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ORIGINAL PAPER

Relationship between the standard penetration test and the pressuremeter test on sandy silty clays: a case study from Denizli

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Abstract The standard penetration test (SPT) is the in situ test most commonly used to investigate the properties of silt, clay, sand and fine gravel. The Menard pressuremeter test (PMT) can be utilized to obtain the strength and deformation properties of any soil or weak rock. The study investigated the relationship between the corrected SPT blow count (N_{cor}) and the PMT parameters of elastic modulus (E_m) and limit pressure (p_L). It is concluded that for the soils tested, E_m and p_L can be estimated as a function of N_{cor} values, with $r = 0.91$ and 0.97, respectively.

Keywords SPT · PMT · Denizli (Turkey)

Résumé L'essai SPT (Standard Penetration Test) est l'essai in situ le plus couramment utilisé pour analyser les propriétés de silts, d'argiles, de sables et de graviers fins. L'essai pressiométrique Ménard peut être utilisé pour obtenir les caractéristiques de déformabilité et de résistance de tout type de sol ou de roche tendre. L'étude s'est intéressée aux relations entre d'une part, l'indice SPT corrigé N_{cor} et d'autre part, les paramètres pressiométriques: le module pressiométrique E_M et la pression limite p_L. On conclut que, pour les sols testés, E_M et p_L peuvent être estimés en fonction de N_{cor}, avec respectivement des coefficients de corrélation $r = 0{,}91$ et $r = 0{,}97$.

Mots clés SPT · Essai pressiométrique Ménard · Denizli · Turquie

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Introduction

Different in situ testing methods have been introduced in order to assess soil properties and to develop models. For many projects, it is common to find that the preliminary design is based on either estimated soil properties or those obtained from basic laboratory tests. The two main field tests—the standard penetration test (SPT) and the Menard pressuremeter test (PMT)—are relatively expensive but essential for the investigation of soil properties during the early stages of geotechnical projects.

The SPT test, developed in the United States, is a well-established method of investigating soil properties such as bearing capacity, liquefaction, etc. As many forms of the tests are in use worldwide, standardization is essential in order to facilitate the comparison of results from different investigations, even at the same site (Thorburn 1986). The quality of the test depends on several factors, including the actual energy delivered to the head of the drill rod, the dynamic properties of the drill rod, the properties of the soil, the method of drilling, and the stability of the borehole. A detailed description and interpretation of the SPT test is given elsewhere (e.g., Seed et al. 1975; Marcuson and Bieganousky 1977; Skempton 1986; Liao and Whitman 1986; Clayton 1995), but it should be noted that the N value is related to the vertical resistance to penetration.

Louis Menard developed the PMT device and considered it to be one of the most precise testing methods available for almost any type of soil (Menard 1965). The basic idea behind the PMT is the expansion of a cylindrical sleeve in the ground in order to monitor the relationship between the pressure (p_L) and the deformation (E_m). The PMT probe is inserted into the borehole and inflated to expand the cavity while recording the volume of cavity change versus pressure increment. A detailed description of the PMT is beyond the scope of this paper; different researchers have published guidelines for testing procedures, applications and data interpretation, such as Menard (1975), Baguelin et al. (1978), and Mair and Wood (1987). However, it should be noted that the measurements obtained are associated with the horizontal stresses compared with the vertical resistance measured by the SPT.

Correlations between various soil parameters and the results obtained from the pressuremeter test and SPT have been reported by Hughes et al. (1977), Baguelin et al. (1978), Ohya et al. (1982), Baguelin et al. (1986), Kulhawy and Mayne (1990), and Akca (2003). Baguelin et al. (1978) proposed a relationship between shear strength and the pressuremeter parameters of soils, while Ohya et al. (1982) investigated the relationship between the values obtained by SPT tests and the results of pressuremeter tests for various types of soils. Kulhawy and Mayne (1990) reported relationships between the SPT blow count and E_m for both sand and clay soils, while Menard (1975) and Nuyens et al. (1996) conducted pressuremeter tests to integrate the parameters into foundation design. Schnaid et al. (1996) 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 standard penetration test (SPT) is the in situ test most commonly used to investigate the properties of silt, clay, sand and coarse sand, but it is not effective for coarser materials such as coarse gravels, cobbles or boulders, as reaching such a "barrier" may result in excessive blow counts. The Menard pressuremeter test (PMT), however, can be used to obtain the strength and deformation properties of most soils, although care must be taken not to rupture the expandable sleeve.

The aim of the present study was to investigate the relationship between the N_{cor} values and both E_m and p_L, utilizing the dataset generated from drilled 15 boreholes in Gumusler County, 10 km north of the city of Denizli, Turkey (latitude 41°N, 29°E).

Geology of the study area

The Aegean region of Turkey is one of the most active earthquake zones in the world and the study area is located on an active graben zone. As seen in Fig. 1, the fault systems create different conditions between the east and west and the central area. The geological units can be divided into two sub-units dating from the Neogene and composed of sand and clay soil, reaching down to a depth of 5–6 m below the Quaternary alluvium. One of the sub-units consists of silt, marl and clay, while the second (underlying) sub-unit comprises silt, sand and gravel. Where observed, the unsaturated geological units contain lenses with variations in grading both vertically and horizontally.

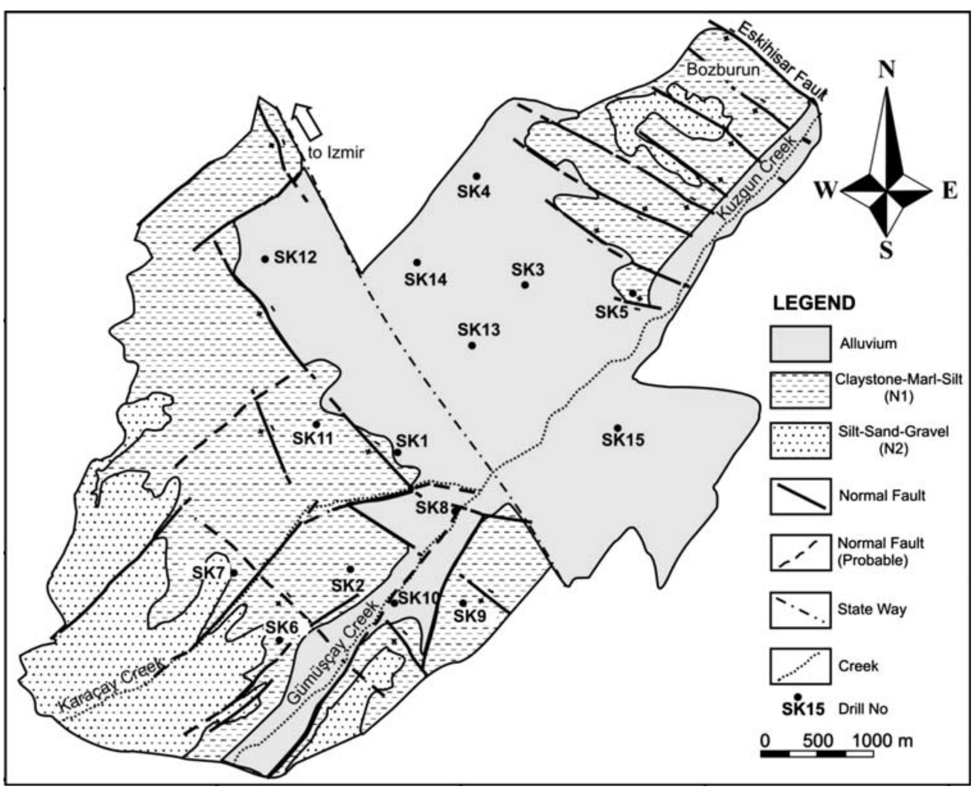

Fig. 1 Geological map of the study area and location of the boreholes in the field

Establishing the dataset

As seen in Fig. 1, fifteen boreholes were drilled to depths of 5–8 m, mainly in the areas where alluvium occurred at the surface. The soil type and structure were recorded and SPT and PMT tests were undertaken in similar material at depths of 1.5–2 m, to investigate the relationship between the parameters obtained by the different tests carried out in alluvial sand, silt and clay soils.

In this study, the SPT test was performed in accordance with ASTM D 1586 (1999), using a standard split-spoon sampler and a 63.5 kg donut-type hammer falling through 762 mm. The penetration resistance for the first 150 mm is ignored, as the soil is considered to have been disturbed by the boring of the hole. The *N* value is the cumulative total of the blows for each 75 mm penetration after the seating blows (the first 150 mm). In this study, the *N* value was corrected to obtain N_{cor}, taking into account the effects of hammer energy, borehole diameter, sampling method and rod length in accordance with ASTM D 1586 and the specification of the test equipment used.

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 was carried out in accordance with ASTM D 4719 (1995), which 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, and this approach was followed in the present study.

The Menard probe used contains three flexible rubber membranes/sleeves. The outer two are “guard cells” to reduce the influence of end effects on the measurements, while the middle membrane provides the measurements used in the calculation. The guard cell membranes are inflated by pressurized gas, while the middle membrane is inflated with water by means of pressurized gas. The pressure in all of the cells is incrementally increased and decreased by the same amount. The measured volume change of the middle membrane is plotted against the applied pressure and the results of the test expressed in graphical form as pressure versus volume change (Fig. 2). In the pseudo-elastic zone, the relationship between cell volume and pressure is virtually linear. The figure shows the pressure-to-volume change generated. The E_m utilized to compute the settlement of the soils was calculated using the theory of expansion of an infinitely thick cylinder as follows:

$$E_m = 2 \cdot (1 + \mu) \cdot (V_o + v_m) \cdot \left(\frac{\Delta p}{\Delta v}\right) \quad (1)$$

where μ is the Poisson ratio (usually taken as 0.33), V_o is the initial volume of the probe, V_m is the average volume of the probe over the considered stress range, and $\Delta p/\Delta v$ is the slope of the linear portion of the stress versus probe volume curve (between p_o and p_f). The p_L (pressure at which failure occurs) was defined as the pressure necessary to expand the probe to twice its original volume ($2V_o$) for a borehole pressuremeter test, and this can be used directly to calculate the bearing capacity of the soil. The p_L was also computed and interpreted from the test data in order to correlate it with the N_{cor} value.

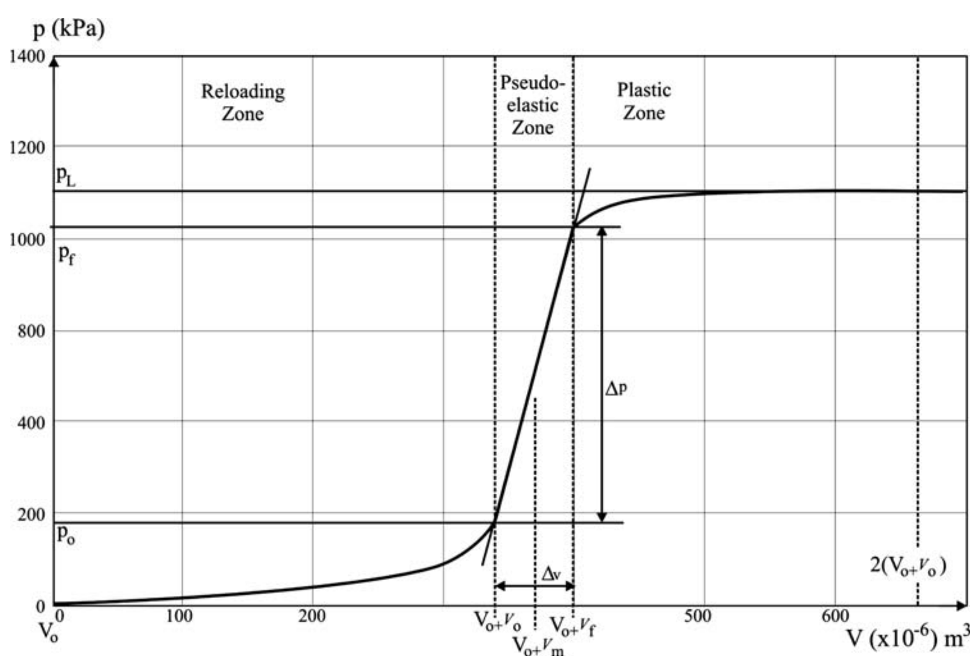

Fig. 2 Typical graphical form of pressure (p) versus total cavity volume change (V) from the PMT test for SK 13; sandy clay soil in the field

Although 15 boreholes were drilled to depths of 5–8 m, the SPT and PMT tests were undertaken at depths of 1.5–2 m. The results are shown in Table 1.

Development of empirical models

Empirical equations are finding increasing use during the early stages of engineering design work since they are a more practical way of proceeding than extensive in situ testing programs. In geotechnical projects, statistical empirical models are widely used (Einstein and Baecher 1983; Hatanaka and Uchida 1996; Rosenbaum et al. 1997; Sonmez et al. 2004; Hasancebi and Ulusay 2007; Yagiz 2008) to predict unknown parameters from simple known parameters, avoiding the time and cost investment involved with high-quality sampling, sophisticated test equipment, etc., and hence statistical analyses were undertaken to investigate the relationships between N_{cor} and both E_m and p_L. Regression analysis was undertaken using a commercial software package (SPSS 2002). Details of the variables E_p, p_L and N_{cor} are given in Table 2. The statistical program found the best-fit regression between the parameters in a linear combination with a 95% confidence level. The empirical equations obtained were:

$$E_m = 388.67 \cdot N_{cor} + 4554 \quad r = 0.91 \tag{2}$$

$$p_L = 29.45 \cdot N_{cor} + 219.7 \quad r = 0.97 \tag{3}$$

where E_m and p_L are in kPa and N_{cor} is the corrected SPT number of blows.

The measured and the predicted values of E_m, p_L and N_{cor} for the 15 boreholes are compared in Table 3. A linear relationship was found between E_m and N_{cor} ($r = 0.91$) and p_L and N_{cor} ($r = 0.97$). It is concluded that E_m and p_L can

Table 1 The measured E_m, p_L and N_{cor} values at a depth of 1.5–2 m in the study area

Hole no.	Soil type	p_L (kPa)	E_m (kPa)	N_{cor}
1	Stiff sand	1,530	19,672	42
2	Silt	892	15,463	25
3	Silt	363	4,500	6
4	Clayey silt	735	9,800	11
5	Clayey silt	883	15,400	20
6	Clayey silt	665	8,675	13
7	Clayey silt	824	14,387	19
8	Silt	559	11,765	15
9	Silt	677	8,182	12
10	Clayey silt	706	8,333	15
11	Clayey silt	539	11,540	18
12	Silt	441	9,091	8
13	Sandy clay	1,098	16,667	33
14	Silty clay	412	7,143	7
15	Silty sand	657	8,929	18

Table 2 Descriptive statistical table of the established dataset

	Data number	Minimum	Maximum	Mean	Standard deviation
E_p	15	4,500	19,672	11,317	4,169.36
p_L	15	363	1,530	733	296.63
N_{cor}	15	6	42	17	9.7

Table 3 The relationship between the measured and predicted E_m ($r = 0.91$ with 1:1)

Borehole no.	Measured p_L (kPa)	Predicted p_L (kPa)	Measured E_p (kPa)	Predicted E_p (kPa)
1	1,530	1,457	19,672	20,920
2	892	956	15,463	14,295
3	363	396	4,500	6,892
4	735	632	9,800	10,009
5	883	809	15,400	12,347
6	665	603	8,675	9,619
7	824	779	14,387	11,957
8	559	661	11,765	10,399
9	677	573	8,182	9,230
10	706	661	8,534	10,399
11	539	623	11,540	9,892
12	441	455	9,091	7,671
13	1,098	1,192	16,667	17,413
14	412	426	7,143	7,282
15	657	750	8,929	11,568

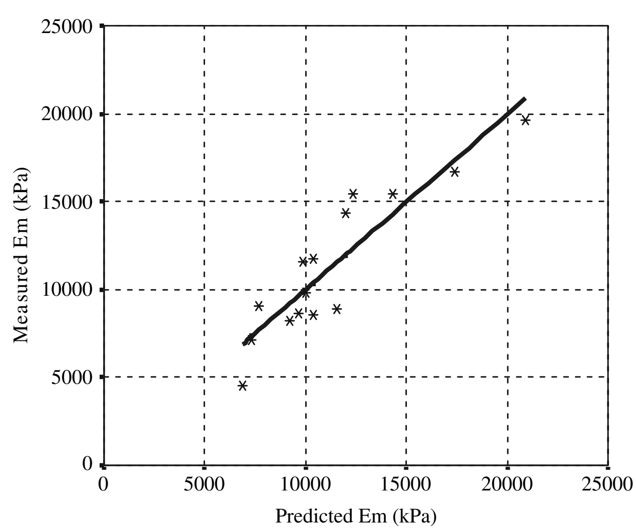

Fig. 3 The relationship between the measured and predicted E_m ($r = 0.91$ with 1:1)

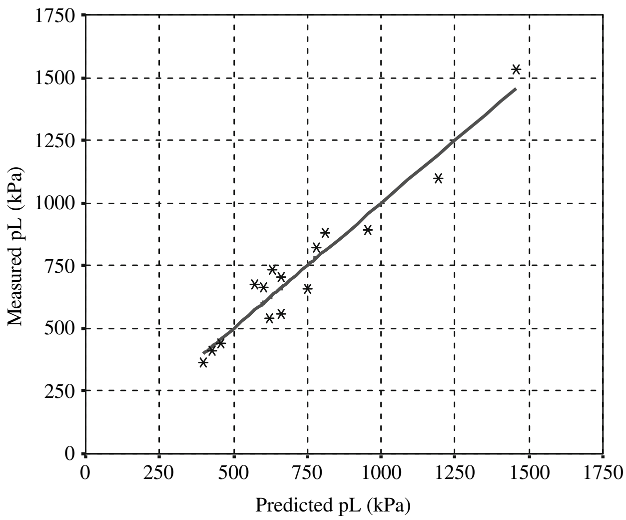

Fig. 4 The relationship between the measured and predicted p_L ($r = 0.97$ with 1:1)

Table 4 Summary of the developed model

Model	R value	R^2	Adjusted R^2	Standard error of the estimate
1 (E_m)	0.907[a]	0.823	0.809	1821.525
2 (p_L)	0.966[a]	0.933	0.928	79.571

[a] Predictors: (constant), SPT

be estimated from N_{cor}, as demonstrated in Figs. 3 and 4, respectively.

Validity of models

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). According to the hypothesis, if the computed *t*-value is greater than the tabulated *t*-value, the *regression* is significant. A summary of the statistical analysis and *r*-values is given in Table 4. Further, as shown in Table 5, the tabulated *t*-value is lower than the computed *t*-values for both the E_m and p_L equations, and so it can be concluded that there is a positive correlation between the measured and predicted parameters. The computed *F*-test value was greater than the tabulated *F*-value (Table 6), supporting a reliable correlation between the measured and predicted variables.

Conclusions

The standard penetration test has been widely used as an 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,

Table 5 Results from *t*-tests of introduced equations and the significances of the *r*-values

Model		Unstandardized coefficients		Standard coefficients	*t*-value	*t*-table	Sig.
		B	Standard error	β			
1 (E_m)	(Constant)	4553.91	989.44				0.000
	SPT	389.66	50.03	0.907	7.768	2.1445	0.000
2 (p_L)	(Constant)	219.67	43.22				0.000
	SPT	29.45	2.185	0.966	13.475	2.1445	0.000

Dependent variables: E_m and p_L

[a] Predictors: (constant), SPT

Table 6 Analysis of variance for the significance of the regressions and *r*-values

Model		Sum of squares	df	Mean square	*F*-value	*F*-table	*F*
1 (E_m)	Regression	2.0×10^8	1	200,236,817	60.349	4.67	0.000[a]
	Residual	43,133,394	13	3,317,953.41			
	Total	2.43×10^8	14				
2 (p_L)	Regression	1,149,560	1	1,149,559.6	181.562	4.67	0.000[a]
	Residual	82,309.4	13	6331.5			
	Total	1,231,869	14				

Dependent variables: E_m and p_L

[a] Predictors: (Constant), SPT

although it is comparatively expensive and time-consuming.

In order to develop a relationship between the SPT and the PMT values, tests were undertaken in an area of sandy silty clayey soils in Western Turkey. Satisfactory relationships with acceptable regression coefficients were obtained between E_m (used to compute the settlement of soils) and both N_{cor} and p_L (which can be utilized to compute the bearing capacities of soils).

The empirical relationships developed between the parameters can be used in the early stages of geotechnical projects when one of the tests cannot be performed for some reason. It is recommended that the relationships should be used with caution considering the limited number of samples tested, all of which were fine-grained soils. Further research should be carried out to check its reliability for medium to coarse grained sand and gravel.

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