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An Empirical Approach to Estimate E_{PMT} and P_L of Silty Clays based on SPT

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Abstract

The use of in-situ soil testing has become popular in many geotechnical projects because of its high measurement accuracy and low disturbance of the soil sample during the testing process. Pressuremeter Test (PMT) and standard penetration test (SPT) are two important in-situ tests in geotechnical engineering. The former is an expensive and time-consuming experiment that can measure some detailed mechanical properties of soil while the latter is low-cost and can estimate some basic soil specifications. Thus, identifying the relationship between PMT and SPT parameters can help improve the mechanical characterization of soil samples through a cost-saving methodology. In this research, 47 SPT and 47 PMT were performed on very stiff and hard silty clay and clay soil samples. The variation range of E_{PMT} and the N_{60} are in the range of 16.55-75.95 MPa and 16-51, respectively. Empirical equations were proposed between E_{PMT}-N_{60}, P_L-N_{60}, and E_{PMT}-P_L with $R^2 \geq 0.65$. Regression analysis by determining 'R^2', '*Sig.*', and '*F*' values demonstrated that the proposed models are highly significant and strongly meaningful. The Mean Square Error (MSE) and Root Mean Square Error (RMSE) values for each relation showed that the estimation error is very small, and the relationships are acceptable. The equations proposed in this research can be used for very stiff and hard silty clay and clay soil types. Also, by comparing the N_{60} and E_{PMT}/P_L values, silty clay and clay soil were classified in terms of consistency according to E_{PMT}/P_L ratio. Finally, the results from this study were grouped and compared with those reported earlier, leading to a practical advisory methodology for the estimation of PMT parameters from the SPT data applicable to a wide range of soil samples.

Keywords

Pressuremeter Modulus; Limit Pressure; SPT; PMT

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Introduction

Over the past few decades, in-situ soil testing has become more popular compared to laboratory experimentation mainly because of its high measurement accuracy and low disturbance caused in the soil sample during the testing process (Salgado, 2008). Pressuremeter test (PMT) is one of the most important in-site soil testing methodologies in this regard. The test was initially developed by Ménard (1956) for the determination of in-situ horizontal stress, undrained shear strength, deformation modulus, and permeability of soils. A pressuremeter device is a cylindrical membrane that is placed inside a borehole such that it inflates due to an increase in the fluid pressure and leads to a borehole volumetric change. A graph of change in the volume versus the pressure can then be plotted for the estimation of limit pressure (P_L), the pressuremeter modulus (E_{PMT}), and the total horizontal stress (σ_{H0}).

The PMT results are conventionally interpreted from the loading pressure-expansion data; however, Ferreira and Robertson (1994) introduced a method to interpret PMT data from the loading and unloading portions of PMT results. Winter (1982), Briaud and Gambin (1984), and Mair and Wood (1987) proposed a standard practice for the accurate preparation of borehole to conduct PMT followed by performing the PMT. Briaud et al. (1983) carried out several strain-controlled PMTs on clayey, sandy, and gravel soils and concluded that E_{PMT} can be obtained from PMT at any strain level with one unloading-reloading cycle. Nasr (1988) developed a new technique to interpret the undrained shear strength of clayey soils using PMT results in which vertical stress and excess pore pressure were deployed. The predicted undrained shear strength by Nasr (1988) had a 5% deviation from those obtained from the triaxial laboratory test. Haberfield and Johnston (1989) carried out several triaxial experiments using a modified triaxial cell to simulate PMT in soft rock. Haberfield and Johnston (1989) found that the development of two or three radial cracks along the length of the specimen can lead to its failure and thus, an increase in the effective confining pressure can result in a ductile behaviour. Elton (1981) evaluated the effect of elastic tube strength on the E_{PMT} and confirmed that a variation in the resistance of tubes has a negligible impact on the E_{PMT}. Huang et al. (1991) and Silvestri (2004) conduced several PMT on clayey soils and reported that the strain rate and disturbance in soils have a significant impact on the shear modulus and the undrained shear strength of clayey soils. Fawaz et al. (2002) analyzed the relationship between the magnitude of deformation and pressuremeter moduli numerically and experimentally to estimate P_L and distortion modulus. Monnet and Allagnat (2005) developed a technique to estimate the elastic shear modulus and the angle of internal friction of granular soils using PMT. Agan and Unal (2013) used PMT to estimate the sliding surface of landslide and demonstrated a good agreement between the failure zone estimated by the inclinometer and that predicted by PMT. Also, Oge (2018) and Omar et al. (2018) determined the deformation modulus and tensile strength in weak rock mass using a pressuremeter test. Kincal and Koca (2019) investigated the relationship between the E_{PMT} in the andesitic rock mass and the values of elastic modulus of intact rock core specimens. Tu (2018) determined the coefficient of horizontal subgrade reaction with the pressuremeter test. Oztoprak et al. (2018) proposed a numerical methodology for capturing the complete curve of a pressuremeter test. In another study, Silvestri and Tabib (2018) analyzed field test results obtained by pressuremeter tests in a sensitive clay of Quebec. Tarawneh et al. (2018) estimated E_{PMT} and P_L from the CPT test for desert sand and compared them with the results of the pressuremeter test. Ecemis (2020) measured shear-wave velocities (*Vs*) from the SCPTs and investigated how fines content and soil-type affect the correlation between *Vs* and liquefaction resistance. Moreover, Cabalar et al. (2018 & 2019) studied the influences of size and shape of sand grains mixed with clay on Vs and showed that both the unconfined compressive strength values of the specimens with angular sand grains were measured to be lower than those with rounded sand grains. Cheshomi et al. (2020) conducted 44 PMT and uniaxial tests on very stiff to hard saturated clayey soils and proposed a linear empirical equation between undrained shear strength (*Su*) and limit pressure (P_L). They showed that total horizontal stress (σ_H) had a nonsignificant effect on the proposed relationship. Li and Tang (2019) investigated the influences of low fines content and fines mixing ratio on the undrained static shear strength of sand-silt-clay mixtures.

PMT is an expensive in-situ experiment that is less performed in conventional geotechnical projects (Charif and Najjar, 2012). In comparison, standard penetration test (SPT) is a low-cost in-situ testing methodology that is routinely conducted in the geotechnical projects to determine basic soil properties, including density, shear strength, and deformation modulus. According to the American Society for Testing and Materials (ASTM: D1586 1999), the SPT and split-barrel sampling of fine-grained soils can be divided into various sub-groups based on SPT-N values (Table 1). Bowles (1997) suggested that the value of measured *N* in SPT should be standardized through a ratio between the measured energy transferred to the rod, and 60% of the theoretical energy of the hammer.

Table 1 Classification of fine-grained soils based on SPT-N value reported by ASTM: D1586 1999.

SPT-N Value	Consistency
<2	Very soft
3-4	Soft
5-8	Medium Stiff
9-15	Stiff
16-30	Very stiff
>30	Hard

Some studies have proposed some empirical relationships for the estimation of PMT parameters (for example, P_L and E_{PMT}) from SPT data. Ohya et al. (1982) developed a linear empirical model between E_{PMT} and N value for clayey soils. Yagiz et al. (2008) performed some SPTs and PMTs on loose, medium, and dense fine-grained soils obtained from western Turkey and yielded some relationships between N_{cor} (corrected SPT blow count) and E_{PMT} as well as P_L. Bozbey and Togrol (2010) carried out an extensive experimental investigation to develop some empirical equations for estimating $\mathrm{P_L}$ and $\mathrm{E_{PMT}}$ through SPT blow counts (N) for sandy and clayey soils. Kayabasi (2012) conducted 52 SPT and 52 PMT on medium, stiff, and very stiff clayey soil. Based on the obtained results, this researcher proposed two empirical relationships for the estimation of P_L and E_{PMT} through N_{60}. Agan and Algin (2014) performed 70 PMT and 77 SPT on clayey soil to evaluate the relationship between PMT and SPT. Cheshomi and Ghodrati (2015) examined silty sand and silty clay soils to examine the relationship between SPT and PMT. In another study, Özvan et al. (2018) carried out 34 SPT and 34 PMT on soft to firm clay soil. Ziaie Moayed et al. (2018) provided a set of relationships between the standard penetration number ($\mathrm{N_{SPT}}$) derived from the SPT values of the pressuremeter modulus ($\mathrm{E_{PMT}}$) and the limit pressure ($\mathrm{P_L}$) obtained from the pressuremeter tests. Zaki et al. (2020) presented an empirical relationship between $\mathrm{E_{PMT}}$ and $\mathrm{N_{60}}$ and unload-reload modulus (E_{ur}) and N_{60} for sandy silt soil.

In the present study, 47 SPT and 47 PMT were carried out on very stiff to hard lean silty clay and clay soil. The energy efficiency of 60% blow count (N_{60}) was used to perform SPT as recommended by Bowles (1997). $\mathrm{P_L}$ and E_{PMT} were estimated from the PMTs conducted on the soil samples. Some empirical models were developed for P_L and E_{PMT} as a function of N_{60}. Next, an empirical equation was proposed between P_L and E_{PMT}. These relationships were evaluated using statistical methods. After that, the selected silty clay and clay soils were classified in terms of consistency according to P_L/E_{PMT} ratio. Eventually, a comparative study was conducted, including the results from this study along with those reported earlier, which led to some practical recommendations.

Materials and Method

Qom is a city located 148 km southwest of Tehran, Iran (34.6416° N, 50.8746° E). In this study, extensive geotechnical studies have been conducted for subway construction in line with a length of 15 km. In this project, 18 boreholes have been drilled at various depths ranging between 25 and 50 m followed by 46 SPT and 46 PMT. Fig. 1 presents the location area and route of the study. Based on the drilled borehole and subsurface conditions, the length of the route can be divided into four segments (a, b, c, and d) that are shown in Fig 1. Along the study rout, five layers can be identified. Description of these layers based on laboratory tests and in situ observation in test pits are presented in Table 2. These soils are composed of sandy gravel and gravelly sand, silty clayey sand, silty clay, and clayey silt. The studied layers in this research are mainly silty clay and clayey silt (L-2 and L-3) according to the unified soil classification system (USCS). Figs. 2a and 2b illustrate the PMT device, the drilling machine, and the SPT device used in this study. Also, Fig. 2c shows an example of a sample box.

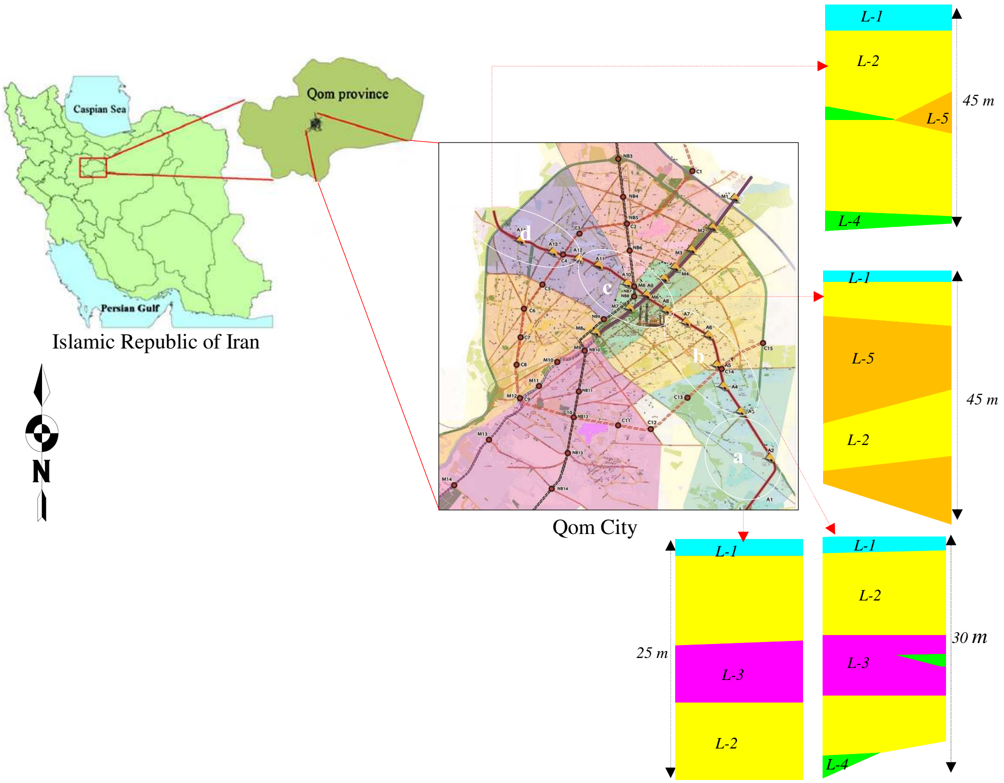
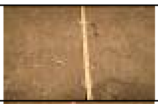
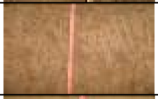
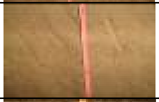
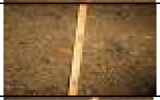


Figure 1. Location of site and subway route under study and subsurface soil condition in the subway route.

Table 2. Description and some physical specification of soil layers.

Layer No.		Description	PI	USCS
L-1		Filled Soil		
L-2		Silty CLAY ((Passing 200 > 65% and PI>7)	< 7	CL-ML, ML
L-3		Clayey SILT (Passing 200 > 65% and PI<7)	7-26	CL
L-4		Sandy GRAVEL and gravelly SAND (Passing 200 = 5-20%)		GP-GC GW-GM
L-5		Silty clayey SAND with gravel		SC-SM SC


a b c

Figure 2. (a) PMT device, (b) drilling machine and SPT device and (c) samples taken from borehole drilling.

PMT was performed according to ASTM D4719. The utilized device was a pre-boring pressuremeter of GC type (Bagelin et al., 1978) for dense and stiff soils. The experiments were carried out using a stress-controlled method having uniform pressure steps (2 to 3 bar) while volume was variable per step at 30 and 60 seconds. Pressure-volume curves from PMT were plotted to estimate the P_L and E_{PMT} values for each sample. SPT was also performed according to ASTM D1586. Based on Bowles' (1997) recommendation, all the measured N values were corrected to N_{60}.

Results and Discussion

Test Results

Initially, P_L and E_{PMT} were estimated from PMT, and then through SPT, the N_{60} values were obtained. The obtained PMT and SPT results are presented in Table 3.

Table 3. PMT and SPT parameters of tested soil at different depths.

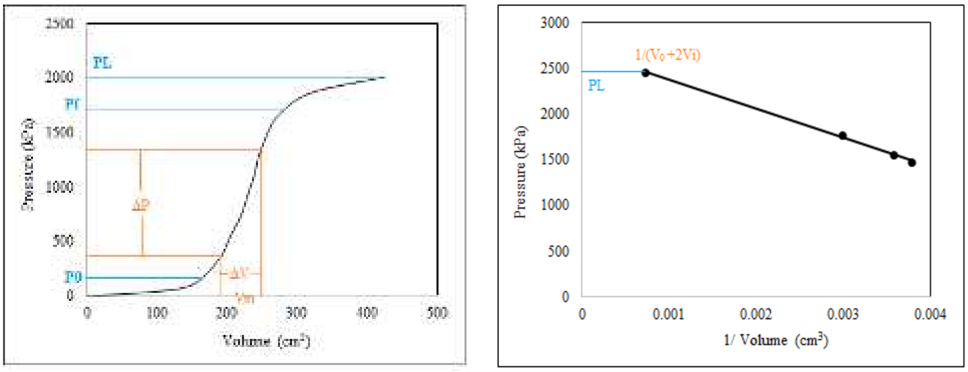
BH No	D (m)	Soil type	N_{60}	E_{PMT}(MPa)	P_L(MPa)	E_{PMT}/P_L
BH-1	10	Silty clay	45	65.17	3.34	19.51
	16		27	49.98	3.58	13.95
BH-2	22	Clay	23	32.24	3.38	9.53
	5		31	39.00	2.28	17.13
	16		26	48.02	2.17	22.11
BH-3	23	Clay	16	33.71	2.38	14.17
	5	Silty clay	37	54.00	3.50	15.45
	16	Clay	25	49.98	2.42	20.62
BH-4	23	Silty clay	21	38.71	2.46	15.76
	10	Clay	20	27.24	1.84	14.83
	16		27	31.36	2.46	12.74
BH-5	23	Clay	39	73.89	3.31	22.33
	8		16	29.79	2.01	14.80
BH-6	15	Clay	21	34.30	2.66	12.88
	8		29	39.00	2.79	13.99
	16		18	24.21	2.28	10.61
	25		20	45.77	3.14	14.56
BH-8	8	Clay	27	43.81	2.38	18.40
	16		51	74.97	4.43	16.94
	24	Silty clay	39	41.45	3.44	12.04
BH-9	32	Silty clay	40	56.84	3.73	15.25
	16	Clay	30	30.09	2.79	10.80
	24		36	47.14	2.80	16.81
BH-10	32	Silty clay	37	41.94	3.73	11.25
	8	Clay	16	17.35	1.39	12.47
	16		41	64.09	3.17	20.24
	24	Silty clay	27	36.65	3.13	11.70
BH-11	32	Clay	39	75.95	3.73	20.37
	8	Silty clay	17	21.07	1.41	14.91
BH-12	8	Clay	18	27.54	2.26	12.21
BH-13	16	Clay	50	73.50	4.46	16.49
	7	Silty clay	17	19.31	1.62	11.92
	19		40	65.66	3.42	19.20
BH-14	25	Clay	42	68.70	3.82	17.97
	5		22	20.38	2.11	9.64
	11		30	34.01	2.94	11.56
BH-15	17	Silty clay	22	35.77	2.48	14.43
	11	Clay	30	38.91	2.66	14.64
	17		18	31.26	2.82	11.07
BH-16	23	Silty clay	32	38.81	2.94	13.18
	15		20	32.05	2.14	14.97
BH-17	21	Clay	26	43.90	2.40	18.31
	5	Silty clay	19	16.56	2.02	8.18
BH-18	23	Clay	25	39.98	3.06	13.06
	5	Silty clay	19	16.56	2.02	8.18
	17	Clay	25	39..98	3.59	11.14
	23		21	30.97	2.50	12.37
Max.			51	75.95	4.46	22.33
Min			16	16.56	1.39	8.18
Ave.			28.02	41.34	2.80	14.57
Std.			9.55	16.54	0.73	3.56

Fig. 3a presents a pressuremeter curve for a specific test. The curve can be divided into three parts. Part 1, which is from P=0 to P=P_0, corresponds to the probe seating against the borehole wall. The difference in borehole and probe diameters also affects this part. Part 2, which is from P=P_0 to P=P_f, represents the pseudo-elastic behaviour of the tested material. The probe is in contact with the borehole walls. The loading is uniform along the probe length. The pressuremeter modulus (E_{PMT}) is determined from this part the curve based on Eq. (1) (Murthy, 2008; and Agan, 2014):

$$E_{PMT} = \frac{2(1+\upsilon)(V_0+V_m)\Delta P}{\Delta V} \tag{1}$$

where E_{PMT} (kPa) is the pressuremeter modulus, v is the Poisson's ratio (equal to 0.33), and V_0 is the volume of the uninflated probe at the ground surface. Also, ΔP, ΔV, and V_m are presented in Fig. 3a.

Part 3, which is from $P=P_f$ to $P=P_L$, P_f, is the pressure at which the mass enters a plastic state. The pressure that defines failure is the limit pressure P_L.



a *b*

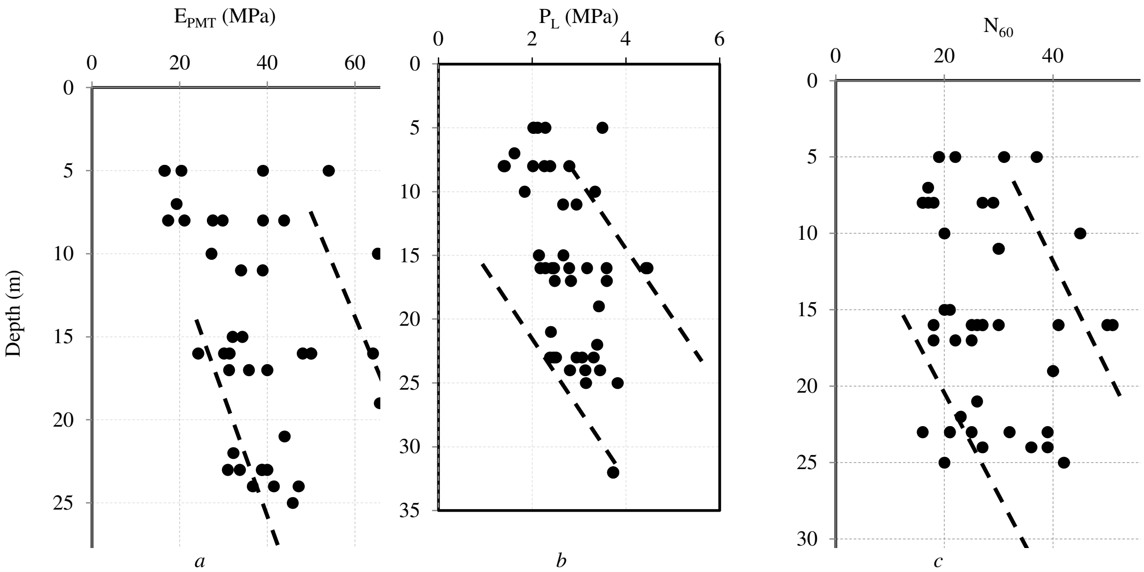
Figure 3 (a) Pressure versus volume curve to calculate E_{PMT}, (b) Pressure versus 1/V to calculate the P_L.

P_L is defined as the pressure where the probe volume reaches twice the original soil cavity volume. This parameter is represented as the volume $V_0 + 2V_i$. Here, V_i is the corrected volume reading at the pressure where the probe contacts with the borehole. If the test was conducted to read sufficient plastic deformation, P_L can be determined by the plot of $1/V$ to P (Fig. 3b).

Pressuremeter moduli (E_{PMT}) were estimated for the tested soil. The result is a graph of E_{PMT} versus depth (Fig. 4a). The change in E_{PMT} is directly proportional to the depth according to Fig. 4a, where E_{PMT} varied between 16.56 and 75.95 MPa.

After estimating the limit pressures (P_L), the graph of P_L versus depth is plotted, as shown in Fig. 4b. In this figure, the upper and lower limits of the resulting data follow an incremental slope with a direct correlation between P_L and the depth. In Fig. 4b, P_L varies between 1.39 and 4.46 MPa.

The resulting N_{60} values from SPT are plotted against the depth in Fig. 4c. Similar to E_{PMT} and P_L, there is a direct correlation between N_{60} and depth. An increase in N_{60} value with a raise in depth indicates that the soils with higher stiffness are at the deeper layers. The N_{60} values for fine-grained silty clay and clay soil varied between 16 and 51, confirming the high stiffness of tested soil.



a *b* *c*

Figure 4. Variation of (a) P_L, (b) E_{PMT} and (c) N_{60}, with depth.

Empirical relationships for estimation of E_{PMT} and P_L based on N_{60}

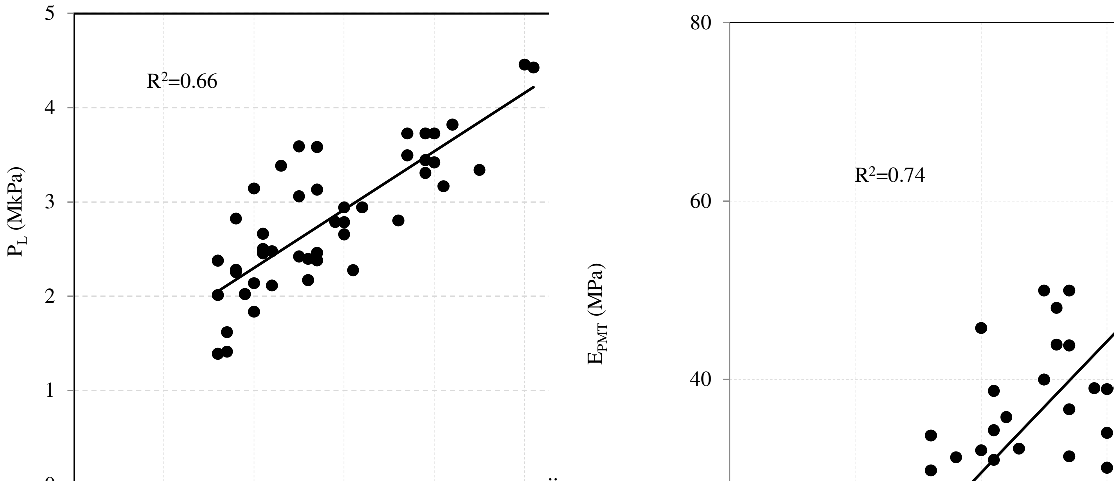
Regression analysis was used to propose an experimental relationship between various parameters measured in the present study. In bivariate regression analysis, there are only two factors (i.e., x and y) that show the relationship between two variables in linear and nonlinear models (for example, quadratic, cubic, logarithmic, and exponential). In a simple regression analysis, the correlation coefficient 'R' confirms the presence of a reliable relationship. The results of the analysis are confirmed by coefficients 'R' and Adjusted 'R^2'. 'R^2' measures the accuracy of predicting the independent variable by the dependent variables. The higher the 'R^2', the greater the success of the model and the closer to the reality of the created relationship. Also, the significance and validity relationship was examined by the 'F' test. In this test, the equation is valid if 'Sig' ≤ 0.05 and F value is high. The analysis was performed using the Excel software. In this study, relationships with 'R^2' greater than 0.65 were considered as valid relationships with strong correlations.

The empirical models for P_L and E_{PMT} were estimated from the graphs of P_L versus N_{60} (Fig. 5a) and E_{PMT} versus N_{60} (Fig. 5b), respectively, as follows:

$$P_L(MPa) = 0.06\, N_{60} + 1.06 \qquad R^2=0.66 \qquad (2)$$

$$E_{PMT}(MPa) = 1.47\, N_{60} \qquad R^2=0.74 \qquad (3)$$

Both P_L and E_{PMT} follow a linear trend, and they are the functions of N_{60} with an acceptable coefficient of determination (Fig. 5). It is noteworthy that Eq. (2) is valid for $16 < N_{60} < 51$ and $1.39 < P_L < 4.46$. Similarly, Eq. (3) is valid for the same range of N_{60} as that defined for Eq. (2) while E_{PMT} varies between 16.56 and 75.94 MPa.



a *b*

Figure 5. Correlations between (a) P_L and N_{60} as well as (b) E_{PMT} and N_{60} for very stiff to hard silty clay and clay soil.

P_L is also plotted against E_{PMT} in Fig. 6. As a result, an empirical relationship between P_L and E_{PMT} with an acceptable coefficient of determination (R^2=0.65) is obtained as follows:

$$P_L = 0.38\, E_{PMT}^{0.54} \qquad R^2=0.65 \qquad (4)$$

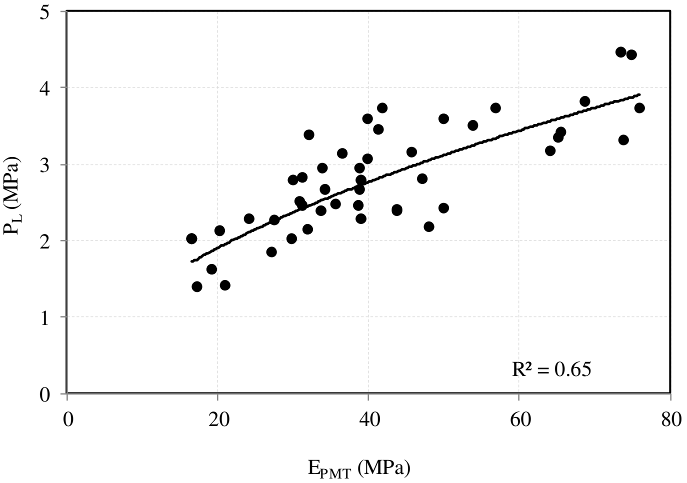


Figure 6. Correlation between P_L and E_{PMT} for very stiff to hard silty clay and clay soils.

To ensure that the proposed empirical models (Eqs. 2, 3, and 4) are statistically significant and logical, the regression analyses were performed and '*R*', 'R^2', 'adjusted R^2', '*Sig*', and '*F*' values were determined (Table 4). Also, E_{PMT} and the P_L were estimated using Eqs. (2), (3), and (4). Then, the Mean Square Error (MSE) and Root Mean Square Error (RMSE) were determined for each relation. These values are presented in Table 4.

Table 4. Main statistical parameters for the proposed regression equations

Equation	Multiple '*R*'	R^2	Adjusted R^2	Standard Error	'*F*'	'*Sig*'	MSE (MPa)	RMSR (MPa)
2	0.86	0.74	0.74	8.40	129.43	7.85×10^{-15}	6.62	8.22
3	0.82	0.66	0.66	0.42	89.42	2.90×10^{-12}	0.33	0.42
4	0.80	0.65	0.65	0.44	78.09	2.16×10^{-11}	0.36	0.43

According to the results given in Table 4 for Eqs. (2), (3), and (4), the 'R^2' is greater than 0.65, indicating the models are highly represented. The '*F*' values are more than 78.09, so the models are statistically significant in its entirety. The '*Sig*' values are very low and close to zero, suggesting that the models are strongly meaningful. Moreover, 'MSE' and 'RMSR' for Eq. 2 are 6.62 and 8.22 MPa, for Eq. 3, they are 0.33 and 0.42 MPa, and for Eq. 4, they are 0.36 and 0.43 MPa, respectively. Therefore, the estimation error in the proposed relationships is very small and acceptable. Thus, it can be concluded that there is a good agreement between the model predictions, and the model is statistically significant in its entirety based on the results obtained from PMT.

Clarke (1995) introduced a classification system for clayey soils based on the ratio of E_{PMT} over P_L versus N_{60} in which the clayey soils with E_{PMT}/P_L ranging from 10 to 20 are considered as stiff to very stiff soils while those with E_{PMT}/P_L greater than 20 are classified as hard soils. The situation of samples tested in this study in the N_{60}-E_{PMT}/P_L graph is shown in Fig. 7. According to N_{60} (Table 1), the tested samples were very stiff to hard. If the soils are classified based on E_{PMT}/P_L, the boundary between stiff and very stiff soils can be $E_{PMT}/P_L = 9$, and the boundary between very stiff and hard soils can be $E_{PMT}/P_L = 15$.

Classification system Fig. 7 demonstrates that if the soils are classified based on Clarke's (1995) classification system, the E_{PMT}/P_L values between 10 and 20 should be considered as stiff to very stiff clays while the results from this study confirm that the soils having E_{PMT}/P_L value ranging between 9 and 15 can also be very stiff clays. Besides, the soils with a ratio of E_{PMT}/P_L greater than 15 can be hard clayey soils. So, comparing the data from this study with the classification system proposed by Clarke (1995) confirms some limitations in the versatility of such a classification system (Fig. 7).

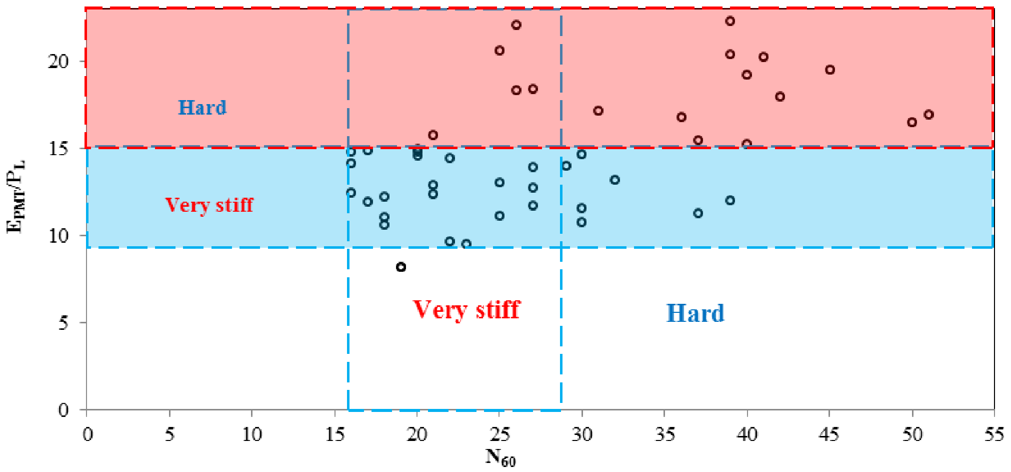
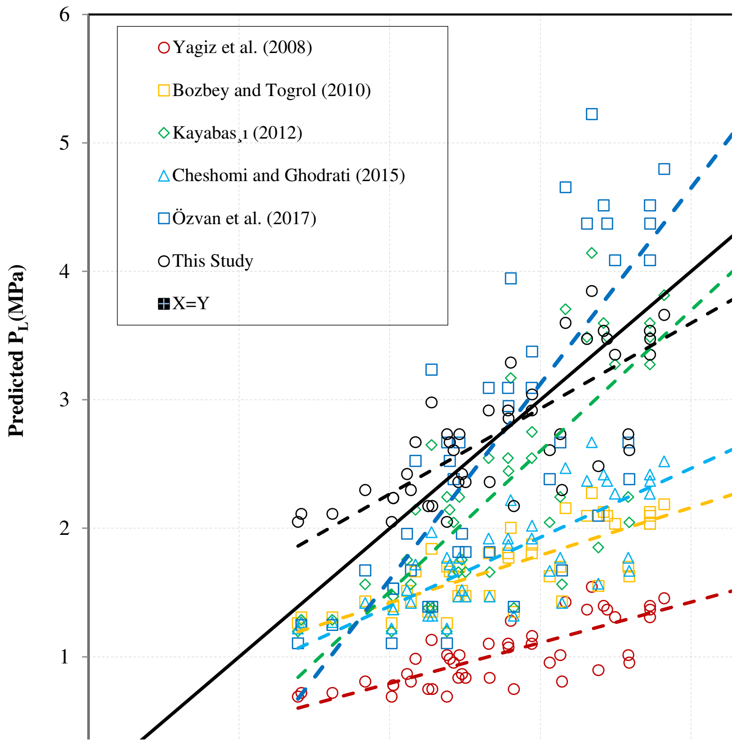


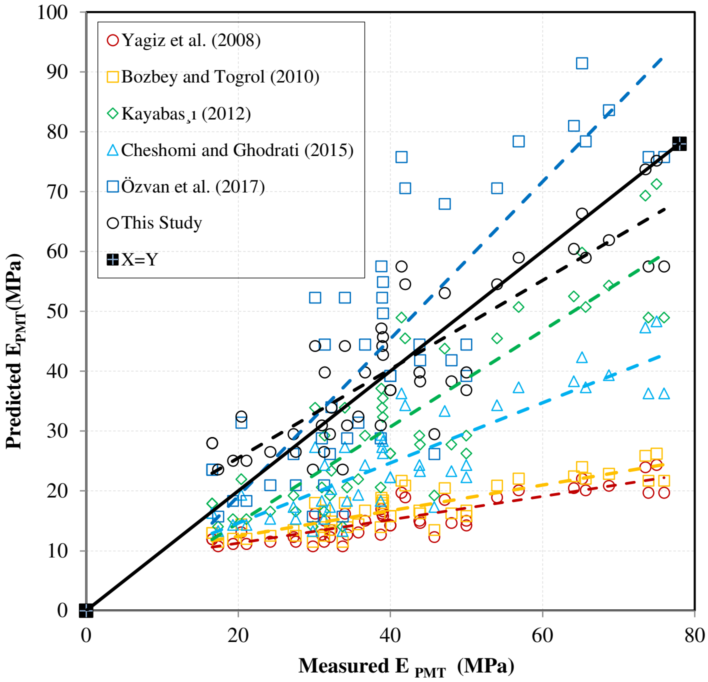
Figure 7. Variation of E_{PMT}/P_L ratio versus N_{60} for very stiff to hard clay soils.

Comparison with earlier studies

Figs. 8a and 8b present the results from this research compared with those conducted by Yagiz et al. (2008), Bozbey and Togrol (2010), Kayabasi (2012), Agan and Algin (2014), Cheshomi and Ghodrati (2015), and Özvan et al. (2018). These authors have proposed some empirical models for P_L and E_{PMT} as a function of N_{60}, according to Table 5. Table 6 gives the detailed specifications of tested soils utilized in the above studies and those included in this investigation.



a



b

Figure 8. Comparison between estimated and measured (a) P_L and (b) E_{PMT} based on equations proposed in this research and previous researchers

From Fig. 8 and Table 5, it is evident that other than the models developed by Bozbey and Togrol (2010) and Kayabasi (2012) for estimation of P_L, the rest follow a linear trend. Similarly, the empirical models proposed for the estimation of E_{PMT} by Bozbey and Togrol (2010), Kayabasi (2012), and Agan and Algin (2014) follow an exponential trend. The simplest linear relationship for E_{PMT}, which was introduced in this study, follows a positive linear trend with no intercept and a coefficient of 1.47.

Table 5. Proposed empirical models for the estimation of P_L and E_{PMT} based on N_{60}

Reference	P_L- N_{60}	E_{PMT}- N_{60}
Yagiz et al. (2008)	P_L (kPa) = 29.45 (N_{60}) + 219.7	E_{PMT} (kPa) = 388.67 (N_{60}) + 4554
Bozbey and Togrol (2010)	P_L (MPa) = 0.26 $(N_{60})^{0.57}$	E_{PMT} (MPa) = 1.61 $(N_{60})^{0.71}$
Kayabasi (2012)	P_L (MPa) = 0.043 $(N_{60})^{1.2}$	E_{PMT} (MPa) = 0.29 $(N_{60})^{1.4}$
Agan and Algin (2014)	P_L (MPa) = 0.067(N_{60}) - 0.872	E_{PMT} (MPa) = 0.0029 $(N_{60})^{2.5}$ + 2.22
Cheshomi and Ghodrati (2015)	P_L (MPa) = 0.05(N_{60}) + 0.42	E_{PMT} (MPa) = N_{60}-2.67
Özvan et al. (2018)	P_L (MPa) = 0.142 (N_{60}) - 1.166	E_{PMT} (MPa) = 2.611 (N_{60}) - 26.03
This study	P_L (MPa) = 0.06 (N_{60}) + 1.06	E_{PMT} (MPa)= 1.47 N_{60}

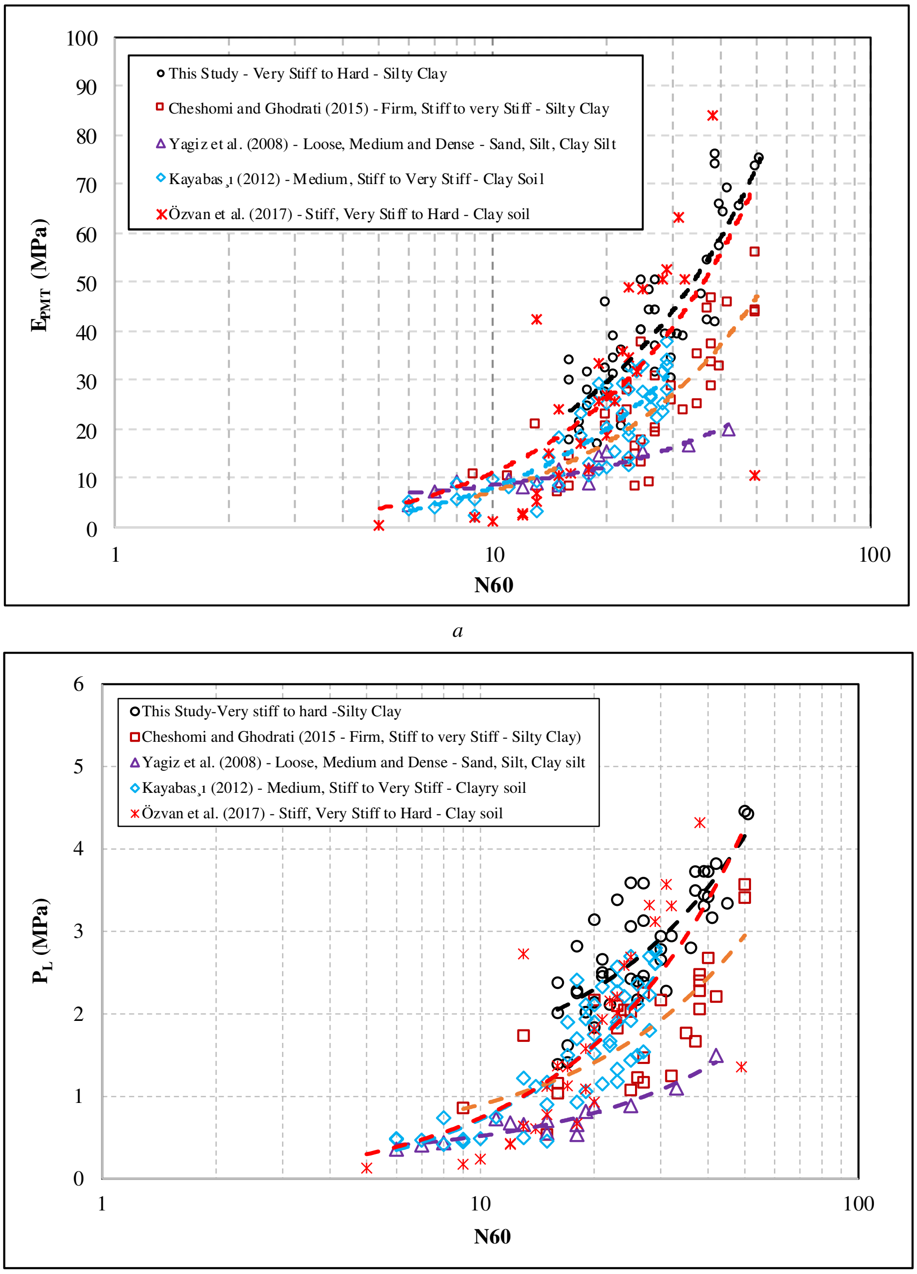
Table 6. Summary of the soils specifications used in the earlier studies along with the one included in this research.

Reference	Soil type	Density/Consistency	Number of tests	N_{60}	P_L(MPa)	E_{PMT} (MPa)
Yagiz et al. (2008)	Sand, Silt, Clayey silt Sandy clay, Silty clay, Silty sand	Loose, medium and dense	15	6-42	0.3-1.5	4.5-19
Bozbey and Togrol (2010)	Clayey soils (CH)	Stiff, very stiff to hard	128	20–70	0.5-3	5-44
Kayabasi (2012)	Clayey soil	Medium stiff, stiff, very stiff	52	6-29	0.42-2.8	5-37.8
Agan and Algin (2014)	Clayey soil	Very stiff to hard	70	22-45	0.56-2.16	8-38
Cheshomi and Ghodrati (2015)	Silty clay	Lowly plastic and firm, stiff to very stiff	38	9-50	0.5-3.5	6.7-55.7
Özvan et al. (2018)	Clayey soil	Stiff, very stiff to hard	34	9-38	0.18-4.32	0.94-83
This study	Silty clay and Clay	Very stiff to hard	47	16-51	1.39-4.46	16.56-75.95

Table 6 highlights a wide range of tested soils used by different researchers to develop an empirical model for the estimation of E_{PMT} and P_L based on SPT results. In particular, Yagiz et al. (2008) performed PMT and SPT on a broad range of soil samples compared to other investigations. Also, Bozbey and Togrol (2010) performed a large number of experiments compared with others, leading to the high confidence level of their proposed empirical models. As shown in Table 5, the silty clay and clay soil with very high stiffness has been examined for the first time in this research. The minimum value of E_{PMT} for the high stiffness silty clay and clay soil tested in this was 16.5 MPa, which was the greatest starting value compared to other soils. This was the case for the P_L values obtained from high stiffness silty clay and clay soil, which varied from 1.4 to 4.4 MPa as the highest listed range in Table 7.

From a practical viewpoint, Table 5 can be used to estimate PMT parameters (i.e., PL and E_{PMT}) in a given soil based on its intrinsic characteristics. For this purpose, first, the soil type is defined using USCS, and then its density and consistency are determined through a simple set of laboratory experiments (e.g. SPT). Hence, the suitable P_L and E_{PMT} values are estimated for the nominated soil sample, and the corresponding empirical models are selected using Table 5 for predicting PL and E_{PMT} at various N_{60} values.

Accordingly, Figs. 9a and 9b can be presented based on the data presented in this research and using the data from previous studies. The figure shows data for each research with the type of soil and its degree of consistency. In this figure, which corresponds to the results of more than 200 tests, the curve moves upwards by increasing the degree of soil consistency as well by changing in the type of soil from sand silt and sandy clay to clayey soils. From this chart, it is possible to estimate P_L and E_{PMT} according to N_{60} values considering the type of soil and its consistency.



a

b

Figure 9. Relationship between (a) E_{PMT} and N_{60} (b) P_L and N_{60} based on data in this research and previous researches.

Conclusions

In this study, some empirical models were proposed for silty clay and clay soil with very stiff to hard to relate their limit pressure (P_L) and pressuremeter modulus (E_{PMT}) obtained from pressuremeter test (PMT) to N_{60} values estimated from standard penetration test (SPT). Overall, 47 SPTs and 47 PMTs were performed by which N_{60}, E_{PMT}, and P_L were measured to be in the range of 16-51, 16.56-75.95, and 1.39-4.46, respectively. The proposed empirical models for P_L and E_{PMT} followed the linear trends as the functions of N_{60} with a high determination of coefficient (R^2 ≥65). Also, the high confidence level of developed models was confirmed through '*Sig*' and '*F*' values. In the proposed equations, the '*Sig*' value is close to zero, and '*F*' is higher than 89. Also, the 'RMSR' values for the relationship between E_{PMT}- N_{60} and P_L-N_{60} are 8.22 and 0.42 MPa, respectively, indicating that the error estimation of the proposed relationships is very low. Also, the empirical equation between P_L-E_{PMT} was determined with R^2=0.65, '*Sig* ~ 0, and *F*=78.09, indicating the validity and significance of this equation.

The results from this study were grouped and compared with those reported earlier. The outcome includes two advisory tables for the practical applications: one for estimating the N_{60} value of a nominated soil based on its specifications and the other for the estimation of PMT parameters including P_L and E_{PMT} using the developed empirical models for each soil type.

In this study, very stiff to hard clay soils were classified based on E_{PMT}/P_L ratio such that soils with E_{PMT}/P_L between 9-15 were very stiff clays and those with E_{PMT}/P_L greater than 15 were hard clay soils.

A comparison between the relationships obtained in this research and previous studies revealed a direct relationship between P_L, E_{PMT}, and N_{60}. Also, it was found that the slope of this relationship depended on the type of soil and its consistency. By increasing the P_L and E_{PMT} values, the line slope of the relationship curves would increase and by increasing the stiffness of soils. In those researches that the values of soil parameters (P_L, E_{PMT}, and N_{60}) were lower than the values of soil parameters in this study, the estimated values of P_L and E_{PMT} for those researches were lower in comparison to those in this study. Similarly, in studies that have reported higher P_L, E_{PMT}, and N_{60} compared to this study, the estimated values of P_L and E_{PMT} were higher.

It is recommended to consider the soil type and range of N_{60} when using empirical relationships. Also, it is better to propose a special relationship for each soil with a significant degree of consistency. In each relation, the range of parameters N_{60}, P_L, and E_{PMT} should be specified, and these relations should be used in soils with parameters in the same range.

Based on the results of more than 200 tests conducted in this study and previous studies, a model was proposed to estimate P_L and E_{PMT} using N_{60} values according to the type of soil and its consistency.

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