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The new empirical formula based on dynamic probing test results in fine cohesive soils

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Abstract

The Dynamic Probe is an effective tool used in site investigation. It is more economic than the use of direct drilling, particularly in explorations with moderate depth. This paper presents an experimental study to investigate the capability of using dynamic probing to evaluate the shear strength and compaction percent of fine soil. A series of dynamic probe tests were carried out at 6 different sites in the Khozestan, Hormozgan and Qom provinces in the central and southern regions of Iran. The repeatability of the results is considered and new empirical equations relating the dynamic point resistance to undrained shear strength and compaction percent are proposed. For undrained shear strength evaluation of fine soils, i.e. clay and silty clay soils, a reliable site-specific correlation between q_d and C_u can be developed when considering the correlation between log q_d and log C_u. Also compaction present can be evaluated by q_d. These equations can be developed to provide site-specific relationships based upon geotechnical data at each new location. Using this approach an estimation of the undrained shear strength Cu and compaction percent CP can be determined from dynamic probe tests with acceptable accuracy. The present paper also encourages the wider application of dynamic probing for site investigation in fine soils.

Keywords: *Dynamic probing, Repeatability, Undrained shear strength, Fine soil, Compaction percent.*

1. Introduction

Probing by penetrometers in conjunction with boring, sampling and laboratory testing has been recognized as a valuable technique for soil investigation for more than 50 years [1]. Sanglerat (1972) listed a large number of the available penetrometers and the range has been greatly increased in recent years [2].

Penetration tests are classified in two general groups. The first is the static type, whose most well-known one is cone-penetration test in which the static pressure is applied [3, 4, 5].

The other important one is the dynamic probe which consists of a tip cone connected to an extension rod and a driving weight for penetration into the ground. The number of blows (M) required to successively driving the cone by each 100 mm (or 200 mm depending on the mass of hammer) increment are recorded as a measure of shear strength.

Geotechnical investigations using dynamic probing have particular advantages including; speed of operation, ease of use in difficult terrain with poor access, low costs, ability to provide a continuous profile, identifying soft thin layers, distinguishing between cohesive and non-cohesive soils and reducing the need for expensive boring [6, 7, 8, 9].

The main application of dynamic probing is to interpolate and extrapolate data between boreholes, i.e. where some geotechnical parameters have been gained by other conventional manners, it is possible to use dynamic probing test to gain rapidly and economically extra engineering parameters by some correlations [10]. Taking all these into account, related issues to dynamic probing is of interest to those involved in geotechnical practice.

This paper presents the results of a series of tests at six sites in Iran and considers the accuracy of the experimental results. The new equations relating dynamic cone resistance to undrained shear strength and compaction percent are proposed.

2. Previous Study

Some researchers tried to present the relations between different characteristics of the soil and the results of dynamic penetration test, e.g. the results of dynamic probing tests have been correlated with undrained shear strength [11].

The dynamic point resistance (q_d) can be calculated using the Dutch formula [12]. The use of this equation needs measurement of the speed of impact by means of

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accelerometer equipment but this is not always available [13]. Using the simplifying assumption of constant acceleration, the following relationships can be determined [11]:

$$q_d = \frac{M_1}{(M_1 + M_2)} r_d \tag{1}$$

$$r_d = \frac{M_1 g h}{A e} \tag{2}$$

Where:

r_d is the unit point resistance (Pa), M_1 , mass of the hammer (kg), M_2 ,the total mass of the extension rods, the anvil and the guide rods (kg), g , the acceleration due to gravity (9.81 m/sec^2), h , the height of fall of the hammer (m), A , the area at the base of the cone (m^2) e , the average penetration in m per blow (0.1/ M from DPL, DPM, and DPH, and 0.2/ M from DPSH, see Table 2) and M is the number of blows per 100 mm penetration.

The value of r_d is an assessment of the work done in penetrating the ground. The values of q_d modifies r_d to take account of the inertia of the driving rods and hammer after impact with the anvil for different equipment configurations [11]. Butcher et al (1996) concluded that the dynamic probe tests result in similar values of q_d being obtained from different configurations of equipment in the same clay soil profile. Based on soil data collected from 10 sites with cohesive soils in the UK and Norway they presented the equations to determine undrained shear strength, c_u (kPa) (Table 1).

These equations are widely referenced but different coefficients might be suggested for various sites or equipment [13].

In order to take into account soil sensitivity (S_t), Butcher et al. (1996) proposed a general equation for all types of clay soil (Table 1).

Table 1 Comparison of correlation for Dynamic probe results and CBR, M_R and C_u from previous studies*

Soil type	Correlation	Researcher and Date
Soft Clay	$C_u = \frac{q_d}{170} + 20 \quad (C_u < 50kPa)$	Butcher et al (1995)
Hard Clay	$C_u = \frac{q_d}{22} \quad (C_u \geq 50kPa)$	Butcher et al (1995)
Clay	$C_u = \frac{q_d}{20}$	Langton (2000)
Clay	$C_u = 0.455\left(\frac{q_d}{S_t}\right) + 10$	Butcher et al (1995)
Fine soil	$\log_{10} CBR = 0.35 + 1.06 \log_{10} q_d$	Amor et al (1999)
Fine soil	$M_R = 532.1(⟦DCPI)⟧^{-0.492}$	Rahim and Georg (2004)
Fine soil	$M_R = 311.92(⟦DCPI)⟧^{-0.104}$	Berazvan and Fakhri(2012)

*M_R is the resilient modulus (MPa); CBR, California bearing ratio (%); q_d, dynamic point resistance (KPa); DCPI, penetration index of the dynamic penetration test (mm/blow); C_u, undrained shear strength (kPa); S_t, sensitivity (%)

Amor et al (1999) by considering tests result of 9 sites in England on layers of fine soil presented a logarithm equation to correlate the California Bearing Ratio to the results of dynamic penetration test [14]. Georg and Rahim (2004) for fine soil of Mississippi region in US presented a practical equation between dynamic penetration test results of the DCP and resilient modulus (M_R) [15]. Mohammadi et al (2008) used DCP for determination of geotechnical properties of soils in laboratory conditions [16]. Berazvan and Fakhri (2012) also presented the relation between the results of DCP and M_R [17]. Lee et al (2014) by implementing DCP test and other tests like Plate Load Test, California Bearing Ratio and Soil Stiffness Gauge, evaluated the results of these tests for determination of engineering properties of soils in Korea. Tests are done on compacted samples in a large chamber with dimensions of 1000 mm height and 750 mm internal diameter. They have provided the correlation between CBR and DCP By regression analyses [18]. Some of these correlations are mentioned in Table (1).

An important note about the results obtained from dynamic tests is the friction between the soil and the extension rods affects the results obtained from dynamic tests. The best method to determine the value of friction is to measure the torque needed to rotate the extension rods. Some researchers have tried to correct the number of blows to overcome the rod friction [11]. Butcher et al (1996) used Bentonite slurry and perforated extension rods to inject slurry to eliminate friction on the extension rods. It was shown that this technique was effective. Torque measurements were recorded and a correction factor relating to the torque equivalent of 1 blow of the hammer determined by the comparison of the results with and without slurry.

3. Equipment and the Procedure

Dynamic probing equipment has been manufactured in

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various dimensions and sizes (DIN 4094, 1974, BS 5930, 1999 and ISO 22476-2, 2005) [19, 10, 20]. The most important specifications for various configurations of equipment used in this research are given in Table 2.

Table 2 Details of dynamic probing test specifications and SPT tools (DIN 4094, BS 5930 and ISO 22476-2)

(SPT)	Super Heavy (DPSH)	Heavy (DPH)	Medium (DPM)	Light (DPL)	Factor
0.5 ± 63.5	0.5 ± 63.5	0.5 ± 50	0.3 ± 30	0.1 ± 10	**Hammer mass, kg**
0.02 ± 0.75	0.02 ± 0.75	0.01 ± 0.5	0.01 ± 0.5	0.01 ± 0.5	**Height of fall, m**
0.5 ± 50.5	0.5 ± 50.5	0.3 ± 43.7	0.3 ± 35.7	0.3 ± 35.7	**Cone diameter, mm**
20 *	20	15	10	10	**Cone area, cm^2**
90	90	90	90	90	**Cone apex angle, deg.**
42	0.3 ± 32	0.2 ± 32	0.2 ± 32	0.2 ± 22	**Rod diameter, mm**
M_{30} :30	M_{20} :20	M_{10} :10	M_{10} :10	M_{10} :10	**No. of blows per x mm**
<50	5-100	3-50	3-50	3-50	**Standard range of blows**

* Pseudo-cone with open tip

A motorized dynamic probe rig was developed to permit the comparison of a range of different specifications and configurations of the dynamic probe. The research tool was designed in such a way that it was possible to change the main parameters including hammer mass, height of hammer drop, diameter of the extension rods and the size of the penetration cone. The research rig could accommodate the light, average, heavy and very heavy specifications shown in Table (2). A Macintosh Probe was used along with the mention equipment to study the very light configuration [21]. Also the Dynamic Cone Penetrometer *(*DCP*)* has been described by ASTM 6951-03 [22]. A detailed description of DPT test and procedure can be found in ISO 22476-2, [20].

4. Study Area

In this study dynamic penetration test has been carried out on 6 sites in Khozestan, Hormozgan and Qom provinces in the central and southern regions of Iran, where other prevalent geotechnical test were accurately conducted (Fig. 1). Some of the major properties sites are shown on Table (3).

Geologically, the Hormozgan region is a part of the Zagros folded structure in the Pleistocene. The Khozestan plain is a continuation of the Saudi Arabian platform. The Qom region belongs to the central Iran zone.

These plains are covered by recent alluvium identified as clay, silt and sand. These deposits are the results of chemical and physical weathering of limestone, marl, sandstone, shale, and conglomerate [23].

Fig. 1 Location of site study

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Table 3 geotechnical properties of study area

Types of Shear	Cu (kPa)	PI (%)	PL (%)	W (%)	Density (t/m^3)	Soil description	Depth (m)	Site
vane shear test, UU triaxial test	18	7	20	32	1.88	Soft to very soft silty clay	2.5	**Emamie Port [24] (7)***
	23	7	18	31	1.96		5	
	32	16	23	47	1.89		7.5	
	46	19	19	36	1.88		10	
vane shear test	10	9	20	31	1.85	Lean clay with silt	2	**Khamir port [25] (4)**
	23	22	22	35	1.91		5	
	30	17	25	39	1.95		7	
vane shear test, UU triaxial test	48	19	26	30	1.80	Soft clay with silt	3	**Emam-Khomeini Port [26] (9)**
	60	12	20	28	1.98		5	
	40	16	18	31	1.96		8	
	48	9	16	29	1.99		12	
UU triaxial test	22	8	22	21	1.65	Soft to medium clay with silt	2	**Mahmoudabad industrial zone (20 km of qom) [27] (3)**
	46	11	21	17	1.75		4	
	65	9	22	11	1.82		7	
UU triaxial test	24	14	20	4	1.34	Soft to medium clay	2	**Shokouhieh industrial zone (10 km of qom) [28] (4)**
	60	12	25	6	1.4		6	
UU triaxial test	24	14	18	32	1.75	Soft to hard silty clay	3.5	Zone 1 — **Rajaii Port [29] (30)**
	86	-	-	20	1.77		8.5	
UU triaxial test	85	7	17	21	1.65	Soft to medium clay	7	Zone 2
	40	9	17	24	1.7		9	
UU triaxial test	130	6	21	-	-	Medium to hard clay with silt	6.5	Zone 3
	75	7	21	25	1.7		11	

*: numbers in parenthesis shows the number of tests; Emamie Port,7 Mackintosh test, Khamir port, 4 Mackintosh test, Emam-Khomeini Port 9 Mackintosh test, Mahmoudabad industrial zone, 3 DPL test, Shokouhieh industrial zone, 3 DPH and 1 DPM test and in Rajaii Port 15 DPL and 15 DPM have been done.

5. Methodology

In this research addition to dynamic probing nearly and between the boreholes, conventional boring and testing including hand-operated and borehole vane shear tests, UU triaxial tests on undisturbed samples of 35mm diameter and unconfined compression tests were undertaken at all 6 sites. The soil properties at the sites are shown in Table 3. Table 3 shows that the sites provided a comprehensive range of undrained shear strength and Plasticity Indices.

The geology and typical profiles of each site illustrate the soil layers are uniform within the studied depth. Therefore it was assumed that the ground conditions and the test sites had little variability in the areas of the study.

As mentioned before, one of the important notes about DPT test is the friction between the soil and the extension rods. In order to minimize the effect of friction in the present study, the rods were regularly rotated, typically after each meter of penetration. Frequent rotation of the rod may not be adequate to fully remove skin friction, but it is effective for the minimization of friction. The torque required to rotate the rods was recorded and the test results corrected using the procedure proposed by Card et al (1990) [30].

As previously mentioned, tests have been done in 6 sites. Figs. 2a to 2f illustrated results DPT tests for only 3 locations in 6 sites.

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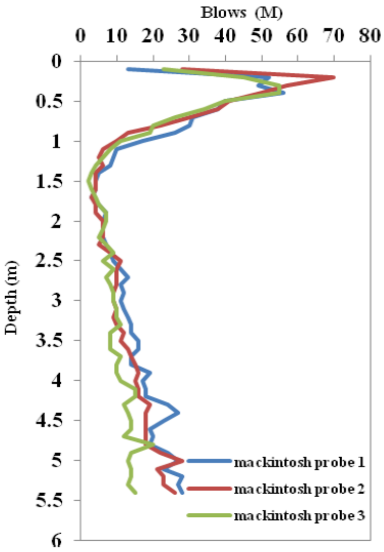

Fig. 2a Dynamic Probe depth profile from Emamie port

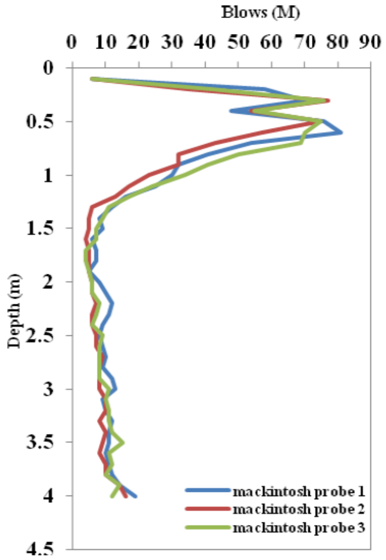

Fig. 2b Dynamic Probe depth profile from Khamir port

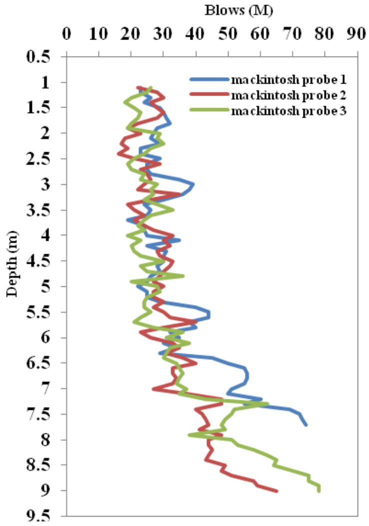

Fig. 2c Dynamic Probe depth profile from Emam khomeyni port

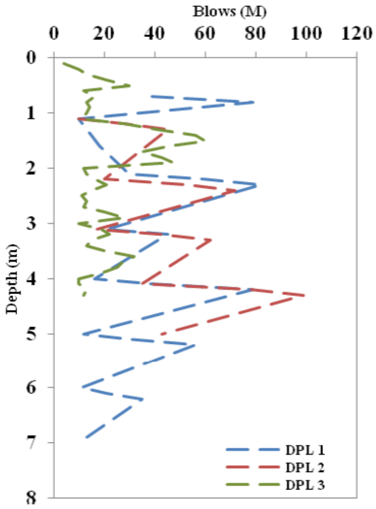

Fig. 2d Dynamic Probe depth profile from Mahmoudabad industial zone

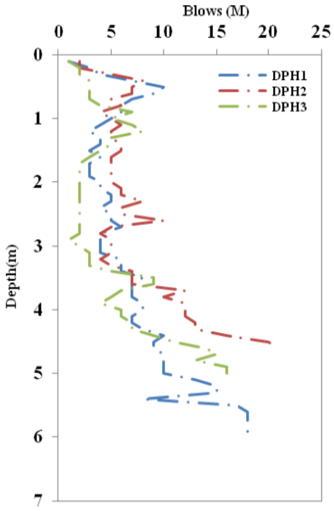

Fig. 2e Dynamic Probe depth profile from Shokouhie industrial zone

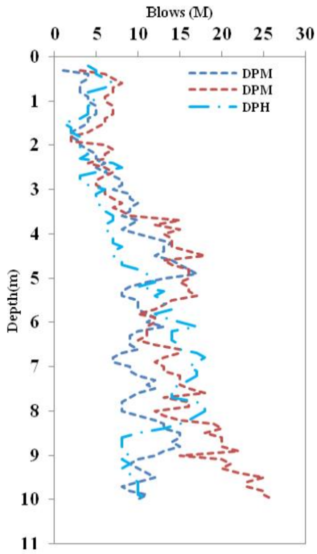

Fig. 2f Dynamic Probe depth profile from Rajaee port

6. Result and Discussion

6.1. Repeatability

In geotechnical testing, it is important considering of repeatability of the results. To study the repeatability, the selection of the appropriate statistical parameters is required. Coefficient of variation (C_v) is an appropriate factor used to study the repeatability. Herrick and Jones (2002) used C_v to study the repeatability of the dynamic penetration test [31]. The C_v can be defined as:

$$C_v = \frac{s}{\bar{x}} \tag{3}$$

Where s is the standard deviation and $\bar{x}$ is the average value derived from the tests results. The coefficient of variation is dimensionless and measures the spread of data in terms of the average value expressed as a percentage. According to the Lee et al,(1983) variation of C_v for the results of the Standard Penetration Test (N), which can be considered as a form of super heavy dynamic probing, is reported to be between 27 to 85 % with a recommended value of 30% for C_v [32].

In this research, two, three or four tests undertaken very closely together (less than 0.5 m apart) were repeated using a number of configurations of the dynamic probe. As an example, Table 4 shows the results of tests carried out using a DPM in the Shokouhieh Industrial Zone trial. The value of C_v in this test varied between 0 to 12.4% with an average of 5.1% .

It is noticeable that the value of (C_v) is less than 10% and 30% for 70% and 95 % of the cases respectively.

Table 4 An example of test results (using DPM)

No.	Depth, m	Test 1	Test 2	Test 3	Mean	C_v (%)
1	0.1	3	3	3	3.0	0.0
2	0.2	3	3	3	3.0	0.0
3	0.3	4	4	4	4.0	0.0
4	0.4	16	19	17	17.3	8.8
5	0.5	7	7	7	7.0	0.0
6	0.6	7	6	6	6.3	9.1
7	0.7	6	5	5	5.3	10.8
8	0.8	6	6	5	5.7	10.2
9	0.9	5	6	5	5.3	10.8
10	1.0	5	5	4	4.7	12.4
11	1.1	6	7	7	6.7	8.7
12	1.2	7	7	7	7.0	0.0
13	1.3	7	6	7	6.7	8.7
14	1.4	6	6	6	6.0	0.0
15	1.5	6	7	6	6.3	9.1
16	1.6	7	7	7	7.0	0.0
17	1.7	7	8	7	7.3	7.9
18	1.8	7	8	7	7.3	7.9
19	1.9	7	7	7	7.0	0.0
20	2.0	12	10	11	11.0	9.1
21	2.1	11	11	10	10.7	5.4
22	2.2	12	11	11	11.3	5.3
23	2.3	11	12	11	11.3	5.3
24	2.4	12	13	13	12.7	4.6
25	2.5	14	15	15	14.7	3.9
26	2.6	15	15	15	15.0	0.0
27	2.7	17	17	16	16.7	3.5
28	2.8	20	20	19	19.7	2.9
29	2.9	21	20	20	20.3	2.8
30		Average (%)			9.2	5.1

6.2. The selection of configuration

The main point in the tests was the realization that the appropriate configuration of a dynamic probe should be selected so that the test results remained within the standard range of blows presented in Table 2. If the results were outside the range, either lighter or heavier equipment were deployed. So the best dynamic explorer for soft soil is the light type, e.g. Macintosh Probe or DCP or DPL. When soil gets harder the results (or the number of the blows to penetrate), from light probe exceed the standard 50 and to keep the results in standard range, the medium or heavy probes should be deployed, according to Table 2. Nevertheless some of the newest researches [e.g.16, 17, 18] were conducted on DCP device on granular soil that energy needed for penetration is not adequate and results are not in standard range.

6.3. Undrained shear strength estimation

Some researchers tried to present the relations between dynamic probing test and undrained shear strength [11, 13].

In order to find any relation between q_d and c_u , the different distribution functions have been tested [33]. In this research, data from other researchers were also included. It was seen the values of $\log q_d$ and $\log c_u$ were normally distributed which suggested that any relationship between q_d and C_u is better based on a $\log q_d - \log C_u$ plot, as shown in Equation 4 and Fig. 3.

$$\log q_d = 0.637 \log c_u + 2.243 \tag{4}$$

which can be rewritten as:

$$c_u = q_d^{1.57} / 3320 \tag{5}$$

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In Fig. 3, the lines of the 90% upper and lower reliance limits are drawn based on the percentage of points inside the region.

The proposed relationship (Equation 5) provides a continuous representation of the data for soft to stiff clays as well as determining a specific value of C_u for any specific value of q_d. In addition, Equations 4 and 5 can be developed to provide site-specific relationships based upon geotechnical data at each new location. Using this approach for clay and silty clay soils, an estimation of the undrained shear strength (C_u) can be determined from dynamic probe tests with acceptable accuracy.

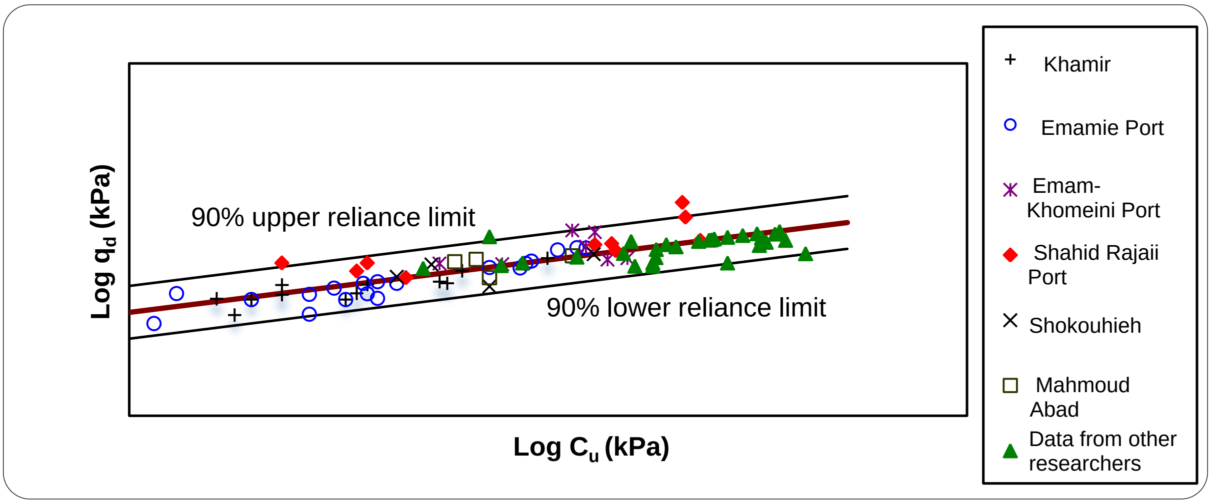

Fig. 3 Correlation between log q_d and log C_u in fine cohesive soils in studied sites

6.4. Compaction percent estimation

One of the applications of dynamic probe test could be to control of the fill compaction quality in several areas, e.g., cohesive material of core of embankment dams and cohesive pavement layer. Historically, the controls of the compaction percent of pavement layers have been determined by means of in-place density testing.

Many researchers have been conducted DPT for estimation of soil compaction parameters, for example CBR and resilient modulus (M_R) form dynamic probe test results. It has been observed that, presented correlations between dynamic penetration test results and compaction parameters are exponential form. Therefore, this study using of two probes, medium and light weight (DPM and DPL, see Table 1), tried to present an experimental correlation for the compaction percent determination in form of exponential or logarithmic function.

Therefore, considerable amount of compaction percent and dynamic penetration tests results, were presented the Equation (6) & (7) for DPL and DPM respectively.

$$CP = 131.27(DCPI)^{-0.240} \quad (6)$$

$$CP = 155.96(DCPI)^{-0.280} \quad (7)$$

Where DCPI is the penetration index of the dynamic penetration test in (mm/blow) and CP is the compaction percent.

As mentioned before , the dynamic point resistance (q_d) is used for various configurations of the dynamic probe, so by calculating q_d in all conducted tests, Equation (8) is produced as shown in Fig. 4. In this Equation coefficient of R^2 is 90%.

$$CP = 16.654 q_d^{\,0.193} \quad (8)$$

Special advantage of this correlation in comparison with others is that while others are related to specific probes for example DCP, this one which is based on the dynamic point resistance (q_d) can be used for different configurations of the dynamic probe.

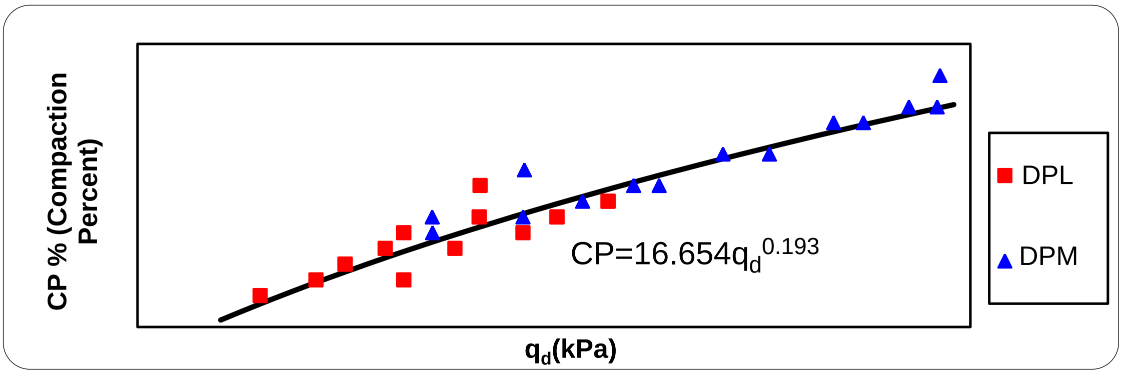

Fig. 4 Correlation between dynamic cone resistance and compaction percent for various configurations of the dynamic probe (DPL & DPM)

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7. Conclusion

In this research, based upon geotechnical data at different locations of Iran (Khozestan, Hormozgan and Qom provinces) some effective equations presented. In this study three methods were used to minimize friction, practically and successfully. It was shown that in almost 95% of the repeated tests undertaken with different configurations of the dynamic probe, the coefficient of variation of results (C_v) was less than the value reported for the Standard Penetration Test. Therefore the dynamic probe offers an acceptable level of repeatability.

For undrained shear strength evaluation of fine soils, i.e. clay and silty clay soils, a reliable site-specific correlation between q_d and C_u can be developed considering regarding the correlation between $\log q_d$ and $\log c_u$ since both $\log q_d$ and $\log c_u$ are normally distributed.

Also compaction percent can be evaluated by q_d. These equations can be developed to provide site-specific relationships based upon geotechnical data at each new location. Using this approach an estimation of the undrained shear strength Cu and compaction percent CP can be determined from dynamic probe tests with acceptable accuracy.

Considering the findings of the present research and simplicity of dynamic probe test conduction, wider application of this technique is recommended.

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