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A correlation between the Dynamic Cone Penetrometer and bearing capacity of a local soil formation

Une corrélation entre le Pénétromètre Dynamique et la portance de la formation d'un sol local

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ABSTRACT
The dynamic cone penetrometer (DCP), especially when combined with a vibrating hammer offers a simple and inexpensive site investigation equipment for simple structures. However, the difficulty in the successful application of this equipment lies in the absence of a credible correlation between the DCP test results and the bearing capacity. This paper discusses the correlation between the DCP test results and the bearing capacity of a shallow foundation. In-mould DCP tests were performed in the laboratory on re-moulded and re-compacted samples of two local soils. Similar samples were subjected to triaxial compression tests to determine the strength parameters from which the allowable bearing pressure of a footing on the material was computed. The DCP values were then correlated with the allowable bearing pressure and the results compared with those predicted with correlations from the literature. Field results to illustrate the potential application of the DCP as a simple site investigation tool for foundation design are also presented

RÉSUMÉ
Le Pénétromètre Dynamique (DCP), spécialement lorsque lié à un marteau vibrant est un appareil simple et peu coûteux pour l'investigation des sites pour des structures simples. Cependant, la difficulté liée à l'utilisation de cet appareil est l'absence d'une corrélation plausible entre les résultats des essais et la portance. Cette étude vise à discuter de la corrélation entre les résultats des essais DCP et la portance d'une fondation peu profonde. Des essais DCP en moule ont été effectués au laboratoire sur des échantillons remoulés et recompactés de deux sols locaux. Des échantillons similaires ont été soumis au test de compression triaxial en vue de déterminer les paramètres de force, desquels la portance admissible d'une semelle sur le matériel a été calculée. Les valeurs DCP ont été alors mises en corrélation avec la portance admissible et les résultats comparés avec ceux prédits par la littérature. Aussi sont inclus les résultats des essais sur le terrain pour illustrer l'utilisation éventuelle du DCP comme un outil simple d'investigation du site pour la conception de la fondation.

1 INTRODUCTION

Proper geotechnical engineering practice requires that the scope of a site investigation be made commensurate with the type of geotechnical problem on hand. For small projects especially in developing countries, simple and economical methods of site investigation are required. Even though the (static) cone penetrometer test (CPT) is a well established rapid, reliable and relatively economical method of in-situ sub-surface characterization, it is used mostly in developed countries and it is not known locally. There is therefore the need for a simple, cost effective, rapid, in situ method for characterizing the sub-surface profile. The dynamic cone penetrometer (DCP), especially when combined with a vibrating hammer has the potential to partially fill such a need, provided that validated correlations between the DCP readings and strength of soils is available. Whereas the DCP furnishes a continuous strength profile, the vibrating hammer rapidly provides samples for visual logging of the profile.

Cones of different sizes and shapes are used in cone penetrometers. Table 1 summarizes the basic characteristics of some DCP's. It can be seen that DCP's reported in the literature vary greatly but it appears most of them have energy per blow per unit cone area of 144kN-m/m^2.

The DCP is extensively used for pavement overlay design where fundamentally it is used as a proxy test for the determination of the California Bearing Ratio (CBR). For this purpose, extensive research by Scala (1956), van Vuuren (1969), Kleyn (1975) and Livney (1987), has been carried out to establish a correlation between the DCP penetration rate and the CBR. For the correlation between the DCP readings and the bearing pressure, a review of the literature indicates that studies appear to be limited to correlations between the DCP readings and the Standard Penetration Test (SPT) N-values, Sowers and Hedges (1966) and Cearns and McKenzie (1988).

Table 1 Basic characteristics of Dynamic Cone Penetrometers

Type	Cone Diameter (mm)	Mass of Hammer (kg)	Height of Fall (mm)	Energy per blow per cone area (kN-m / m^2)
Sowers and Hedges (1966)	38	6.8	508	30
Scala (1956)	20	9.08	508	144
Kleyn (1975)	20	8	575	144
This Study	20	10	460	144
Borros Penetrometer	50	63	750	231

Apart from pavement studies, no equivalent "calibration chamber" tests for DCP's appear to have been carried out despite the fact that calibration chambers have been extensively used for establishing correlations between CPT and soil properties.

This study therefore, attempts to use in-mould tests to establish a correlation between the DCP readings and the bearing capacity using two soils from the same formation. The results of in-mould DCP tests and the allowable bearing pressure computed from the strength parameters determined from the equivalent triaxial compression tests are reported and discussed. The results are compared with those derived from the literature and also from a site investigation to illustrate the potential application of the DCP as a simple site investigation tool.

2 METHODOLOGY

The essential features of the DCP equipment used in this study are shown in Fig. 1. Two types of moulds were used, the CBR mould and a specially designed "large" mould, 300mm in diameter and 600mm high with a 150mm detachable collar. The soil is prepared in the "large" mould with a 150-mm cube wooden rammer of total mass 5.25-kg attached to a 1.2m long wooden handle.

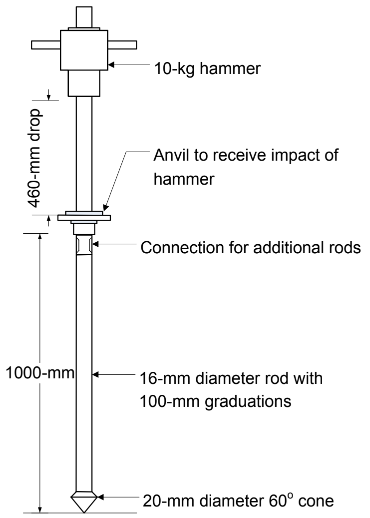

Figure 1 Sketch of assembled DCP Equipment

Two laboratory test programmes are reported. In the first programme, samples retrieved from a trial pit in a study site on campus (SL samples) were used. Pairs of samples were prepared in the CBR mould at the optimum moisture content according to the modified AASHTO compaction specification (ASTM D1557-91) but using 50, 40, 20, 10 and 5-blows respectively of the 4.54-kg rammer. On the first sample of each pair, the DCP test was performed and the penetration achieved by each blow was measured until a depth of about 100-mm was achieved. On the second sample, triaxial specimens were cut from the trimmed surface and subjected to unconsolidated undrained triaxial compression test to determine the strength parameters.

The second test programme was conducted in the "large" mould on samples of a soil type referred to as "Hwereso Clay" (HC sample). Samples of this material were prepared in the mould at the optimum water content, filling the mould in 5 layers each layer receiving 10, 20, 30 and 50 -blows of the wooden rammer. After trimming the top, the DCP test was performed through the centre of the mould and the penetration was recorded for each drop of the hammer until a depth of about 500-mm has been attained. At the end of the test, samples were taken from the undisturbed portions for the subsequent triaxial compression test

3 DISCUSSION OF RESULTS

3.1 *The Characteristics of Test Material*

The index properties and the compaction characteristics of the two samples tested in the laboratory are summarized in Table 2. Figure 2 shows the grading curves of the two soils while Figure 3 shows the compaction curves as well as the initial condition of each test sample. Both soils may be described as *sandy to silty clay* and have similar maximum dry densities and comparable optimum moisture contents.

Table 2 Basic properties of Samples Tested in the Laboratory

Type of Soil	Atterberg Limits		Gs	Compaction	
	LL	PI		OMC (%)	MDD (kN/m^3)
HC	49	19	2.60	18.30	17.18
SL	55	29	2.63	17.02	17.14

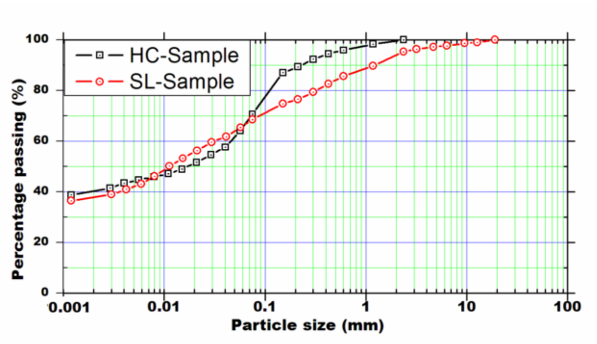

Fig. 2 Grading curves for two soils tested in the laboratory

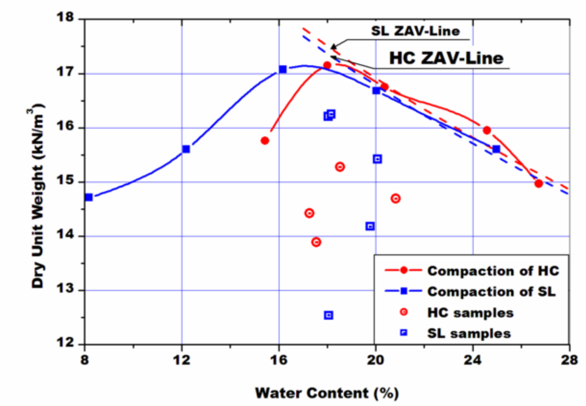

Figure 3 Compaction Characteristics of soils tested in the laboratory

Table 3 is a summary of the laboratory test results. It can be deduced that HC samples achieved between 81 and 89% level of compaction while the SL sample achieved between 73% and 95% level of compaction. For SL tests, the moulding water contents were between 1 and 3% above the optimum but for HC test they were within 2.5% of the optimum. Typical plots of the cumulative number of blows against penetration for the HC and SL test series are shown in Figures 4 and 5 respectively. The plots show that except for the top 10-mm of the SL and 40-mm of the HC test series, the sample preparation by compaction in the moulds may be said to have achieved high degrees of uniformity

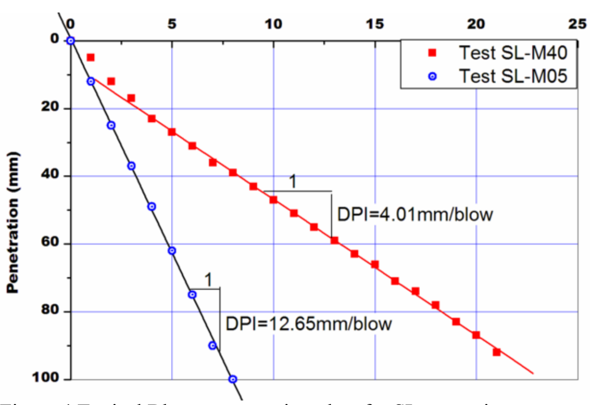

Figure 4 Typical Blows- penetration plots for SL test series

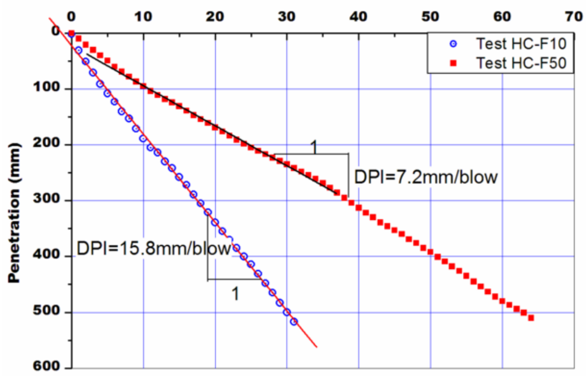

Figure 5 Typical Blows-Penetration plots for HC test series

3.2 *Correlations between DCP and Bearing Pressure*

The allowable bearing pressure, q_{allow}, for a 1.2-m square footing at a depth of 1.2-m on a soil of c_u, ϕ_u and γ_{bulk} values shown in Table 3 were computed using the Terzaghi bearing capacity formula with a factor of safety of 3. The depth of 1.2-m is normally considered locally as the depth of seasonal variation of moisture content and therefore the minimum recommended foundation depth. In the field, it is the number of blows of the DCP hammer required to achieve a 100-mm penetration (i.e. DCP n-value) that is recorded. The DPI-values have therefore been converted to DCP n-values by dividing 100-mm by the DPI values. The results are plotted in Figure 5.

No significant difference in the results of the two soils was observed. A common linear regression analysis of the 9 data points gives Equation 1 with a coefficient of regression of 0.971 and a standard deviation of 188.

$$q_{allow} = 164n - 504 \qquad (1)$$

Equation 1 applies only for n-values greater than 6. As a "calibration chamber" test, the results are affected by the boundary conditions and the chamber-to-cone-diameter ratios. For CPT in cohesionless soils, studies have shown that the chamber-to-cone-diameter ratio can have very large effects on the cone resistance, Salgado et al. (1998). For the DCP, Kleyn (1975) and Gabr et al. (2001) found out that the DPI-values obtained in the 150-mm diameter mould were 15-20% lower than those obtained in a 250-mm diameter mould, suggesting that as the ratio increases from 7.5 to 10, the DPI values increase by up to 20%. In this investigation, the chamber-to-cone-diameter ratios were 7.6 and 15 respectively for the SL and HC series. The DPI-values for the SL series have therefore been increased by 20% to account for the difference in chamber-to-cone-diameter ratios between the two test programmes in Figure 6

Table 1 Results of triaxial compression test and in-mould DCP test

Soil and Mould Type	Test No.	Initial Sample Condition			Triaxial		q_{allow} (kPa)	DCP readings	
		γ_{bulk} (kN/m^3)	Water Content (%)	Void Ratio	c_u (kPa)	ϕ_u (^{O})		DPI (mm/blow)	n-value (Blows/100mm)
HC in Large Mould	HC-F10	16.3	17.56	0.837	33	26.1	334	15.8	6.3
	HC-F20	16.9	17.27	0.769	120	24.0	809	11.6	8.6
	HC-F30	17.8	20.82	0.736	85	28.8	1,023	9.4	10.6
	HC-F50	18.1	18.52	0.669	157	27.8	1,714	7.2	13.9
SL in CBR Mould	SL-M05	14.8	18.06	1.057	69.5	32.5	938	12.7	7.9
	SL-M10	17.0	19.77	0.820	128.6	25.4	945	10.0	10.0
	SL-M20	18.5	20.07	0.674	147.9	23.8	968	8.9	11.2
	SL-M40	19.1	18.04	0.592	234.8	31.6	2,778	4.0	25
	SL-M50	19.2	18.16	0.588	285.1	24.3	1,909	5.7	17.5

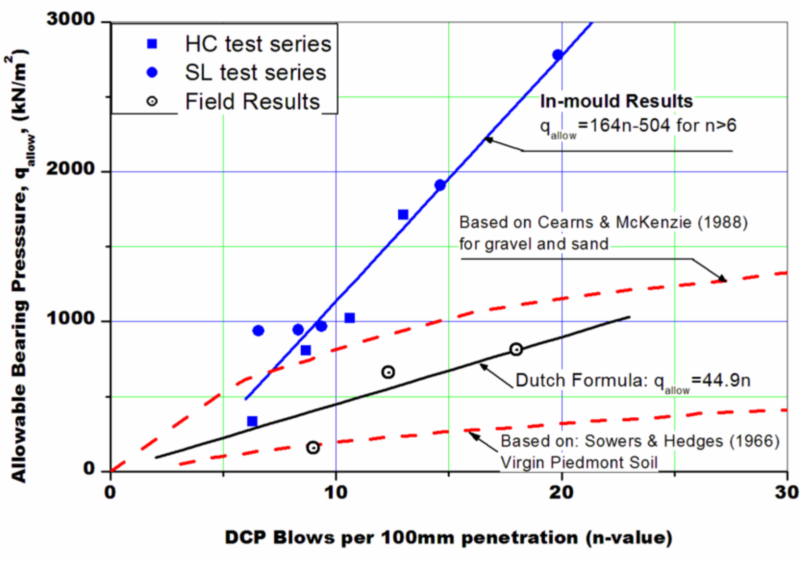

Figure 6 Correlations between allowable bearing pressure and DCP readings

An approximate theoretical correlation between the DCP penetration and the bearing capacity which is commonly used locally for shallow foundations is described by Sanglerat (1972). It is based on the original "Dutch formula" for estimating the dynamic capacity of piles. Given a DCP equipment with a hammer of mass M, dropping over a distance, H, onto an equipment of mass P, and driving a cone of base area A to achieve a penetration per blow, D, the dynamic resistance to penetration R_d is given by Equation 2.

$$R_d = \frac{M^2 H}{AD(M+P)} \qquad (2)$$

For a shallow foundation in a cohesionless soil for which the ratio of the foundation depth, D_f, to the foundation width, B, lies between 1 and 4, Sanglerat (1972) approximated q_{allow} value from R_d by dividing by a factor of 20. Substituting the DCP basic properties shown in Table 1 into Equation 2 for an equipment weight of 6-kg, q_{allow} for a shallow foundation may be estimated from Equation 3.

$$q_{allow} = 44.9n \qquad (3)$$

This equation does not take into account pore pressure development in cohesive soils. For non cohesive soils, assuming a ratio between the static and dynamic resistance of 0.5, Sanglerat (1972) showed that the factor of safety using Equation 3 is about 4. The q_{allow} values predicted by this equation are shown in Fig. 6.

The q_{allow} values were also derived from the SPT and DCP correlation studies of Sowers and Hedges (1966) and of Cearns and McKenzie (1988) noting that for a footing width not exceeding 1.2m with a 25mm settlement, Bowles (1993) proposed Equation 4 for estimating the allowable bearing pressure directly from the SPT N-value. The factor K_d is $1+0.33D_f/B$ and for this study, $D_f/B=1.00$ giving $K_d=1.33$.

$$q_{allow} = {N}/{0.05} \times K_d \qquad (4)$$

It must be pointed out that the DCP penetration increment for the Sowers and Hedges (1966) study was 44-mm instead of the standard 100 mm and also that the energy per blow per unit cone area was only about 21% of that of the DCP used in the present study. The Cearns and McKenzie study (1988) using the Borros penetrometer had energy per blow per unit cone area that was about two times that of the cone used in this study.

Comparing the in-mould results of this study with the other correlations, it is clear that the former predicts higher q_{allow} values than the others especially for n-values exceeding about 12. Results from three in-situ DCP tests and equivalent q_{allow} values determined from triaxial tests on undisturbed soils shown in the figure also appear to confirm this observation.

3.3 *Field Test Results*

Figure 7 shows the final log and the summary of laboratory test results from a typical site investigation conducted using a vibrating hammer and DCP. During the DCP test when 900-mm of penetration is achieved, an additional rod is screwed onto the penetrating rod and the test continued to the required depth usually not exceeding 6m. The number of blows required to drive the cone 100-mm into the ground was recorded as the DCP n-value against the cumulative penetration. The log was obtained by using the vibrating hammer to drive open-drive samplers into the ground which were then jacked out to recover samples. The figure shows the variation with depth of q_{allow} computed from the DCP n-value using Equation 3. The q_{allow} value computed from triaxial results of an undisturbed sample obtained from a trial pit sunk close to the site is also shown.

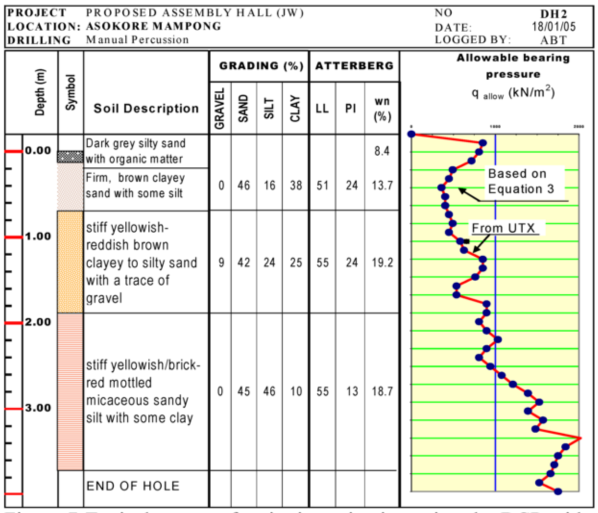

Figure 7 Typical output of a site investigation using the DCP with a vibrating hammer.

4 CONCLUSIONS

Based on the limited triaxial compression and in-mould DCP test results on re-moulded and re-compacted samples of a sandy to silty clay soil found in the Kumasi area, a correlation of good fit was derived between the DCP n-values and the bearing pressure of a 1.2m square footing at a depth of 1.2m. However, the correlation predicts higher allowable bearing pressure values when compared with results measured in the field and also derived from the literature

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