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ON USE OF DYNAMIC PROBING IN SANDY SOILS

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ABSTRACT:The Dynamic Cone Penetration Tests (DCPT) is a rapid inexpensive field test that can be used to assess the compactness of soils. However, correlation between the results of DCPT and soil properties or any other trusted field test is not well established yet. In this paper, a General Method of Data Handling (GMDH) approach was utilized to investigate the correlation between Dynamic Probing Super Heavy (DPSH) and Standard Penetration Tests (SPTs) using test results obtained from an intensive site investigation study carried out on sandy soils in Egypt. Linking these two tests will enable DPSH to make use of well-established correlations between SPT and soil properties. The developed GMDH model indicates that the relation between the results of the two penetrometer tests is nonlinear for sandy soils and is a function of soil relative density and effective overburden pressure. The validity of the proposed correlation was verified using test results on sandy soils from different sites.

Keywords: Field test, cone, dynamic, penetration.

INTRODUCTION

The Dynamic Cone Penetration Test (DCPT) is a simple ground investigation technique in which a solid penetrometer is driven into the ground and the number of blows required to drive it to a given depth is recorded. Dynamic cone penetrometers were originally designed to obtain qualitative and quantitative data on the soil resistance to penetration and in particular to determine the compactness of cohesionless soil which are usually difficult to sample. Four different dynamic probing types are recommended for use by the international reference test procedures (Stefanoff et al. 1988). These are: Dynamic Probing Light (DPL), Dynamic Probing Medium (DPM), Dynamic Probing Heavy (DPH) and Dynamic Probing Super Heavy (DPSH). They differ in cone size, hammer weight and drop height to fit different soils conditions and various investigation purposes.

In the pavement construction field, light DCPT under ASTM standard specification (ASTM D6951-03) has been used extensively. Moreover, several investigations were conducted to establish a correlation between the results obtained from the DCPT and the pavement material properties such as CBR, unconfined compressive strength, resilient modulus and shear strength (Jayawickrama et al. 2000; Gabr et al. 2000; Chen et al. 2005). On the other hand, although DCPT is internationally recognized as a soil investigation tool for designing shallow and deep foundations (BS EN ISO 22476-2:2005, DIN 4094-1 (1974), DIN 4094-2 (1980)), only limited research work has been conducted in relation to foundation engineering (Sanglerat 1972; Kayalar 1988; Butcher et al. 1996). The advantages of DCPT over other penetration tests are its low cost and portability. However, although DCPT is a blind investigation tool which does not give direct information on soil type; its data can be exploited in combination with the results of borehole or trial pit investigations to provide an economic method of assessing the ground characteristics between each investigation location. It is particularly useful to detect different strata horizons, strength characteristics, obstructions or voids.

The relationship between soil strength parameters and DCPT results is not well established yet. An approach that can be used to find a link between the DCPT and soil strength parameters is to establish a correlation between DCPT results and the results of a widely recognized penetrometer test such as the Standard Penetration Test (SPT). Such approach has been used by some researchers (Bergdahl and Eriksson 1983; Cearns and Mckenzie 1988; Butcher et al. 1996; Spagnoli 2007). However, a reliable correlation does not yet exist (Spagnoli 2007). It is thought that the main reason behind the difference and uncertainty of the available DCPT-SPT correlations are their failure to

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Note: Discussion on this paper is open until June 2012

account for the effect of hammer efficiency, soil strength, effective overburden pressure, and soil type.

The aim of this paper is to develop a correlation between DPSH-SPT results that take into consideration these effects using the results obtained from an intensive site investigation program on sandy soils conducted in Egypt. The approach of general method of data handling (GMDH) was used to model such relationship. The developed GMDH model was used to investigate the effect of soil strength, effective overburden pressure, and soil type on the DPSH-SPT correlation. Furthermore, the validity of the developed DPSH-SPT correlation was tested using the results obtained from Egyptian sites that were not used in developing the correlation; two sites located in Auckland, New Zealand; one site located in the south of Portugal; and the correlation equation proposed by Cearns and McKenzie (1988).

STUDY DATABASE

The database of this study was drawn from 14 different sites located in Egypt. The soil investigation program for each site included one SPT borehole and three to five adjacent DPSH tests to depths of 15.00 m. The distances between SPT and DPSH tests locations varied between 2.0 to 6.0m. SPT tests, at one meter depth intervals, were conducted according to ASTM standard specifications (ASTM, D1586-99) where the first 15 cm of penetration was disregarded and the number of blows for the next 30 cm penetration was recorded as N_{30}.

DPSH test equipment and procedure followed the guidelines recommended by British standard (BS EN ISO 22476-2:2005) as listed in Table 1. The number of blows required to drive the cone penetrometer 0.20 m into the ground, DC_{20}, was measured continuously throughout the test depth (15.0 m). The DPSH rods were rotated one and half turns every 0.20 m to keep the rods straight and vertical. The torque necessary to turn the driving rods is usually measured to evaluate the effect of the skin friction on DPSH blow count measured during probing. The skin friction could develop along the rod length due to the annulus around the rods squeezing in or collapsing. However, in this site the torque was not measured since according to the international reference test procedures for dynamic probing (Stefanoff et al. 1988) dynamic cone test equipment with cone/rod diameter ratio exceeding about 1.3 leads to results that are little or not at all influenced by skin friction in cohesionless soils. This justification is also supported by the experimental results reported by Waschkowski (1982) which shows that in sandy soils the dynamic skin friction is negligible.

Table 1 Technical data of the DPSH (BS EN ISO 22476: Part 2)

Factor	DPSH
Hammer mass, kg	63.5 ± 0.5
Height of fall, m	0.75 ± 0.02
Mass of anvil and guide rod (max), kg	30
Max mass of rod, kg/m	8
Rod OD, mm	35
Apex angle, deg	90
Nominal area of cone cm^2	20
Cone diameter, new, mm	50.5 ± 0.5
Mantel length of cone, mm	50.5 ± 2
Cone taper angle, upper, Deg.	11
Length of cone tip, mm.	25.3 ± 0.4
Number. of blows/cm penetration	20 cm; N_{20}
Standard range of blows	5 - 100
Specific work per blow; Mgh/A, kJ /m^2	238

The SPT-borehole samples were described and classified according to ASTM standard specifications as shown in Fig. 1 for some of these sites. In general, the sites' stratigraphy consists mainly of sandy soils with occasional silty clay lenses. For the soil classified as SM or SC, the percentage of passing sieve no. 200 (0.075 mm) is less than 26%. Soil description was converted into a continuous numerical value using a soil classification index, I_c, proposed by Robertson (1990) as shown in Fig. 2. The ground water level was determined from boreholes and the effective overburden pressure (p) at penetration test depth was calculated.

To eliminate the hammer efficiency effect on DPSH-SPT relation, the standard SPT blow count $(N_1)_{60}$, corrected to overburden stress equal to 1.0 atmospheric pressure and normalized to an effective energy delivered to the rods at 60% of free fall theoretical energy, was used instead of N_{30} as follows:

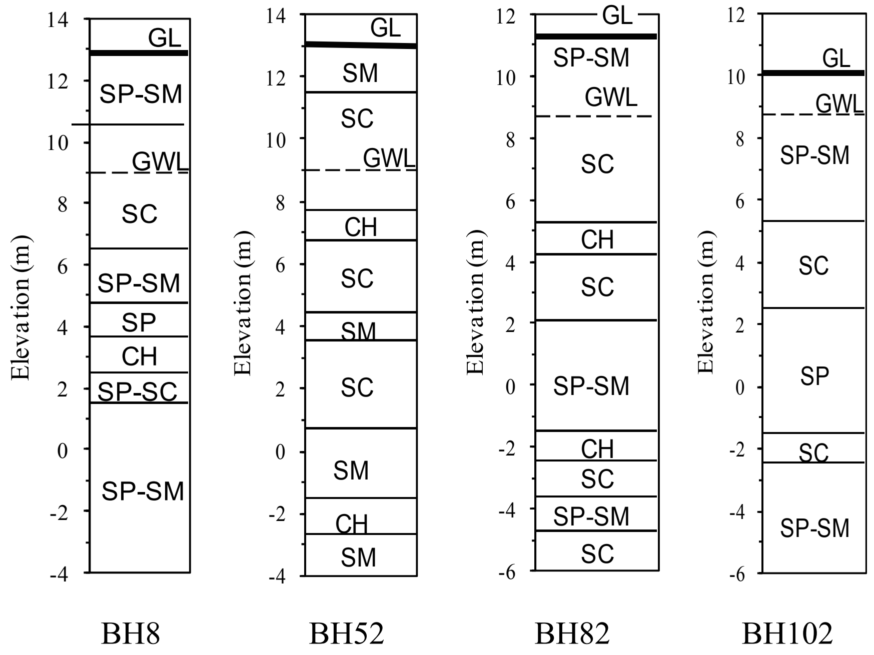

Fig.1 Soil profile at the Egyptian sites

$$(N_1)_{60} = N_{30} \times C_1 \times C_2 \times C_3 \times C_4 \qquad (1)$$

where C_1, C_2, C_3, and C_4 are correction factors for hammer energy, anvil, rod length, and overburden pressure, respectively. In this study, the correction factors C_1, C_2, and C_3 were determined by McGregor and Duncan (1998) whereas C_4 can be estimated based on Tokimatsu and Seed (1987) as listed in Table 2. As a pulley safety hammer was used for both tests, correction factors C_1 and C_2 can be also used for DPSH test results. Furthermore, since the SPT rod length correction is only applied for very shallow depths, it can be concluded that C_3 is an insignificant correction factor. Therefore, assuming the validity of SPT rod length correction factor for DPSH test results will not produce measurable errors. The validity of SPT overburden pressure correction, C_4, for DPSH test results will be investigated in the following section. Therefore, the standard blow count of DPSH test, DC_{60}, normalized to an effective energy delivered to rod at 60% of free fall theoretical energy can be computed from the measured DC_{20} as follows:

$$DC_{60} = DC_{20} \times C_1 \times C_2 \times C_3 (2) \qquad (2)$$

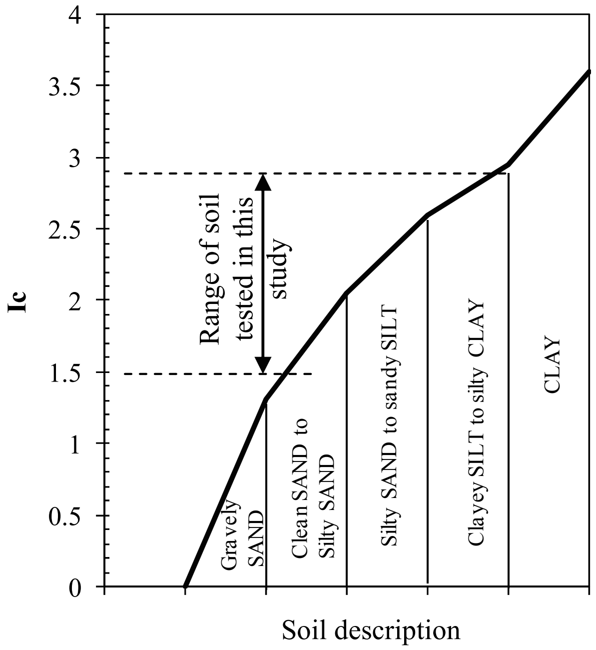

Fig. 2 Soil classification index (Robertson, 1990)

The data base of this study consists of 201 records. The maximum, minimum and average of the database variables are listed in Table 3. However, it should be mentioned that about50% of the patterns haveI_c between 1.5 and 2.0 and 35 % of the patterns have I_c between 2.0 and 2.5. Therefore, the developed correlation reported in this study will be only valid for sandy soils.

Table 2 SPT correction factors

Factor	Variable	Correction
Energy Ratio[1] (c_1)	Trip or Automatic Hammer	1.67
	Rope and Pulley	1.0
	Safety Hammer*	
	Donut Hammer	0.75
Anvil[1] (c_2)	Small (4.4 lbs)	0.85
	Large (26.5 lbs)	0.7
	Safety (5.5 lbs)*	0.9
Rod Length[1] (c_3)	0 to 3.0 m	0.75
	Over 3.0 m	1.0
Over-burden pressure[2] (c_4)	2.90 t/m^2	1.60
	4.80 t/m^2	1.30
	9.60 t/m^2	1.00
	19.15 t/m^2	0.70
	28.75 t/m^2	0.55
	38.30 t/m^2	0.50

[1] Mcgregor and Duncan (1998)
[2] Tokimatsu and Seed (1987)

Table 3 Range of database variables

	N_{60}	DC_{20}	p/P_a	I_c
Average	21	15	0.85	-
Maximum	47.5	49.5	1.64	2.9
Minimum	5	1.33	0.04	1.5

DESIGN OF GMDH MODEL

The GMDH modelling approach is based on sorting out procedure, which implements consequent testing of models chosen from a set of model-candidates in accordance with the given criterion. Using a supervised learning procedure, this method allows finding functional dependence of the output on the most significant inputs of the system. The algorithm of GMDH model was originally developed by Madala and Ivakhnenko (1994). Comprehensive testing of GMDH proves that it is a powerful tool for mathematical modeling of a wide variety of different real-life problems (Dolenko et al. 1996). Recently, several geotechnical studies have used GMDH algorithm to interpret the results of field penetration tests (Ardalan et al. 2009; Kalsntary et al., 2009). NeuroShell II (1996) code produced by Ward System Group was used in this study to develop, train, and test the GMDH model.

The algorithm of GMDH model involves generating a set of model-candidates in accordance with the specific iterative rule. These models compete between themselves for a chance to be selected for the next step of the procedure as shown in Fig. 3. Selection of the model-candidates is based on the external selection criterion. For example, as shown in Fig. 3, a particular description in the form is used in the first layer,

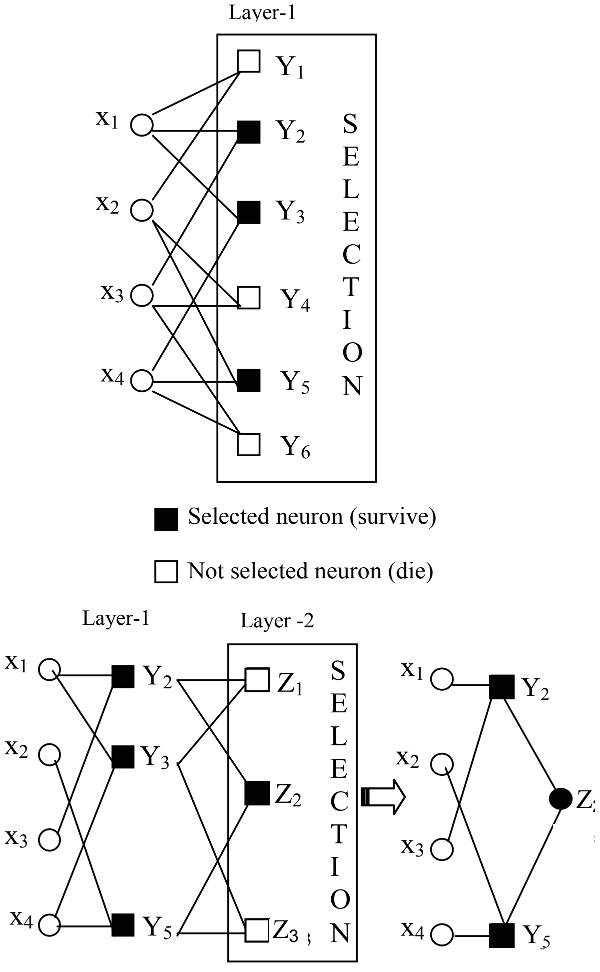

Fig. 3 The architecture of GMDH

$$Y = a_0 + a_1 x_i + a_2 x_j + a_3 x_i x_j \tag{3}$$

Then, a particular description in the second layer can be used as follows, and so on:

$$Z = b_0 + b_1 Y_i + b_2 Y_j + b_3 Y_i Y_j \tag{4}$$

In other words, the output values of a preceding layer serve as arguments in the succeeding layer. This process continues until the net stops getting better according to a pre-specified selection criterion. Actually, the algorithm checks (2d-1) possible models for each two variables xi and xj, where d is the number of terms in a particular description (in our example d=4 as the set of basic functions is $\{1, x_i, x_j, x_i x_j\}$). For all possible pairs of input variables, (2d-1)[m(m-1)/2] models must be evaluated, where m is the number of input variables.

The available database in this study was divided into two groups. The first group, including 9 sites (128 records), was used as a training set whereas the remaining 5 sites (73 records) were used for testing the robustness of the developed GMDH model. The designed GMDH model has three inputs (DC_{60}, p, and I_c), and one output ($(N_1)_{60}/DC_{60}$). The iterative multilayered algorithm was used. The design control criterion used in this network was as follow: Max. Variable in connection was set to (x1, x2), which means two variables are selected. Max. Product term in connection was set to (None), which means no covariant allowed. Max. Variable degree in connection was set to x. Selection criterion of the model-candidates was set to regularity that minimizes the normalized mean square error of the model on the test set. The maximum number of survivor models in each layer was set to 3.

DISCUSSION OF RESULTS

The accuracy of the developed DPSH-SPT correlation using the GMDH model was assessed statistically using the training and testing data sets, as listed in Table 4. High coefficients of correlations were obtained for both of the training and testing data sets. The developed GMDH model was used to investigate the effect of soil type and overburden pressure on $(N_1)_{60}/D_{60}$ as shown in Fig. 4. In general, for sandy soils, the results indicate that $(N_1)_{60}/D_{60}$ has a non-linear relation with DC_{60}. Moreover, the overburden pressure has more influence on $(N_1)_{60}/D_{60}$ than the soil type. However, for $DC_{60}>20$, the effect of both parameters can be ignored as shown in Fig. 4. Therefore, for simplicity the parameter I_c can be given a constant value of 2.0 for sandy soils.

Table 4 Evaluation of GMDH model output results

Statistical measurement		Training data set	Testing data set
Mean squared error		0.1523	0.3271
Mean absolute error		0.2899	0.3577
Min. absolute error		0.0009	0.0043
Max. absolute error		1.3922	3.2253
Correlation coefficient r		0.972	0.9586
Percentage of data	within 5% error	35.938	28.767
	within 5% to 10% error	28.906	28.767
	within 10% to 20% error	17.969	28.767
	within 20% to 30% error	7.031	10.959
	over 30% error	10.156	2.74

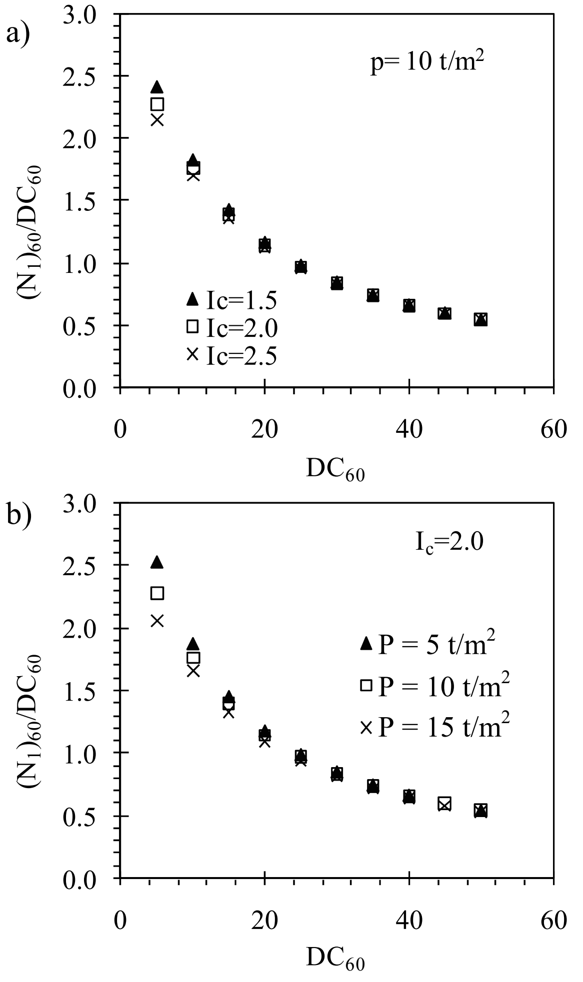

Fig. 4 The effect of soil type (a), and overburden pressure (b) on the ratio $(N_1)_{60}/DC_{60}$

The results of Fig. 4b can be used to estimate the overburden correction factor (C_4) for DPSH test. As $(N_1)_{60}$ values are corrected for overburden pressure, the change of DC_{60} with overburden pressure at constant $(N_1)_{60}$ can be used for this purpose as shown in Fig. 5a. The DPSH overburden correction factor can be calculated by normalizing DC_{60}, at each $(N_1)_{60}$, for its value at 1.0 atmospheric pressure as shown in Fig. 5b. The SPT overburden correction factor proposed by Tokimatsu and Seed (1987) was also plotted in Fig. 5b. It shows close agreement with the DPSH results. Therefore, it can be concluded that the SPT overburden correction factor can also be used for DPSH test. To check the soundness of this finding, the Tokimatsu and Seed (1987) correction factor was applied to the DC_{60} results given in Fig.4b to calculate $(DC_1)_{60}$; the standard DPSH blow count corrected to overburden stress equal to 1.0 atmospheric pressure and normalized to an effective energy delivered to the rods at 60% of free fall theoretical energy. The results at different overburden pressures, shown in Fig. 4b, have collapsed into one line, as shown in Fig. 6, confirming the validity of Tokimatsu and Seed (1987) correction factor for DPSH test. Therefore, if similar hammer system is used for both tests, the following equation is valid:

$$N_{30}/ DC_{20} = (N_1)_{60}/ (DC_1)_{60} \qquad (5)$$

Moreover, as $(DC_1)_{60}$ can reflect the soil compactness (relative density), it can be concluded that $(N_1)_{60}/(DC_1)_{60}$ decreases non-linearly as soil relative density increases.

VALIDATION OF THE PROPOSED MODEL

The validity of the developed DPSH-SPT correlation using GMDH model was tested using the five testing sites in Egypt which were not used in developing the proposed DPSH-SPT correlation. A typical comparison between the model predictions and the field results is shown in Fig. 7 where an acceptable agreement between predicted and measured $(N_1)_{60}$ values can be observed.

The proposed model was also assessed using SPT and DPSH penetration results from two different sites in Auckland, New Zealand as shown in Figs. 8 and 9. The stratigraphy at these sites consists mainly of a sandy soil layer underlying a silty clay soil layer. The distance between SPT and DPSH was between 3.0 to 5.0 m. The torque necessary to turn the DPSH driving rods was measured due to the presence of the upper cohesive soil layer. Such measurements are usually used to assess the amount of skin friction developed on the driving rods.

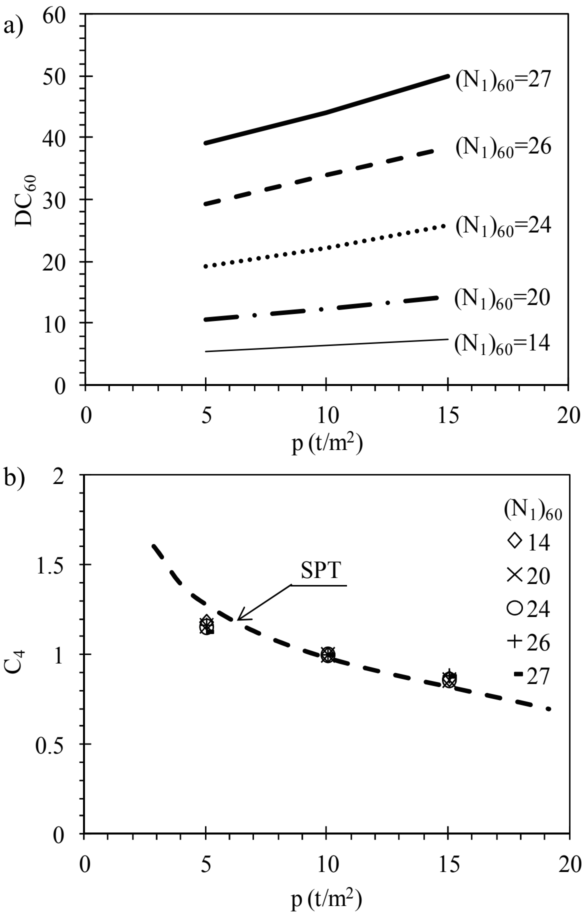

Fig. 5 Determination of overburden pressure correction factor for DPSH results

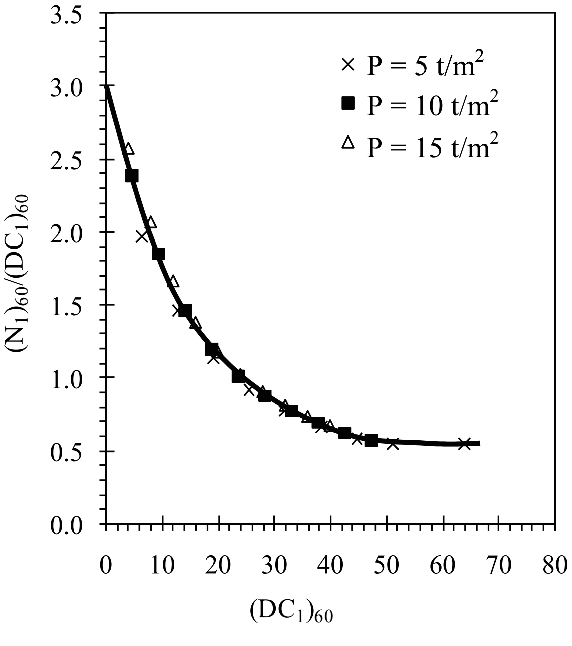

Fig. 6 DPSH results corrected for overburden pressure using Tokimatsu and Seed (1987)

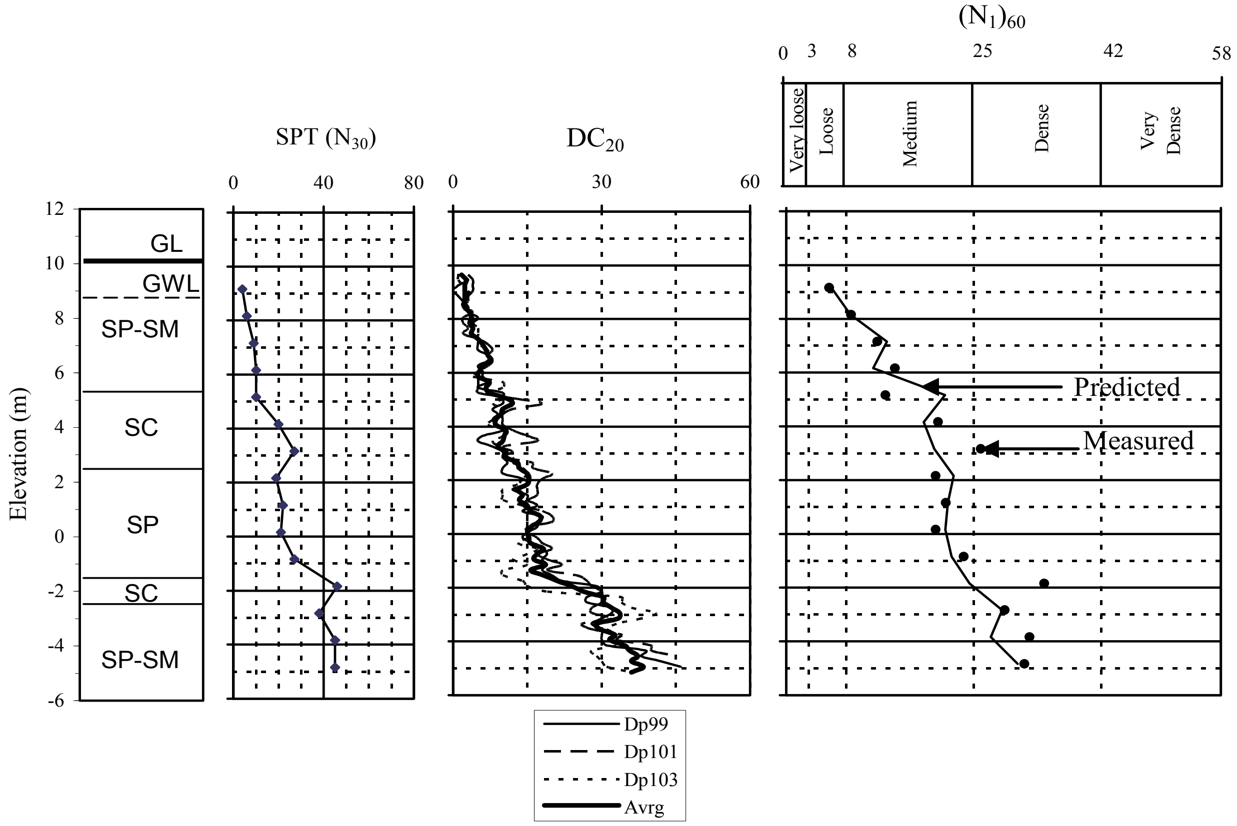

Fig. 7 Comparison between predicted and measured $(N_1)_{60}$ for atypical testing site in Egypt

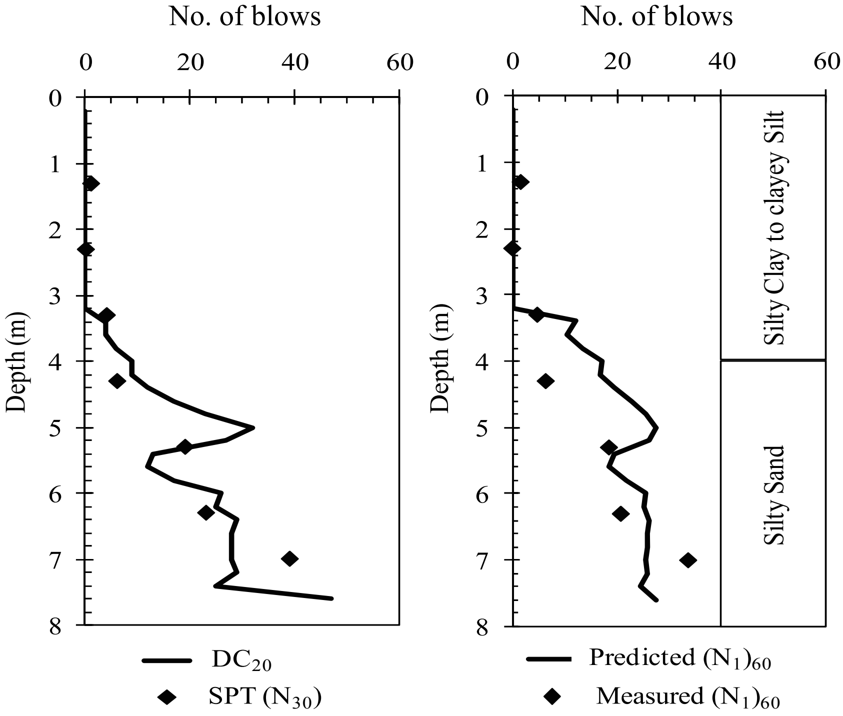

Fig. 8 Comparison between predicted and measured $(N_1)_{60}$ for site no.1 in Auckland

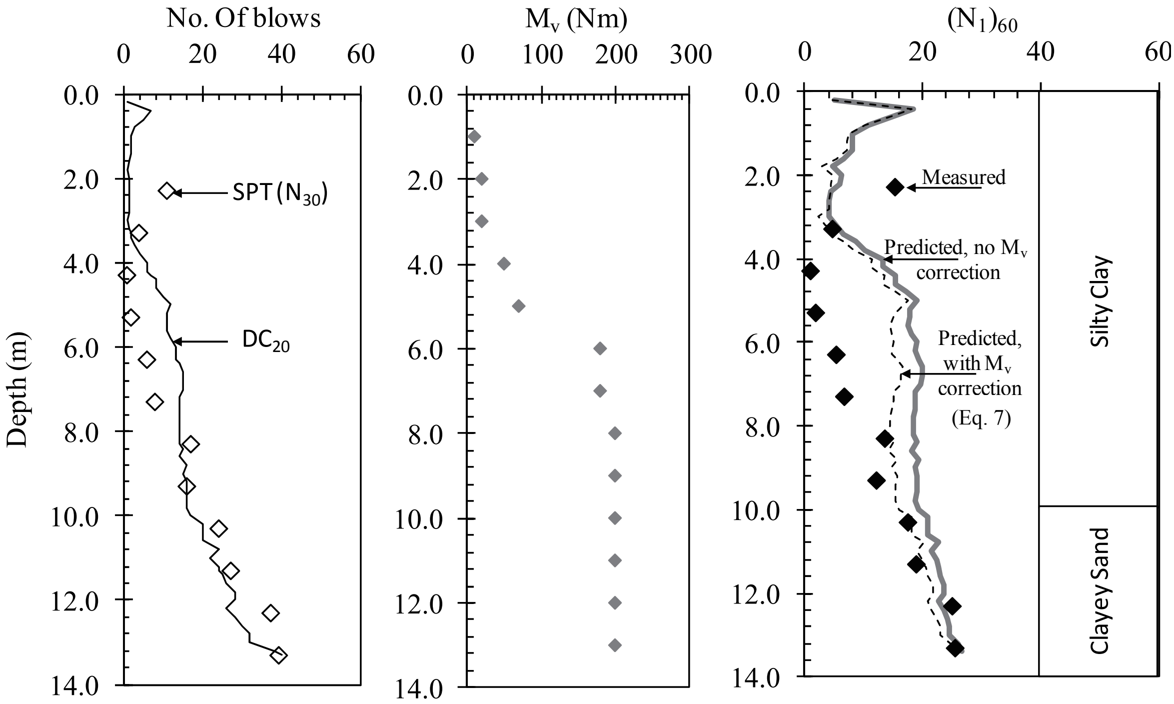

Fig. 9 Comparison between predicted and measured $(N_1)_{60}$ for site no.2 in Auckland

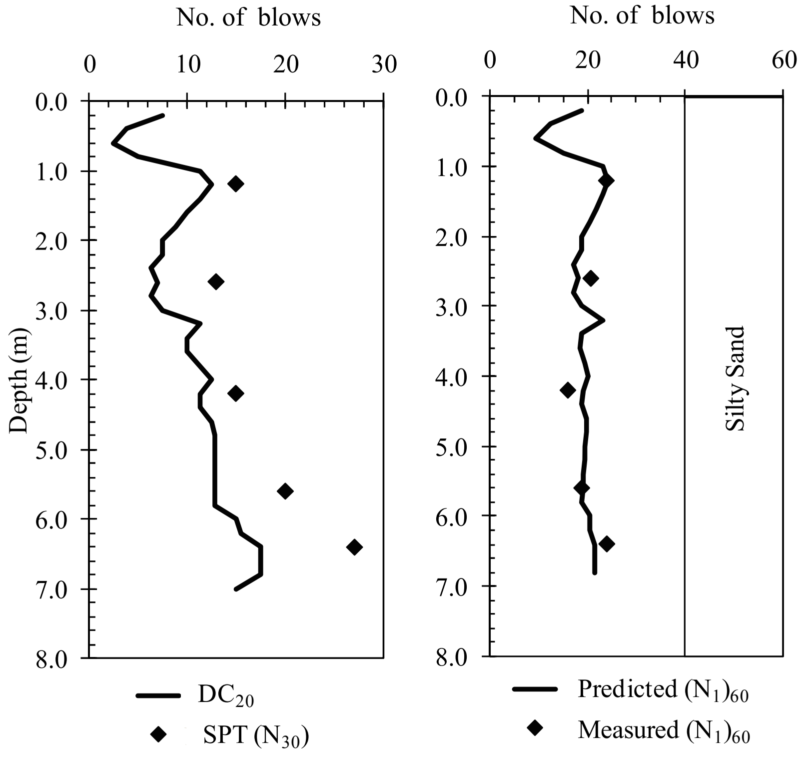

Fig. 10 Comparison between predicted and measured $(N_1)_{60}$ for site in Marvao, Portugal (Duarte et al. 2004)

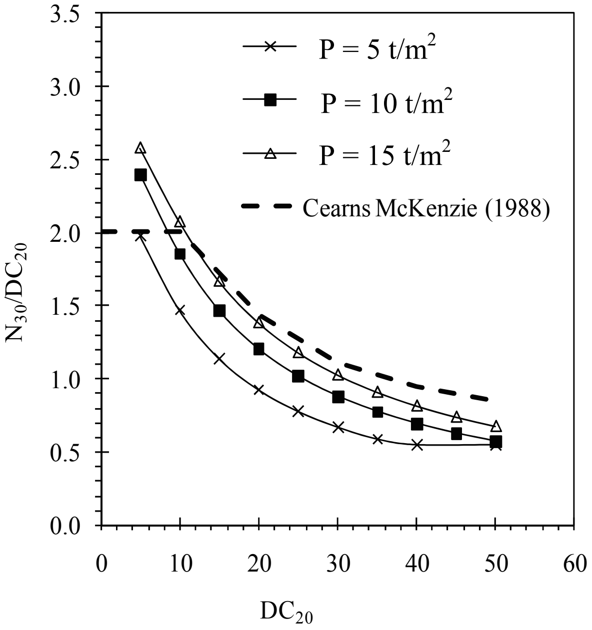

Fig. 11 Comparison between the proposed DPSH-SPT correlation in this study and the correlation by Cearns and McKenzie (1988)

For the first site (Fig. 8), the torque measurements were very low through the soft clay and the sandy layer (less than 10 Nm). Therefore the effect of developed skin friction can be ignored. Such insignificant dynamic skin friction of soft clay soils was also reported by Waschkowski (1982). Consequently, the measured DPSH penetration resistance at this site is totally due to the cone penetration resistance and consequently no skin friction correction is required. Taking into consideration the possible effect of the spatial soil heterogeneity at the testing points of DPSH and SPT, the comparison between the measured and predicted (N1)60 shown in Fig. 8 can be considered reasonable from the practical view point.

For the second site, the torque measurements show different behaviour as it builds up through the upper clay layer reaching to 200 Nm which is the maximum capacity of the utilized torque wrench as illustrated in Fig. 9. However, as the sandy layer is not expected to add significant skin friction to the DPSH driving rods, it was assumed that the torque measurements through the sandy layer are equal to 200 Nm. In fact such high torque measurements indicate that the measured DPSH penetration resistance is not purely due to cone penetration resistance and consequently skin friction correction is required.

Based on the simplified assumption that average skin friction along the rod is the same when the rod is driven down by the hammer, as it is when the rod is rotated and the torque is measured, Dahlberg and Bergdahl (1974) have suggested a correction for the effect of skin friction as follows:

$$N_{skin} = \frac{2M_v e}{DM_o gh} \qquad (6)$$

where N_{skin} is the number of blows required to overcome skin friction resistance, e is the standard depth increment, D is rod diameter, M_o is hammer mass, h is hammer drop height, Mv is torque measurement on rod. For DPSH this formula gives $N_{skin}= 0.0244M_v$.

i.e. 41 Nm torque = 1 blow/20 cm (7)

Fig. 9 shows a comparison between $(N_1)_{60}$ field measurements and the proposed model prediction considering no torque correction, and with torque correction according to Eq. (7). Better agreement can be obtained with torque correction made according to Eq. (7). In fact the observed deviation between the predicted and the measured results through the silty clay layer can be also explained in light of the fact that the data used in the development of the proposed model in this study was mainly from sandy soils and extrapolating the modelworking range to include cohesive soils is not recommended before investigating the effect of soil type on the correlation between SPT and DPSH test results.

The proposed correlation in this study was also tested using the field test results reported by Duarte et al. (2004) for a sandy soil from Marvao in the south of Portugal. The Marvao soil was classified as SM with 84.72 % and 17.05% passing from sieve no. 4 (4.75 mm) and 200 (0.075 mm), respectively. The distance between SPT and DPSH test location was between 0.5 and 1.0 m. Fig. 10 shows very good agreement between $(N_1)_{60}$ field measurements and the proposed model prediction.

Finally, the soundness of the proposed DPSH-SPT correlation can be also supported by comparing it with the correlation proposed by Cearns and McKenzie (1988) as shown in Fig. 11. Both correlations have approximately similar non-linear pattern in N_{30}/DC_{20}-DC_{20} plane. However, since Cearns and McKenzie (1988) did not consider the influence of effective overburden pressure and it wasn't clear whether similar hammering system was used for both tests, their correlation can be considered as a special case of the general correlation proposed in this study.

CONCLUSIONS

As Standard Penetration Test (SPT) is well developed for the sandy soils, correlations between SPT and other test results (SCPT, DCPT, etc.) are best established for sands only. In this study, GMDH model was used to predict the SPT results from the results of DPSH test for sandy soils. The salient conclusions that can be drawn from this study are:

- GMDH approach is a useful tool for establishing a correlation between SPT and DPSH test results.
- The SPT overburden pressure correction factor can also be used for DPSH test results.
- DPSH-SPT correlation is function of soil relative density and overburden pressure.

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