Journal of Al-Azhar University Engineering Sector

Vol. 17, No. 63, April 2022, 512 - 527

CORRELATING PHYSICAL AND MECHANICAL PROPERTIES OF SOIL WITH DYNAMIC PENETRATION TESTS

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Received:7 Nov. 2021 Accepted: 11 Feb. 2022

Abstract

Penetration testing is one of the indirect in-situ testing techniques that used to characterize soil. Dynamic probing has been used as an alternative to the standard penetration test (SPT). Different types of dynamic probing had been used in the literature depending on to the mass and the energy used of the hammering. This study presents a statistical study to investigate the possibility of utilizing the dynamic cone penetration test to evaluate the shear strength parameters of cohesive and non-cohesive soils.

استنتاج علاقة رياضية بين الخواص الطبيعية والميكانيكية للتربة واختبارات الاختراق الديناميكي

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الملخص:

نظرا لسهولة ورخص تكلفة استخدام جهاز الاختراق بالمخروط الديناميكي والتي تعطينا توصيف مستمر لقطاع التربة فان إيجاد علاقات تجريبيه تأكيديه ظل في اهتمام الكثير من الباحثين في مجال الهندسة الجيوتقنية ولذلك فإن في هذا البحث تم التركيز على استنتاج معادلات ارتباط مع معاملات القص الخاصة بالتربة المتماسكة أو المفككة وذلك حتى أعماق مختلفة عن تأثير الأجهزة ذات التوصيف الثقيل واللذي تصل وزن مطرقته ل ٥٠ كجم تقريبا والثقيل جدا يصل وزن مطرقته ل ٦٣,٥ كجم تقريبا وهو ما يسهل مقارنتها بالجسات والقادرة على الاختراق في هذه الأعماق وذلك اعلى واسفل منسوب المياه الجوفية والذي تختلف فيه قيم القراءات بشكل كبير وتم ذلك عن طريق جمع نتائج اختراق للمخروط الديناميكي ونتائج الاختراق القياسي ومعاملات القص المختلفة والمستنتجة من تقارير الجسات بمشاريع مختلفة داخل مصر وبالامارات العربية المتحدة. المعادلات الرياضية المستنتجة ذات معاملات ارتباط عالية جدا مما يعطي دلالات تأكيدية لتوصيف التربة الرملية والطينية مع ضرورة مراعاة تصحيح قراءات الاختراق للتربة الطينية أسفل منسوب المياه الجوفية وذلك لتأثير كل من الاحتكاك وضغط المياه البينية بين حبيبات التربة المتماسكة.

الكلمات المفتاحية : تجربة الاختراق القياسى، المخروط الديناميكي، مقاومة القص الغير منصرفة، الكثافة النسبية

Abstract

Penetration testing is one of the indirect in-situ testing techniques that used to classify and characterize the soil. Penetrometers in general are divided into two broad groups, the simplest are dynamic penetrometers. In these penetrometers, dynamic energy is applied on rods using repeated blows of a drop weight.

Dynamic probes are considered an economical approach compared direct drilling. Different types of dynamic probing have been used in the literature depending on to the mass and the energy used of the hammering.

This study presents a statistical study to investigate the possibility of utilizing the dynamic cone penetration test to evaluate the shear strength parameters of cohesive and non-cohesive soils. A series of dynamic probing (DP) were collected from different sites in Egypt and United Arab Emirates. A mathematical correlation equations are proposed in this study by regression analysis for the non-cohesive soils to predict the soil relative density and friction angle and the un-drained shear strength of cohesive soil based on the penetration number from the collected database.

From the literature there is a great variety of types of the dynamic penetrometers, but some countries follow the German standards (DIN). Yet there don’t exist correct correlations between the results of penetration testing and soil mechanical parameters. This paper is an attempt to provide mathematical correlations can be very useful to predict the soil shear strength parameters for shallow soils in order to choose the foundation level and to predict soil bearing capacity.

Keywords: SPT, Dynamic Probing, Un-Drained Shear Strength, Relative Density.

1. Introduction:

The dynamic probing test is a simple, rapid and cost-effective soil investigation technique by driving an enlarged solid conical penetrometer attached to an extension rod into the ground by a constant energy hammer and recording the number of blows required for each 10 or 20 cm of penetration.

One of the major challenges is the correlation of the penetration results to different soil parameters (depending on soil type). This can be used to develop continuous soil profile by the dynamic probing test that reflects the shear strength parameters for different soil layers. Between the world wars, dynamic probing known was besides the traditional boring methods as means of subsoil exploration in the field of foundation engineering especially in Europe. During the early 20th century in Germany, a light dynamic penetrometer was developed by Künzel, (1936). The first heavy dynamic penetrometer was developed in Sweden around 1935 by a company called Borros and patented in (1942). Dimensions and masses of the four types of dynamic probing apparatus are specified in (EN-ISO-22476-2-2012).

Dynamic probing has been divided into the following main types

Light weight dynamic probing (DPL), it can be used in quality control of compacted soil besides the regular site investigation. Blows are counted every 10 cm: N_{10L}. Medium dynamic probing (DPM) representing the medium mass range of dynamic cone penetrometers N_{10M}. Heavy dynamic probing (DPH) test: $N_{10H.}$ Super heavy dynamic probing (DPSH). This test represents the upper limit of the mass range It is closely related to the dimensions of the standard penetration test (SPT). Blows are counted every 20 cm: N_{20}.

Hashmat, (2000) showed that dynamic probing mainly used in cohesion-less soils. For many soils especially soft cohesive and organic soils, the skin friction can have substantial effect on the penetration resistance, hence, the penetration resistance increases with depth in these cases. Also, using the (DP) below ground water table develops an excess water pressures that can affect the accuracy of the measurements.

Several correlations were proposed in literature. They were developed based on specific geological conditions and specific type of dynamic penetrometers for different soil shear parameters like (relative density (DR %) for cohesion-less soil, un-drained cohesion strength of clayey soils).

The widespread relationships were used in practice in Germany they are based on the blow count of the dynamic probing DPL and DPH and they are summarized in DIN 4094-3, Annex G, DIN EN 1997-2.

All equations for density index (ID) have the general form:

$$\mathbf{ID = a_1 + a_2 * \log N_{10}} \qquad \mathbf{(1)}$$

Where, N corresponds to: N_{10L} for DPL, N_{10H} for DPH, ID = Density Index = DR % / 100, C_U = coefficient of uniformity of soil. Values for the constants a_1 and a_2 for the three subsoil conditions (**Sands with $C_U \leq 3$, Sands with $C_U \leq 3$, Sand-gravel mixtures with $C_U \geq 3$)** above and below ground water.

Card, (1990), in UK proposed connecting dynamic examining test (DPH, SRS15) to the standard penetration test (SPT) in chalk and different kinds of non-firm soils as follows:

$$\mathbf{DPN_{300} = K_1 * SPT\ N_{30}} \tag{2}$$

Where, DPN_{300} is the number of (DP) blows for 3oo mm penetration depth. Values of constant K_1 and correlation coefficient R^2 for different subsurface soils were determined using statistical analysis which $K_{1=}$ 1.40 for sand with correlation coefficient R^2 = 75%.

Spagnoli, (2007) proposed the correlation between Super Heavy Dynamic Penetrometer (DPSH-ISSMFE) and SPT using the collected data by Muromachi & Kobayashi, (1982) as follows:

$$\mathbf{N_{30} = 1.15 * N_{SPT}} \tag{3}$$

Where N_{30}: Dynamic Probing N value (blows per 300 mm penetration).

Cestari, (2005) developed the following correlations between DPSH and SPT standardizes with 60% (the efficiency of both types of equipment).

$$\mathbf{N_{30}(_{60\%}) = C * N_{20}(_{60\%})} \tag{4}$$

Where, C is coefficient that depends on the soil type as follows:

C = 1.50 – 2.0 for gravely soils, C = 2.0 – 2.80 for sandy soils

C = 2.80 – 4.0 for argillaceous soils

The correlations between heavy German penetrometer (DPH) and the SPT in according to DIN 2002 is presented by the following equation.

$$\mathbf{N_{SPT} = 1.4 * N_{10}} \tag{5}$$

Curie et al., (2017) modified the mathematical formulation used to obtain the allowable bearing capacity (q_a) from dynamic probing tests in order to extend its applicability to the design of shallow foundations. Relationship that permits the estimation of this pressure in cohesion-less soils, from the results of (DPSH) tests taking into account a 25-mm settlement of shallow foundations shown in Equation (6):

Where:
B: Foundation width, D: Foundation depth and N DPSH: (number of blows every 20 cm penetration)

$$\mathbf{q_a = 20 * \left(350 * \frac{N\ DPSH}{(250+N\ DPSH)}\right) * \frac{(0.7.B^4+13)}{(\ B^4+13) * \frac{\left(1+2*\left(\frac{D}{B}\right)\right)}{\left(3*\left(\frac{D}{B}+1\right)\right)}}} \tag{6}$$

Bagińska, (2020). presents a comparison of geotechnical soil testing with the use of piezo-cone penetration test (CPT_u) and dynamic probing heavy (DPH) in a uniform coarse-grained medium located in southwest part of Poland.

Bucher et al., (1996) conducted a study on dynamic probing using ten well documented tests in sites with known soil properties under the auspices of the (International Society for Soil Mechanics and Foundation Engineering ISSMFE), 1989, A committee was assigned to revise and documenting the test.

The work of this committee was then extended to set out (Recommended Test Procedures) (RTP) for each penetration test including equipment specifications and tolerances. The RTP for dynamic probing formulated in 1977 and reported in (ISSMFE N_{10}) values interpreted to give the unit point resistance (r_d) or the dynamic point resistance (q_d) all against depth of point using the following formula:

$$\mathbf{r_d = M*g*\frac{h}{(A*e)}} \tag{7}$$

$$\mathbf{q_d = M*\frac{r_d}{M+M`}} \tag{8}$$

Where: (r_d) and (q_d) are resistance values in Pa. (M) is the mass of the hammer in kg. (g) is the acceleration due to gravity in m/sec^2. (h) is the falling height of fall of the hammer in m. (A) is the area of cone base in m^2. (e) is the average penetration in m per blow ($0.1/N_{10}$ for DPL, DPM15, DPM, and DPH, and $0.\ 2\ /\ N_{20}$ for DPSH). N_{10} is the number of blows per 10 cm.

M' is the total mass of the extension rods, the anvil and the guiding rods in kg. The value of r_d is the driving work done in penetrating the soil, it is used to calculate q_d values. (q_d) is modified value of (r_d) to account for the inertia of the driving rods and hammer after impact with the anvil.

The aim objective of this study is to develop correlation to predict various soil parameters using (DPT) test results based on dataset collected from Egypt and United Arab Emirates. These correlations are considered more representative to our local conditions compared to other correlations developed in the research.

To achieve that aim, an empirical correlation, to interpret geotechnical properties from dynamic cone penetration test. Values developed then, the effect of different field conditions such as ground water level, soil type on the dynamic penetrometer (DP) test were investigated. Finally, comparison between the proposed correlations and several correlations reoported in the literature will be conducted.

2. Methodology and Collected database

The first phase of this study was to collect the comprehensive dataset for dynamic penetration test (DPT) along with results for Standard penetration test. The database was collected from different projects in Egypt and United Arab Emirates that have similar geological features.

For each site, both DPT and SPT tests were performed at the same locations allowing a comparison between DPT and SPT results, also laboratory-tests results from these investigation reports were collected and used to develop the proposed correlations. Based on the field and laboratory test results, the relationship between the DPT results and soil properties such as unconfined compression strength, liquid and plastic limits, soil relative density, soil friction angle was investigated. The DP test equipment is compacted, portable and able to be utilized when access constraints prevent the use of conventional larger truck mounted borehole drilling rigs.

The relationship between soil strength parameters and DPT results are presented in this study using different tests like DPSH-B & DPH with different depths in different locations in delta Nile delta zone & Ain-Sokhna port in the east of Egypt & United Arab Emirates.

2.1 DPSH database –Egypt

The project's site is located in the eastern desert of Egypt in the Suez Gulf zone, the main aim of the investigation program is to provide adequate information necessary for project foundation design and construction. Dynamic cone & SPT tests were conducted in this site. The penetration resistance value (N_{20}) which is the number of blows required to penetrate the cone for 0.2 m were recorded.

Each record in the dataset of this project includes depth of sandy layer, N_{20} reading for DPSH-B test, N_{30} reading for SPT test, corrected SPT readings $(N_1)_{60}$ and the estimated relative density of each layer of sand DR%.

The following Tables (1), (2) summarized the statistical features of grain size distribution and penetration resistances of this database.

Table (1): Grain size distribution of the collected database of DPSH project

	$N\#_{200}$ (%)	d_{30} (mm)	d_{50} (mm)	d_{60} (mm)
Mean	21.540	.080	.200	.280
Median	21.080	.0820	.200	.250
Std. Deviation	8.390	.007	.060	.100
Range	32.320	.016	.160	.260
Minimum	3.830	.077	.100	.119
Maximum	36.150	.093	.260	.379

Table (2): Statistical analysis of DPSH project database

	Depth	N_{20}	N_{30}	$(N_1)_{60}$	DR %
Mean	6.98	13.21	22.10	22.21	53.65
Median	6.20	11	18.50	22	55
Std. Deviation	4.45	11.40	17.55	16.17	17.13
Range	15.00	52	68	65	68
Minimum	1.00	2	4	5	29
Maximum	16.00	54	72	70	97

2.2 DPH database (Sheikh Ammar road project, Al zahraa, Ajman, U.A.E)

During this Project, 3 Boreholes and probe holes (dynamic probing & SPT tests) were drilled to 5.0 m depth to provide adequate information necessary for the design and construction of the project. The DPH test were performed using a solid cone that has a diameter of 50.8 mm and a 60-degrees angle. The solid cone is driven into ground using 50 Kg automatic release hammer falling freely from 0.50 m.

The penetration resistance values (N_{10}) which is defined as the number of blows required to penetrate the cone for 0.1 m were recorded. The recorded data were the depth of each test, N_{10} reading for DPH test, N_{30} reading for SPT test, corrected SPT readings $(N_1)_{60}$ and the estimated relative density DR%. The following Tables (3) and (4) summarized the statistical features of fine percent and penetration resistances of this database.

Table (3): Fine percent $N\#_{200}$ (%) of collected data for Sheikh Ammar road, Al zahraa, Ajman, U.A.E project

	$N\#_{200}$ (%)
Mean	11.04
Median	6.30
Std. Deviation	9.62
Range	29.6
Minimum	0.80
Maximum	30.40

Table (4): Statistical analysis of Al zahraa, Ajman, U.A.E project database

	Depth	N_{20}	N_{30}	$(N_1)_{60}$	DR %
Mean	1.89	11.50	28.56	39.40	74.34
Median	1.75	11.50	29.50	40	75
Std. Deviation	0.98	3.78	13.44	13.40	11.01
Range	3.50	15	44	50	40
Minimum	0.50	3	6	11	50
Maximum	4.00	18	50	61	90

2.3 DPH results in different locations in the National highway projects in Egypt

Dynamic cone tests were conducted in the site of each highway project in Nile delta zone. The DPH tests were performed using a solid cone that has a diameter of 50.8 mm and a 60-degree angle. Laboratory tests on selected representative soil samples to evaluate the engineering properties of the soil where conducted.

The conducted tests include classification, pocket penetrometer, grain size analyses, Atterberg limits, specific gravity, direct shear, one-dimensional consolidation, calcium carbonate content, organic content, resistivity test and soil and water chemical analyses. The dataset of this project represented by the depth, un-drained cohesion from pocket tests C_u (KN/m2), N_{10} value and the calculated uncorrected dynamic point resistances above $q_{d.a}$ and below ground water level $q_{d.b}$ (KN/m2).

The following Tables (5) and (6) summarized the statistical features of penetration resistances of this database.

Table (5): Statistical analysis of the National highway projects in Egypt database (above ground water level)

	Depth	C_u	N_{10}	$q_{d.a}$
Mean	3.05	81.87	13.02	10929.32
Median	3.00	73.50	9	8090.72
Std. Deviation	1.32	36.53	10.83	8745.58
Range	6.00	156.80	35	30641.84
Minimum	1.00	24.50	1	835.05
Maximum	7.00	181.30	36	31476.89

Table (6): Statistical analysis of the National highway projects in Egypt database (below ground water level)

	Depth	C_u	N_{10}	$q_{d.b}$
Mean	4.10	85.35	18.90	15116.84
Median	4.00	76.02	20	16260.00
Std. Deviation	1.25	30.47	10.19	8658.02
Range	4.00	122.17	36	29326.64
Minimum	2.00	49.50	2	70.98
Maximum	6.00	171.67	38	29397.62

3. Regression results

Mathematical regression analysis method using excel sheets or SPSS (statistical package of social science) are used for correlation determination coefficient (R^2) that used as fitting function for the developed formulas.

3.1 For sandy soils

3.1.1 DPSH Sokhna project

Figure (1) shows the proposed formula to correlate (DR%) of sand & dynamic probing index (N_{20}) using Sokhna project database. Equation (9) presents the developed formula.

$$DR\% = -0.028*(N_{20})^2+2.70*(N_{20})+26 \qquad (9)$$

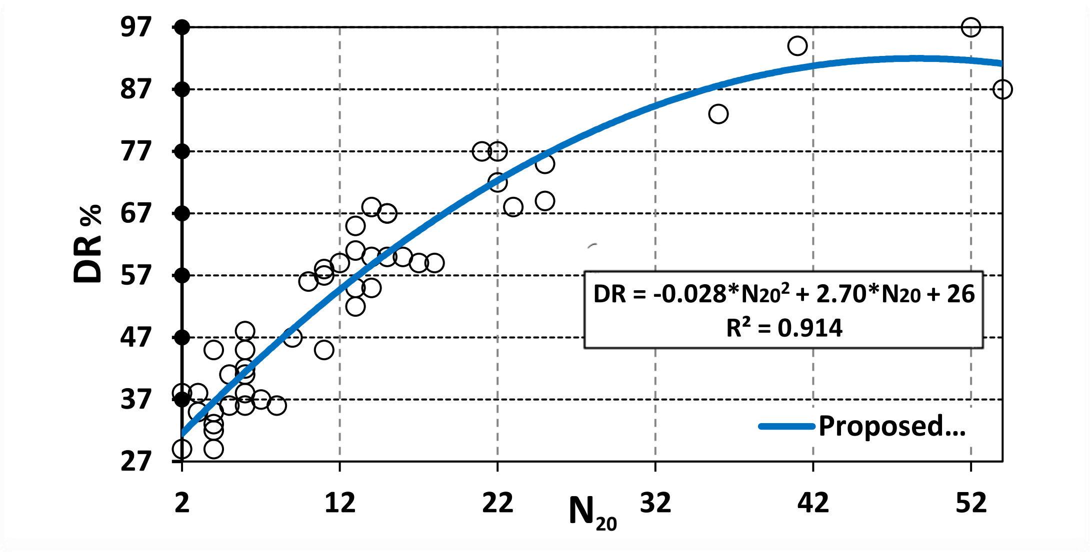

Figure (1): Proposed correlation model between relative density DR% of sand and dynamic probing index N_{20} for Sokhna project

Another proposed formula was developed to correlate N_{20} and $(N_1)_{60}$ values as shown in Equation (10). Figure (2) illustrates a comparison between the proposed correlation model and other previous correlation models (Muromachi and Kobayashi, 1982), (Spagnoli, 2008), (Cestari, 2005).

$$N_{20} = 0.64*((N_1)_{60)})^{\wedge}(0.97) \qquad (10)$$

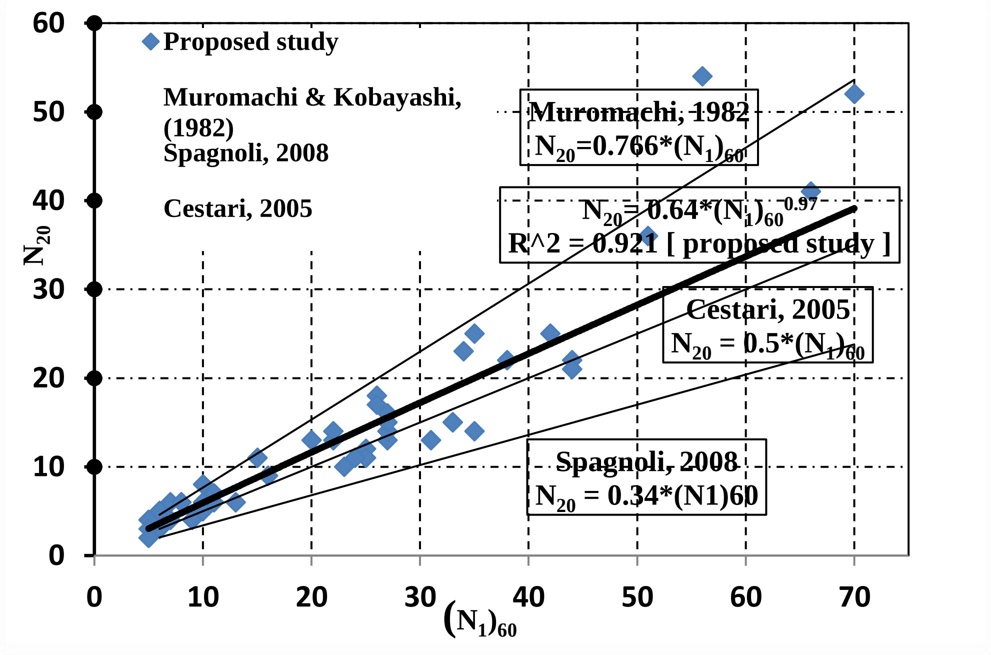

Figure (2): Comparison between the proposed correlation model and previous correlation model between $((N_1)_{60}$ and N_{20}

3.1.2 Sheikh Ammar road project

Figure (3) compares the proposed correlation model between (DR%) , (N_{10}) and DIN(4094) formula using project database. Equation (11) presents the developed formula

$$DR\,\% = 46.50 * e^{(N_{10}/25)} \qquad \textbf{(11)}$$

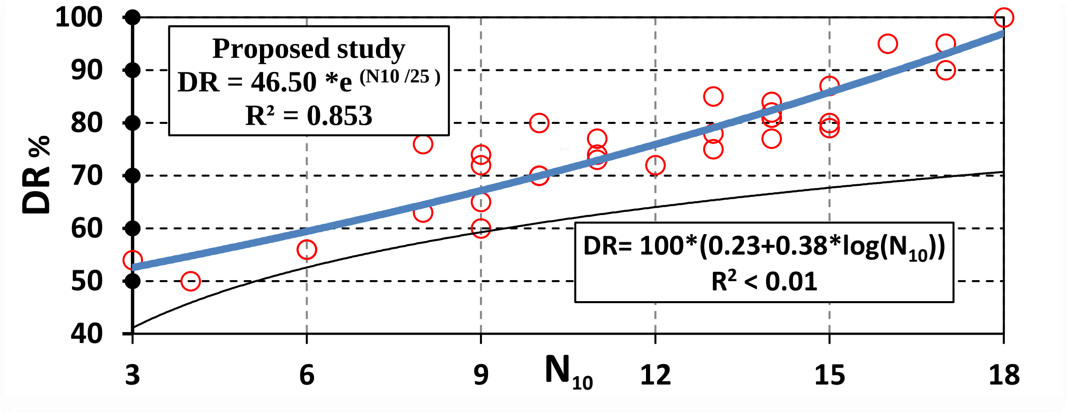

Figure (3): Comparison between the proposed correlation model and DIN(4094) correlation model for DR% and N_{10}

Another correlated model was conducted between N_{10} and $(N_1)_{60}$ as presented in Equation (12). Figure (4) compares between the proposed correlation model and other previous correlation model by Card and Roche, (1990) between $(N_1)_{60}$ and N_{10} using Sheikh Ammar road project database.

$$N_{10}=0.32 * \left((N_1)_{60}{}^{0.97}\right) \qquad \textbf{(12)}$$

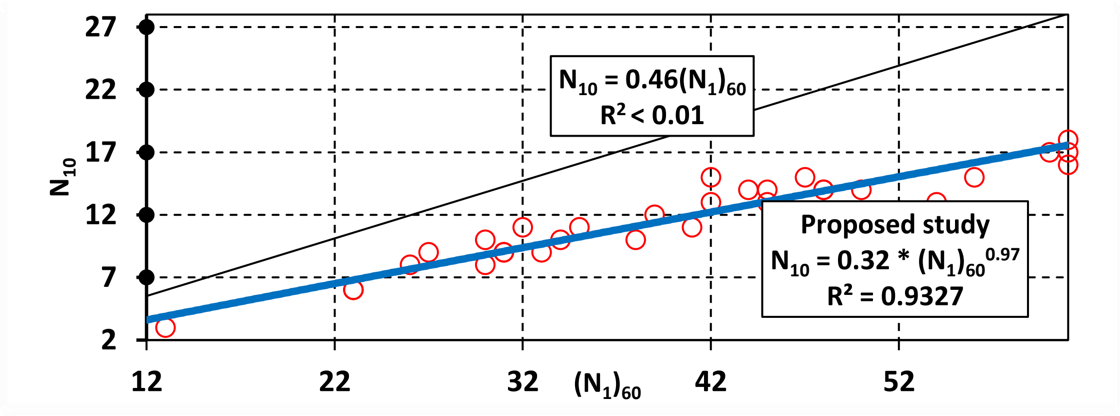

Figure (4): Comparison between the proposed correlation model and Card and Roche, (1990) for $(N_1)_{60\ SPT}$ and N_{10}.

3.2 For clayey soil

Figure (5) shows the proposed formula to correlate (c_u) of clay & and uncorrected dynamic point resistance above ground water level ($q_{d.a}$) using the database of National roads project. Equation (13) presents the developed formula.

$C_u = 1.68 * q_{d.a}$^ 0.42 **(13)**

With **R^2 = 88. 87% (High correlation) Model**

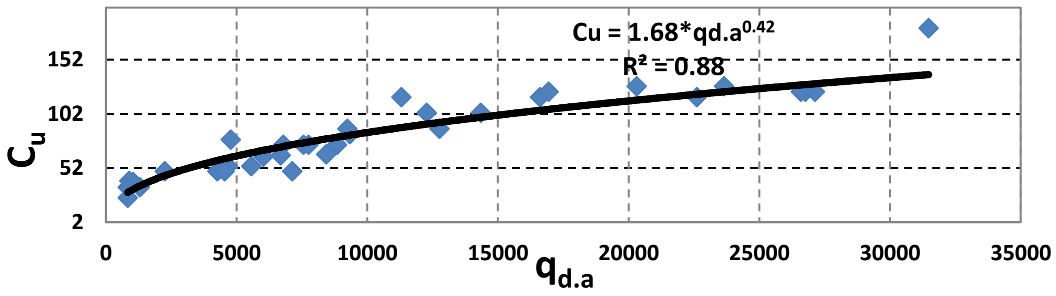

Figure (5): Proposed correlation model between un-drained cohesion of clay c_u and dynamic point resistance $q_{d.a}$ for National highways project

Figure (6) shows the proposed formula to correlate (c_u) of clay and uncorrected dynamic point resistance below ground water level ($q_{d.b}$) using the database of National roads project. Equation (14) presents the developed formula.

$C_u = 47.50 * e$^((3E-05)*$q_{d.b}$) **(14)**

With **R^2 = 76% (correlation) Model**

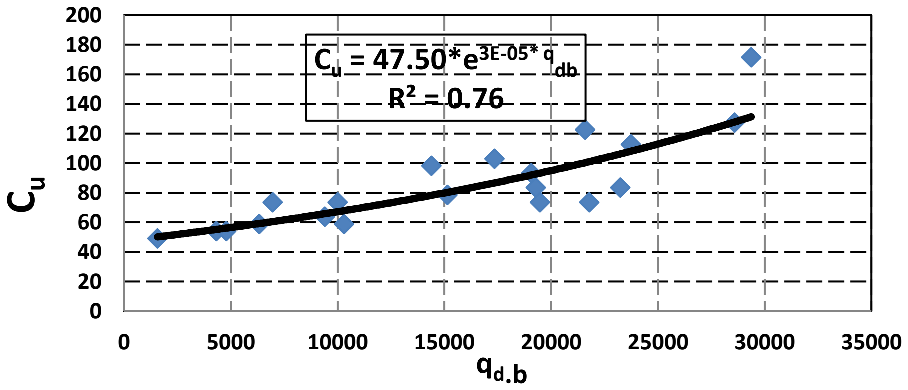

Figure (6): Proposed correlation model between un-drained cohesion of clay c_u and dynamic point resistance $q_{d.b}$ for National highways project

4. Verifications

To validate the results, it is recommending to take into account repeatability of the data results. So, the selection of the appropriate statistical parameters is required. Coefficient of variation (C_v). Herrick, (2002) considered C_v to study the repeatability of the dynamic penetration test. (C_v) is dimensionless and measures the spread of data in terms of the average value expressed as a percentage. According to Lee et al., (1983) variation of Cv for the results of (SPT), which can be considered as a form of (DPSH), to be between 27 to 85 % with a recommended value of 30%.

4.1 Verification of the proposed model correlation between N_{20} of DPSH-B for sandy soils by another data (Muromachi and Kobayashi, 1982) study

The following Figure (7) represents the verification of the proposed model between predicted N_{20} and N_{20} field data extracted from (Muromachi and Kobayashi, 1982) study.

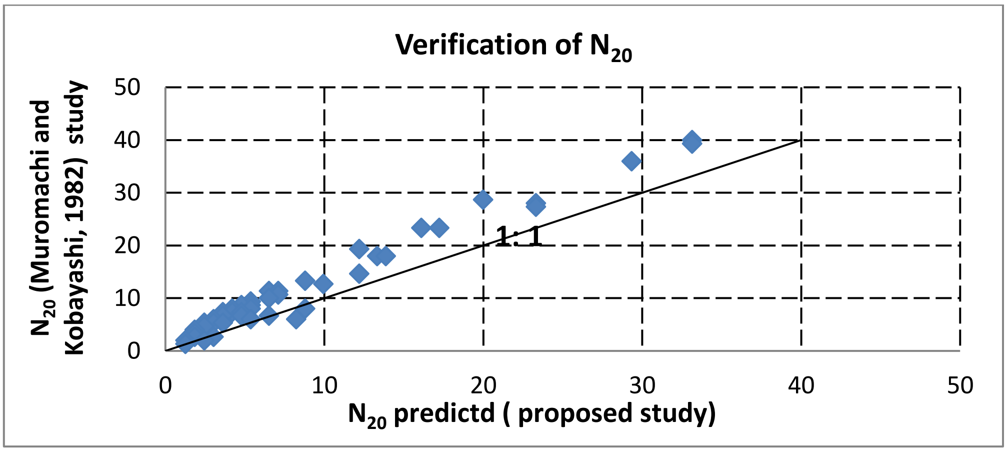

Figure (7): verification for the proposed correlation using the data given by (Muromachi and Kobayashi, 1982) study

As well as seen in the Figure (7) the predicted and data extracted from (Muromachi and Kobayashi, 1982) study are closely to the 1:1 line with an acceptable variation for the proposed model **(C_v) = 27.94%** which tends to the highly strength of proposed correlation model $\mathbf{R^2 = 83.6}$ % calculated by SPSS program by testing the proposed model correlation with data field of (Muromachi and Kobayashi, 1982) study.

4.2 Verifications of the proposed model correlation between N_{10} of DPH for sandy soils by another data (Card and Roche, 1988) study

The following Figure (8) represents the verification of the proposed model between predicted N_{10} and N_{10} field data extracted from (Card and Roche, 1988) study

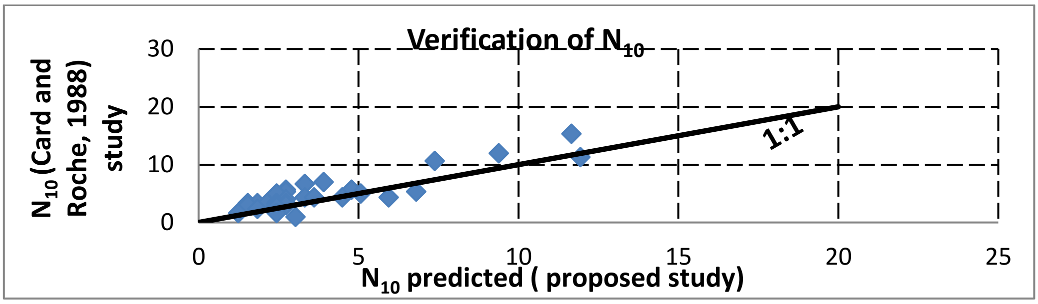

Figure (8): verification for the proposed correlation using the data given by (Card and Roche, 1988) study

As well as seen in the Figure (8) the predicted and data extracted from (Card and Roche, 1988) study are closely to the 1:1 line with an acceptable variation for the proposed model **(C_v) = 32.68 %** which tends to the highly strength of proposed correlation model $\mathbf{R^2 = 81.1\%}$ calculated by SPSS program by testing the proposed model correlation with data field of (Card and Roche, 1988) study.

5. Conclusions .

- The present study indicated that dynamic cone penetrometer test could be a valid test for estimation of the relative density of sandy soils, the results correlated with the corrected SPT number which can modify directly the consistency without corrections.

- Acceptable coefficient of variation for results (Cv) within the value reported for the SPT. Therefore the dynamic probing test offers an acceptable level of repeatability for different tests as follows :

1- (DPSH) test for depths reaches more than 20 m with high correlation proposed equation:

$$\mathbf{DR\% = -0.028*(N_{20})^2+2.70*(N_{20})+26}$$

2- (DPH) test for depths can reach to 10 m with high correlation proposed equation:

$$\mathbf{DR\ \% = 46.50*e^{\left(\frac{N_{10}}{25}\right)}}$$

- A reliable site-specific correlation between uncorrected q_d and C_u based on geotechnical data can be developed.

1- above ground water table: $\mathbf{C_u = 1.68 * q_{d.a}\hat{}\ 0.42}$

2- below ground water table: $\mathbf{C_u = 47.50 * e\text{^} ((3E\text{-}05)*q_{d.b})}$

- Further steps should be done by studying the correlation between DPSH N_{20} with C_u in cohesive soil to reach deeply depths which can estimate the q_u for clayey soil strata in Delta Nile area, taking into account the friction correction of penetration readings above and below the ground water table**.**

6. References

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