$$

A simple regression analysis between the measured pressure modulus (E_M) with the E_{UCS} gives Eq. (16) with a exponential relationship (Figure. 14a). So non-linear multiple regression will be more suitable than the linear multiple regression.

$$E_M = 11.8Exp(0.13\ E_{UCS})\ MPa \quad (R^2 = 0.56) \tag{16}$$

Combination of Equations 12 and 16 can be defined as follows:

$$E_M = b_1Exp(b_2N_{60}) + b_3Exp(b_4E_{UCS}) + b_5 \tag{17}$$

Where b_i (i = 1,5) are the coefficients of the nonlinear multiple regression equation. The following equation for predicting the pressuremeter modulus is obtained by applying a nonlinear regression analysis using the SPSS:

$$E_{M(predict)} = 0.67Exp(0.09N_{60}) + 4.92Exp(0.13\ E_{UCS}) + 4.40\ MPa \tag{18}$$

The coefficient of determination (R^2) between $E_{M(measured)}$ and $E_{M(predicted)}$ from Equation (18) is 0.82, which is greater than the same coefficient of determination as Equation (12) (Figure14b).

$$E_{M(measured)} = 0.9604E_{M(predicteded)} + 0.6248 \text{ MPa} \quad (R^2 = 0.82) \tag{19}$$

Also the correlation of the measured limit pressure (P_L) and the E_{UCS} give Equation (20) (Figure 15a):

$$P_L = 0.44\, E_{UCS} + 1.22 \text{ MPa} \quad (R^2 = 0.52) \tag{20}$$

The combination of Equations 13 and 20 can be expressed with the following equation:

$$P_L = b_1 N_{60}^{b2} + b_3 E_{UCS}^{b4} + b^5 \tag{21}$$

Where b_i (i = 1,5) are the coefficients of the equation. Equation (22) is obtained by employing a nonlinear statistical regression analysis:

$$P_{L(predict)} = 0.12N_{60}^{0.93} + 0.0006\, E_{UCS}^{4.48} + 0.41 \text{ MPa} \tag{22}$$

The $P_{L(predict)}$ data derived from Equation (22) and the $P_{L(measured)}$ values correlated with the basic regression analysis results in a regression coefficient (R^2) of 0.66, which is nearly the same as the coefficient of determination of Equation (13) (Figure 15b).

In the third stage of clayey soils statistical studies, the correlations between pressuremeter parameters and the SPT and UCS and moisture content (w%) are evaluated together. So the pressuremeter parameters are defined as a function of three variables as follows:

$$f(SPT, E_{UCS}, w) = E_M \tag{23}$$

$$f(SPT, E_{UCS}, w) = P_L \tag{24}$$

A simple regression analysis between the measured pressure modulus (E_M) with the w% gives Eq. (25) with an exponential relationship (Figure 16a). So non-linear multiple regression will be more suitable than the linear multiple regression.

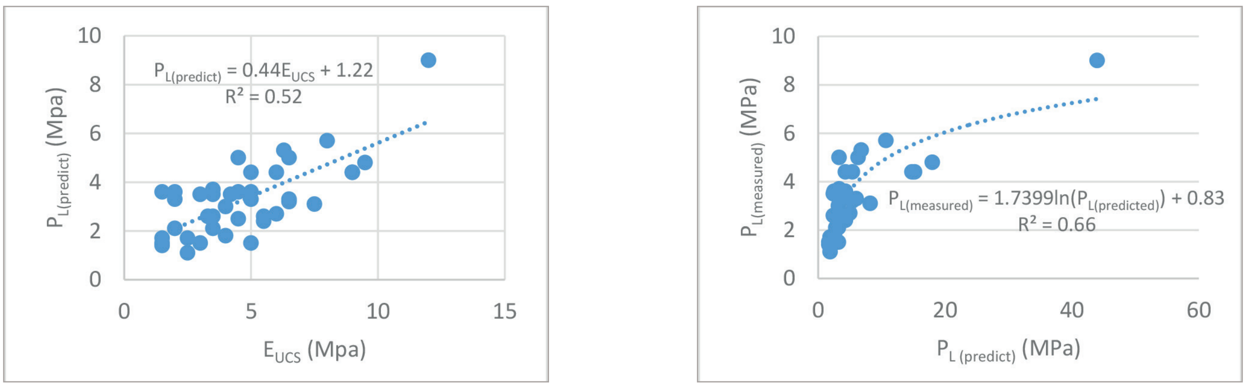
$$E_{M(predict)} = 0.074\, w^{1.867} \text{ MPa} \quad (R^2 = 0.51) \tag{25}$$

The combination of Equations 12, 16 and 25 can be defined as Eq. (26) where b_i (i = 1,7) are the coefficients of the equation:

$$E_M = b_1 Exp(b_2\, N_{60}) + b_3 Exp(b_4\, E_{UCS}) + b_5\, w^{b6} + b_7 \tag{26}$$

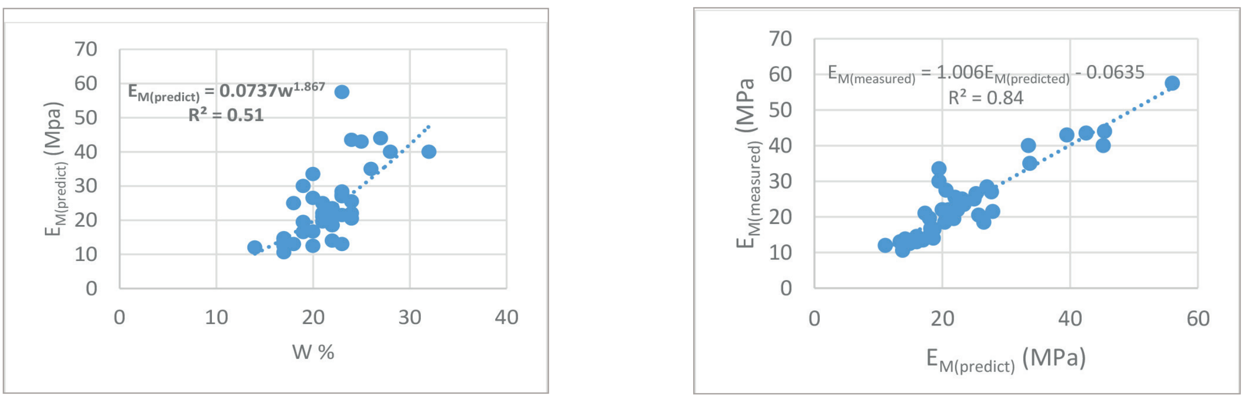
Performing the nonlinear analysis with three variables versus the pressuremeter modulus gives Eq. (27):

$$E_M = 0.17Exp(0.115N_{60}) + 6.78Exp(0.1\, E_{UCS}) + 0.225w^{1.235} - 3.35 \tag{27}$$



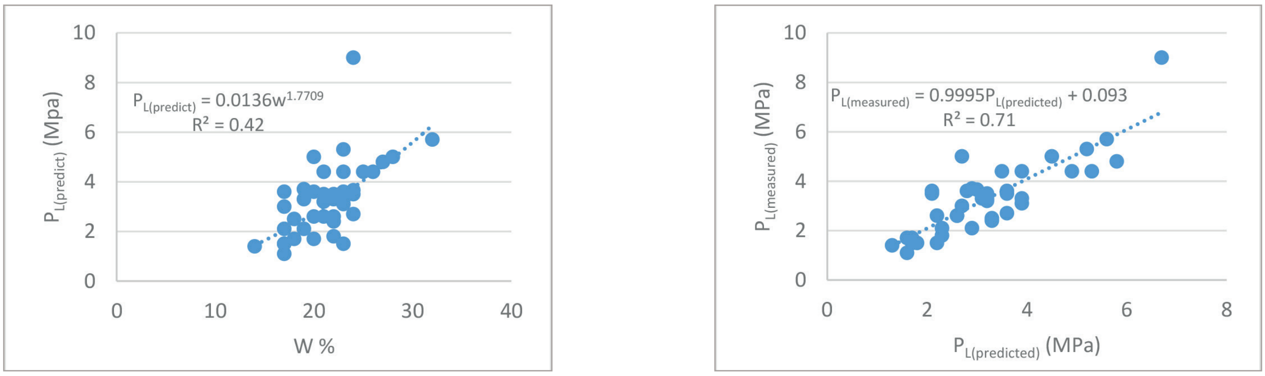
(a) (b)

Fig. 15 Correlation of a) P_L and E_{UCS} and b) $P_{L\,(measured)}$ and $P_{L\,(Predicted)}$ with two variables in clayey soils



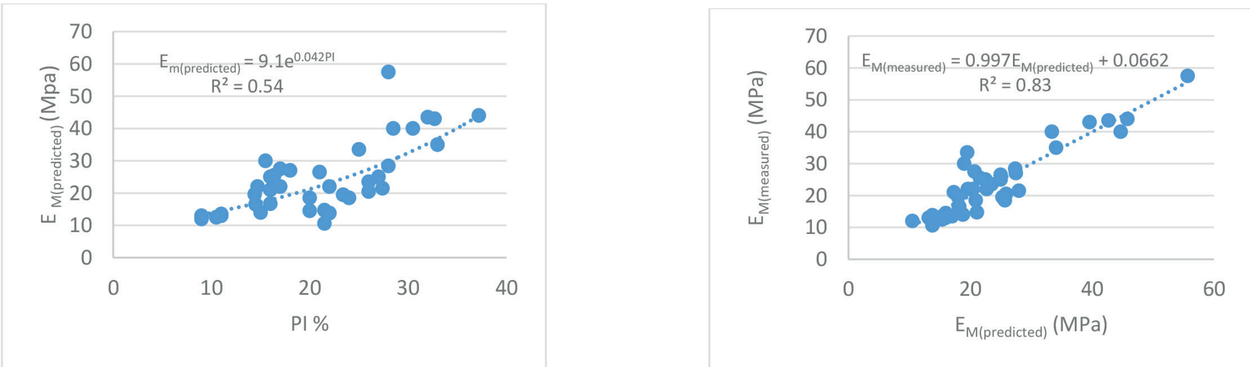
(a) (b)

Fig. 16 Correlation of a) E_M and w% and b) $E_{M(measured)}$ and $E_{M(Predicted)}$ with three variables in clayey soils



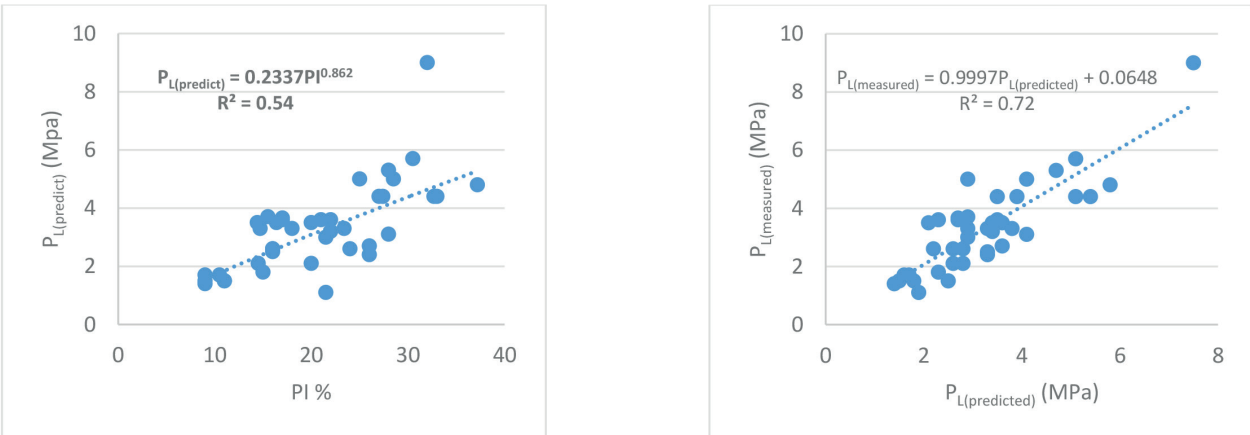
(a) (b)

Fig. 17 Correlation of a) P_L and w% and b) $P_{L\ (measured)}$ and $P_{L\ (Predicted)}$ with three variables in clayey soils



(a) (b)

Fig. 18 Correlation of a) E_M and PI% and b) $E_{M(measured)}$ and EM(Predicted) with four variables in clayey soils



(a) (b)

Fig. 19 Correlation of a) P_L and PI% and b) $P_{L(measured)}$ and $P_{L\ (Predicted)}$ with four variables in clayey soils

The coefficient of determination (R^2) between $E_{M(measured)}$ and $E_{M(predicted)}$ from Equation (27) is 0.84, which is greater than the same coefficient of determination as Equations (12) and (16) (Figure 16b).

Second the correlation of the measured limit pressure (PL) and the w% gives Equation (28) with a power relationship as follow (Figure 17a):

$$P_L = 0.014w^{1.77} \text{ MPa} \quad (R^2 = 0.42) \tag{28}$$

The combination of Equations 13, 22 and 28 can be expressed with the following equation:

$$P_L = b_1 N_{60}^{b2} + b_3 E_{UCS}^{b4} + b_5 w^{b6} + b_7 \tag{29}$$

b_i (i = 1,7) are the coefficients of the equation. Equation (30) is obtained by performingnonlinear statistical regression analysis with a three variables versus the measured limit pressure:

$$P_L = 0.03N_{60}^{1.25} + 0.003\ E_{UCS}^{2.77} + 0.013w^{1.394} \tag{30}$$

The $P_{L(predict)}$ data derived from Equation (30) and the $P_{L(measured)}$ values correlated with the basic regression analysis results in a regression coefficient (R^2) of 0.71, which is greater than the same as the coefficient of determination of Equations (13) and (22) (Figure 17b).

In the fourth stage of clayey soils statistical studies, the correlations between pressuremeter parameters and the SPT, E_{UCS}, moisture content (w%) and plasticity index (PI%) are evaluated together. So the pressuremeter parameters are defined as a function of four variables as follows:

$$f(SPT, E_{UCS}, w, PI) = E_M \tag{31}$$

$$f(SPT, E_{UCS}, w, PI) = P_L \tag{32}$$

A simple regression analysis between the measured pressure modulus (E_M) with the PI% gives Equation (33) with a exponential relationship (Figure 18a). So non-linear multiple regression will be more suitable than the linear multiple regression.

$$E_{M(predict)} = 9.1Exp(0.042PI) \;\; MPa \quad (R^2 = 0.54) \tag{33}$$

The combination of Equations 12, 16, 25 and 33 can be defined as Equation (34) where b_i, (i = 1, 9) are the coefficients of the function with four variables versus pressureneter modulus (E_M):

$$E_M = b_1Exp(b_2 N_{60}) + b_3Exp(b_4 E_{UCS}) + b_5 w^{b6} + b_7Exp(b_8PI) + b_9 \tag{34}$$

Performing the nonlinear analysis with four variables versus the pressuremeter modulus gives Equation (35):

$$E_M = 0.113Exp(0.123N_{60}) + 9.28Exp(0.085E_{UCS}) + 2.05w^{0.71} + 0.04Exp(0.09PI) - 14.04 \tag{35}$$

The coefficient of determination (R^2) between $E_{M(measured)}$ and $E_{M(predicted)}$ from Equation (35) is 0.83, which is greater than the same coefficient of determination as Equations (12), (16) and (25) (Figure 18b).

The correlation of the measured limit pressure (P_L) and the w% give Equation (36) with a power relationship as follow (Figure 19a):

$$P_L = 0.2337PI^{0.862} \; MPa \quad (R^2 = 0.54) \tag{36}$$

The combination of Equations 13, 22, 30 and 36 can be expressed with the following equation:

$$P_L = b_1 N_{60}^{b2} + b_3 E_{UCS}^{b4} + b_5 w^{b6} + b_7 PI^{b8} + b_9 \tag{37}$$

Where b_i (i = 1,9) are the coefficients of the equation. Equation (38) is obtained by performingnonlinear statistical regression analysis with a four variables versus the measured limit pressure:

$$P_L = 0.368N_{60}^{0.62} + 0.007 E_{UCS}^{2.56} + 0.041w^{0.385} + 0.246PI^{0.34} - 1.0 \; (MPa) \tag{38}$$

The $P_{L(predict)}$ data derived from Equation (38) and the $P_{L(measured)}$ values correlated with the basic regression analysis results in a regression coefficient (R^2) of 0.72, which is greater than the same as the coefficient of determination of Equations (13), (22) and (30) (Figure 19b).

Table 10 summarizes the empirical equations derived in this study. The high regression coefficients in all the equations are noteworthy. In fact, in both sandy and clayey soils, the main parameter controlling E_M and P_L is the N_{60}. The increase in input parameters does not dramatically increase the model performance. However, the deformability and strength of soils are strongly affected by their physical states. For this reason, the multiple regression equations, including uniaxial compression strength, moisture content and the plasticity index are important because they represent the mechanical and physical state of the soils. In practical use, the simple regression equation including only N_{60} can be used. However, if the user has additional parameters, such as modulus of uniaxial compression strength, moisture content and the plasticity index, then the results can be controlled by employing the multiple regression equations.

Table 10 Empirical equations derived in this study

Equation	Soil Type	Coefficient of Determination
$E_{M\_(predicted)} = 10.1exp(0.034N_{60})$ MPa	Sand	$R^2 = 67$
$E_{M(predict)} = 2.222Exp(0.058N_{60}) + 12.252UCS_{0.281} - 3.898$ MPa	Sand	$R^2 = 71$
$E_{M\_(predict)} = 6.76Exp(0.05N_{60})$ MPa	Clay	$R^2 = 70$
$E_{M(predict)} = 0.67Exp(0.09N_{60}) + 4.92Exp(0.13 E_{UCS}) + 4.40$ MPa	Clay	$R^2 = 82$
$E_M = 0.17Exp(0.115N_{60}) + 6.78Exp(0.1 E_{UCS}) + 0.225w^{1.235} - 3.35$	Clay	$R^2 = 0.84$
$E_M = 0.113Exp(0.123N_{60})+9.28Exp(0.085E_{UCS}) + 2.05w^{0.71} + 0.04Exp(0.09PI) - 14.04$	Clay	$R^2 = 0.83$
$P_{L\_(predicted)} = 0.12N_{60} + 0.1$ MPa	Sand	$R^2 = 0.69$
$P_{L(predict)} = 0.72Ln(E_{UCS}) + 0.034N_{60}^{1.23} + 1.06$ MPa	Sand	$R^2 = 0.77$
$P_{L\_(predict)} = 0.1N_{60}^{1.06}$ MPa	Clay	$R^2 = 0.62$
$P_{L(predict)} = 0.12N_{60}^{0.93} + 0.0006 E_{UCS}^{4.48} + 0.41$ MPa	Clay	$R^2 = 0.66$
$P_L = 0.03N_{60}^{1.25} + 0.003 E_{UCS}^{2.77} + 0.013w^{1.394}$	Clay	$R^2 = 0.71$
$P_L = 0.368N_{60}^{0.62} + 0.007 E_{UCS}^{2.56} + 0.041w^{0.385} + 0.246PI^{0.34} - 1.0$ (MPa)	Clay	$R^2 = 0.72$

4 Conclusions

The standard penetration test has been widely used as in situ test for estimating the soil properties of fine granular soils (up to gravel size). The pressuremeter test can be used for the same purposes in almost all soils and weak rocks, although it is comparatively expensive and time-consuming.

It can be stated that the many commonly used correlations in the geotechnical practice to estimate the geotechnical parameters from in situ tests contain a certain amount of inaccuracy. The reasons for this result can easily be related to quality of the in situ and laboratory tests. In addition, there is also a more important reason that affects the obtained results which is the heterogenous nature of the soil. Therefore, applicability of these correlations should be evaluated in detail and the reasonability of the results should be checked with other available correlations. On the other hand, this study proves once more that the cross correlations between in – situ test parameters still involves a large amount of uncertainties as presented by many researchers and they should not be preferred unless there is not any other data available. Aside from the mentioned issues above, the accuracy of the evaluated correlations can be increased by more carefully performed and well controlled in–situ testing, borehole sampling and laboratory testing. In this way, some of the uncertainties can be reduced and the reliability of the correlations would be enhanced.

In order to develop a relationship between SPT and pressurmeter parameters values, data obtained from an area of sandy clayey soils in the 2nd line of Tabriz metro. The SPT and pressuremeter test data, which were obtained from the same borehole and at the same meters of the depth, were correlated and Satisfactory relationships with acceptable regression coefficient were obtained between E_M and both N_{60} and P_L. The regression analyses were carried out in two steps for sandy soils and four steps for clayey soils. In the first step, E_M and N_{60} as well as P_L and N_{60} values were correlated and a good prediction performance was determined. The relationship between modulus of uniaxial compression strength (E_{UCS}) and pressuremeter parameters were determined with simple regression analysis in sandy soils. Also the relationship between modulus of uniaxial compression strength (E_{UCS}), moisture content (w%) and plasticity index (PI%) and pressuremeter parameters were determined with simple regression analysis in clayey soils. In the second step of the regression analysis, both in sandy and clayey soils, the modulus of uniaxial compression strength (E_{UCS}) were added to the equations as a second variable with N_{60} values, which resulted in a better performance relative to the first step of the statistical analysis. In the third step, in the clayey soils, the w% values were also added in the equations, and empirical equations estimating pressuremeter parameters from N_{60} values, modulus of uniaxial compression strength (E_{UCS}) and moisture content (w%) were developed. In the fourth step, in the clayey soils, the PI% values were also added in the equations, and empirical equations estimating pressuremeter parameters from N_{60} values, modulus of uniaxial compression strength (E_{UCS}), moisture content (w%) and plasticity index (PI%) were developed. All of the derived equations have high regression coefficients. The performance of previous empirical equations was also tested with the SPT blow counts of this study, and the estimated E_M and P_L values of the previous equations were correlated with the measured E_M and P_L values of this study. The results were also found to be within acceptable limits.

Major difficulties occur in assessing appropriate soil parameters due to such factors as the degree of disturbance caused during testing, drainage conditions and levels of strains imposed during in situ testing as well as the wide variety of soil types, drilling equipment and testing conditions and procedures. In this context, correlations may help designers to evaluate, compare, interpret or cross check the soil parameters obtained from different field tests. Despite these difficulties, the empirical equations in this study result in high regression coefficients. To interpret one empirical equation as the general equation, countless data must be correlated. The same statistical analysis must be carried out on the numerous parameters of SPT and Pressuremeter tests by a group of experts and a general equation that could be acceptable by all engineers must be evaluated. Otherwise, every project could produce independent empirical equations derived from their own data correlations.

For the characterization of the physical and mechanical state of the sandy and clayey soils employed in the present study, the E_{UCS}, PI and water content are used as the input parameters during the multiple regression analyses. However, the empirical equations introduced in this study may be useful for the preliminary design stages of civil engineering projects. However, the obtained results would not correspond to the exact values of the in situ pressuremeter parameters or the SPT blow counts. The parameters calculated with these empirical equations could be used to obtain advance information about soil conditions (see also [61]).

Acknowledgement

The authors would like to thank the Iman Sazan Consulting Engineering Company and Tabriz metro Organization for technical and financial support that made this research available.

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