Dynamic Cone Penetrometer (DCP) Relative Density Correlations for Sands

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Abstract. The dynamic cone penetrometer (DCP) is a widely used in-situ device to determine the engineering properties of soils. This paper reports a meta-analysis of laboratory calibration studies to establish a relationship between the rate of penetration and relative density for sands. Fourteen (14) different sands from different geographic and geological settings are compared. A direct relationship between the rate of penetration and relative density is proposed with a standard error in relative density predictions of 11%. A relationship incorporating the sand's median particle size is also proposed with a standard error in relative density predictions of 9%. Whilst there is good agreement between most of these studies, local conditions should be considered before adopting a proposed correlation in engineering design.
Keywords: Dynamic Cone Penetrometer (DCP), Dynamic Penetration Index (*DPI*), poorly graded sandy soil (SP), Relative Density (D_r), well graded sands (SW).

1. Introduction

The manner in which a site investigation is carried out is dictated by the cost and importance of the intended work. For many daily soil mechanics problems a simple *in-situ* test is required. These problems may include determining whether shallow or deep foundations are required, estimating allowable bearing capacities and predicting whether excessive settlements are likely. Sanglerat (1976) suggested that in many of these cases a simple static-dynamic test is suitable. One such test is the Dynamic Cone Penetrometer (DCP), a light hand operated device, in which a cone tipped rod is driven into the ground by the repetitive impact of a falling hammer.

Various standards exist for carrying out the DCP, however the same theoretical maximum specific energy is imparted per blow for most standards (Table 1). Little research has been undertaken to examine actual energies imparted by different arrangements. The efficiency of the DCP system will be influenced by user efficiency, rod length, rod weight, cone geometry and permanent rod penetration. Ayers (1990), based on California bearing ratio (CBR) correlations, suggested that 30° cones can result in higher penetration rates compared to 60° cones, particularity in dense materials. A more rigorous assessment of DCP efficiencies, as carried out by Odebrecht *et al.* (2005) on the Standard Penetration Test (SPT), would shed greater light on its use.

Results from the test are reported in two ways. The first is to record the number of blows to penetrate a specified depth. Usually this depth is 100 mm and is reported as an N_{10} value with units of blows. The second approach is to record the depth penetrated by each blow. Typically, this is an average over a representative depth and is reported as a dynamic penetration index (*DPI* or *DN*) with units of mm/blow. The latter approach is more widely used.

Recent work on the SPT (Odebrecht *et al.*, 2005) considering energy measurements and the wave equation (Schmertmann & Palacios, 1979) has resulted in an alternative means to interpret dynamic penetration tests. This method determines the dynamic penetration resistance of respective tests and allows a direct comparison between different tests. This removes the necessity of developing empirical correlations between different tests. Correlations between engineering parameters can then be used irrespective of original test to which parameters were correlated. Schnaid *et al.* (2017) presented data showing the promising direct comparisons possible with this approach. The simplicity of the DCP test and dependence of results on user efficiency may preclude such an approach being developed for this test, however, it would be the most rigorous. Consequently, direct empirical relationships are likely to remain the state of practice for some time to come.

Various researchers have attempted to develop direct empirical relationships between DCP results and engineering parameters (Table 2). The DCP was originally developed as a tool for road design (Scala, 1956). Consequently, it is widely accepted for pavement design, particularly to determine California bearing ratio (CBR) values. Soils making up pavements are compacted heavily in thin layers resulting in heavily overconsolidated soils. Natural soils exist at a much wider range of densities limiting the DCP's

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Submitted on November 30, 2018; Final Acceptance on May 14, 2019; Discussion open until December 31, 2019.
DOI: 10.28927/SR.422201

Table 1 - DCP standards.

Standard	Rod diameter (mm)	Cone angle (°)	Cone diameter (mm)	Hammer mass (kg)	Hammer fall (mm)	Specific work per blow# (kJ/m^2)
ASTM (2003)	16	60	20	8	575	144
Australian	16	30	20	9	510	143
South African	16	30	20	10	460	144

#Cross sectional area used is the plan area.

Table 2 - DCP correlations proposed in literature.

Correlation	Reference
California bearing ratio	Al-Refeai & Al-Suhaibani (1997); Ese *et al.* (1994); Gabr *et al.* (2000); Harison (1989); Kleyn (1975); Livneh (1989); Paige-Green & Pinard (2012); Smith & Pratt (1983); Van Vuuren (1969)
Unconfined compressive strength	De Villiers (1980); McElvaney & Bundadidjatnika (1991)
Standard penetration test	Ampadu *et al.* (2018); Ibrahim & Nyaoro (2011); Sowers & Hedges (1966)
Stiffness parameters	Alshibli *et al.* (2005); Lee *et al.* (2014); Mohammadi *et al.* (2008); Sawangsuriya & Edil (2005)
Shear strength parameters	Ayers (1990); Hamid (2013); Mohammadi *et al.* (2008); Rahim *et al.* (2004)
Density parameters	Azad (2008); Chennarapu *et al.* (2018); Hamid (2013); Hossain (2009); Katakiya & Parekh (2017); Salgado & Yoon (2003)

applicability in these cases. This paper compares correlations proposed in the literature for determining the relative density of sands. It will be shown that good agreement exists between some studies but not others. This disagreement is shown to be as a result of different grain mineralogy, highlighting the importance of knowing local geology.

2. Relative Density Correlation

The behaviour of non-plastic soils is closely related to relative density (D_r) given by Equation 1 (Holtz & Kovacs 1981):

$$D_r = \frac{e_{\max} - e}{e_{\max} - e_{\min}} \quad (1)$$

where e_{max} and e_{min} are reference void ratios determined from minimum and maximum densities respectively, and e is the soil current void ratio.

2.1. Database

A database of studies correlating D_r to either *DPI* or N_{10} was collected (Table 3). Studies were excluded from the meta-analysis using the following criteria. Firstly, DCP tests had to be carried out according to ASTM (2003). Secondly, tests had to have been done in containers larger than 500 mm. Chamber size relative to probe size, boundary conditions (stress or strain controlled), particle size and relative density all influence the results of chamber based correlations (Schnaid & Houlsby 1991). An explicit assess-

Table 3 - Details of calibration testing.

Study	Details of calibration chamber	Reference void ratio procedure
R1	Air dried sand was placed in a 0.5 m diameter by 1 m high calibration chamber by air pluviation and vibration. The calibration chamber was formed from 13 mm thick steel.	ASTM (2006a) ASTM (2006b)
R2	Air dried sand was placed in a 0.5 m diameter by 1 m high calibration chamber by air pluviation and vibration. The calibration chamber was formed from 13 mm thick steel.	ASTM (2006a) ASTM (2006b)
R3	Air dried sand was placed in a 1.6 m diameter by 1.5 m high calibration chamber by funnel filling, air pluviation and vibration tamping. The calibration chamber was formed from 25 mm thick glass fibre reinforced plastic.	ASTM (2006a) ASTM (2006b)
R4	Air dried sand was placed in a 0.6 m square by 0.75 m high calibration chamber filled by tamping. The calibration chamber was formed from Plexiglas.	IS 2720 (Part 14) - 1983 BIS (1983)
R5	Air dried sand was placed in a 0.7 m diameter by 0.7 m high calibration chamber in 0.1 m lifts and vibration tamping. The calibration chamber was formed from steel.	Not specified.

R1 - Azad (2008), R2 - Hossain (2009), R3 - Hamid (2013), R4 - Katakiya & Parekh (2017), R5 - Mohammadi *et al.* (2008).

ment of chamber effects has not been undertaken for the DCP, however, experimental work by Mohammadi *et al.* (2008) suggested that confining effects are reduced above a diameter of 500 mm or a chamber to probe diameter ratio of 25. Details of container boundary conditions are given in Table 3.

Details of the soils tested are given in Table 4. All soils investigated were non-plastic sands with the percentage of sand ranging between 86 and 100%. Five (5) soils had gravel fractions ranging between 4 and 14% and nine (9) had fines contents ranging between 2 and 8%. Most of the sands were poorly graded with three (3) being well graded. Particle size can have an influence on penetration results, with gravel particles in particular, potentially impeding the probe. This can result in high blow counts that are not representative of the overall consistency of the deposit. The influence of median particle size is therefore explored in this paper.

2.2. Correlation

2.2.1. Overall correlation

Data from the first four studies is plotted in Fig. 1. A logarithmic trend line was found to fit best. The average coefficient of determination (R^2) for individual data sets was on average 0.97 and the average standard error in D_r estimates for individual data sets was 3%. It is apparent that very accurate relationships between *DPI* and D_r can be obtained for particular sands. The best-fit line (solid line in Fig. 1) through the entire dataset resulted in an R^2 value of 0.7 and a standard error in D_r estimates of 11% (dashed lines in Fig. 1).

Tavenas & La Rochelle (1972) estimated that the error of determining relative density was in the order of 10-22%. The error in the best-fit line is within this suggested range, suggesting that D_r estimates from *DPI* are within expected accuracies. It must be kept in mind that this error is based on tests done under laboratory conditions and field conditions may result in substantially larger errors. Further, the regression analysis predicts $D_r > 100\%$ for *DPI* < 10 mm/blow. This is an artefact of the statistical analysis as well as inherent error in the DCP and D_r. Practitioners using this relationship should therefore place greater emphasis on the range of D_r values predicted than the specific D_r value predicted. The DCP should only be used to obtain a qualitative estimate of relative density.

2.2.2. Influence of particle size

Some authors (Hossain 2009; Lee *et al.*, 2014) have suggested the influence of particle size can be incorporated by including the median particle size (D_{50}) as an additional prediction variable. Including D_{50} as a regression variable did result in a marginally better fit to the data (Fig. 2). For this regression an R^2 value of 0.8 and a standard error in D_r estimates of 9% were obtained. The suitability of this relationship for field use is limited as D_{50} requires laboratory determination.

Table 4 - Details of non-plastic soils.

Study	Soil names	Gravel (%)	Sand (%)	Fines[1] (%)	C_u[2]	C_c[3]	D_{50}[4] (mm)	USCS[6]	e_{max}	e_{min}
R1	Jamuna sand	0	95	5	2.2	1.3	0.20	SP	1.20	0.57
	Sylhet sand	0	100	0	3.2	1.1	0.50	SP	0.84	0.54
R2	Medium sand	0	100	0	2.9	1.1	0.47	SP	1.23	0.56
	Fine sand	0	100	0	2.0	0.8	0.27	SP	1.21	0.56
R3	Dune sand (1% silt)	0	99	1	2.0	0.9	0.27[5]	SP	0.68	0.48
	Dune sand (4% silt)	0	96	4	NP	NP	NP	SP	0.66	0.41
	Dune sand (8% silt)	0	92	8	NP	NP	NP	SP	0.63	0.33
R4	Khanpur sand	6	94	0	3.3	1.2	2.24[5]	SP	0.60	0.39
	Sevaliya sand	4	93	3	2.6	0.8	0.79[5]	SP	0.63	0.38
	Ahmedabad sand	0	95	5	2.2	1.1	0.30[5]	SP	0.71	0.56
	Combo 1	14	86	0	6.1	1.0	1.60[5]	SW	0.48	0.22
	Combo 2	9	88	3	9.4	1.0	1.31[5]	SW	0.51	0.20
	Combo 3	11	87	2	6.5	1.0	1.42[5]	SW	0.47	0.17
R5	Terrace deposits	0	98	2	1.2	1.0	0.17	SP	0.97	0.46

R1 - Azad (2008), R2 - Hossain (2009), R3 - Hamid (2013), R4 - Katakiya & Parekh (2017), R5 - Mohammadi *et al.* (2008).
[1]Passing 0.075 mm sieve. [2]$C_u = D_{60}/D_{30}$. [3]$C_c = D_{30}^2/(D_{10} \times D_{60})$. [4]Particle size at percentage passing shown by subscript. [5]Interpolated from D_{60} and D_{30}. [6]Unified Soil Classification System ASTM (2017).

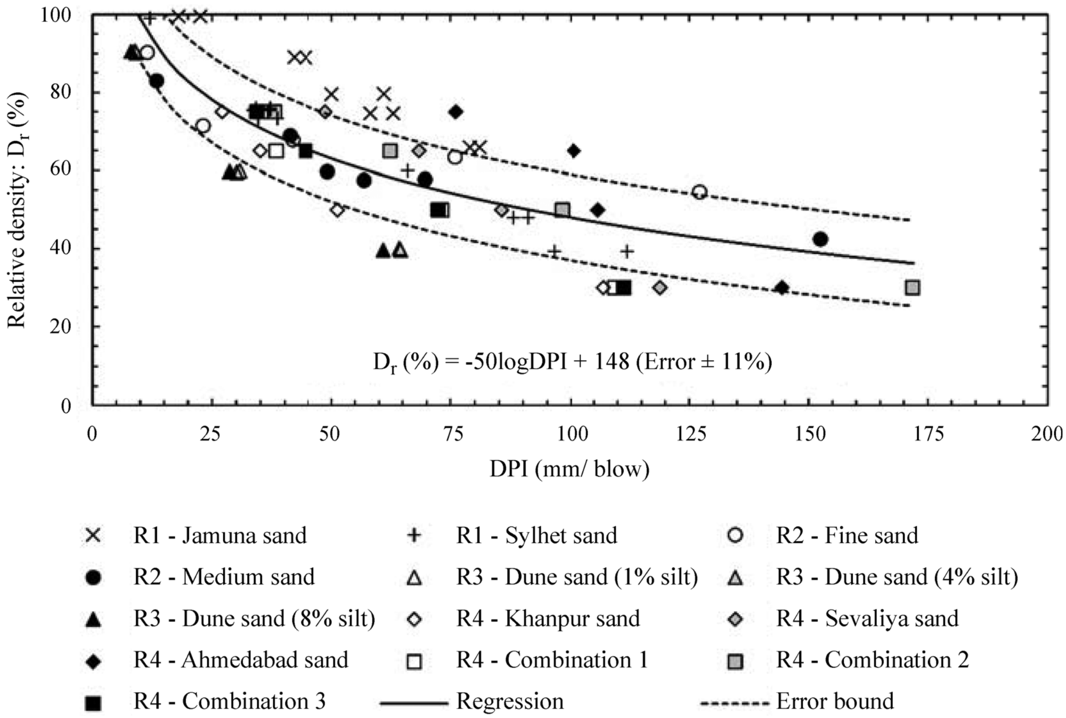

Figure 1 - *DPI vs.* D_r relationship.

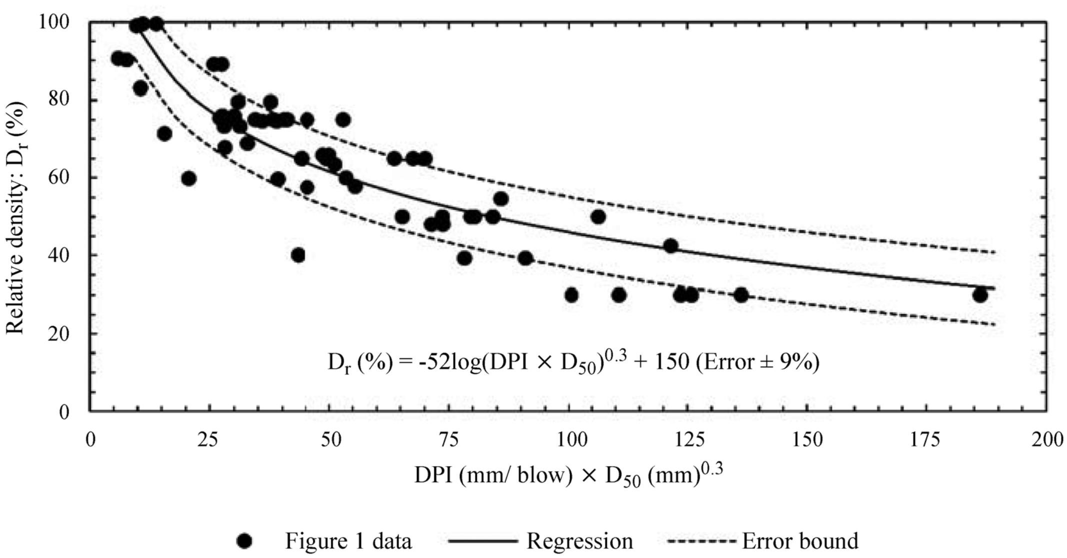

Figure 2 - *DPI* and D_{50} *vs.* D_r relationship.

Azad (2008) suggested that the fines content can be included to improve predictions. However, considering R1 – Jamuna sand, R3 – Dune sand (8% silt) and R4 – Ahmedabad sand in Fig. 1 it is evident that fines content does not have a consistent influence on D_r values at a given *DPI* value. Including fines content in the regression model did not improve the accuracy of predictions. Further, the influence of small fractions of gravel particles on DPI (see R4 - Khanpur sand, R4 - Sevaliya sand, R4 – Combo 1, R4 – Combo 2 and R4 – Combo 3 in Fig. 1) appeared to be limited.

2.2.3. Influence of mineralogy

Data set R5 reported by Mohammadi *et al.* (2008) is compared to the entire data set in Fig. 3. Despite the sand tested by Mohammadi *et al.* (2008) having similar particles sizes to the other data, statistical testing shows the probability of the data set falling within the larger data set is less

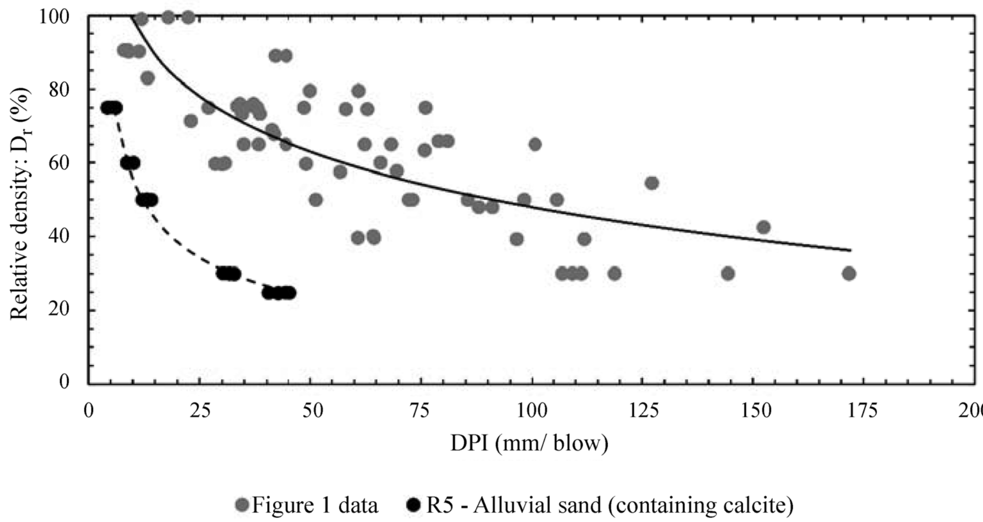

Figure 3 - Comparison of regression model to sands containing calcite.

than 0.005. According to Mohammadi *et al.* (2008), X-ray analysis has shown that the sandy samples are made of quartz, feldspar, pyroxene and calcite. It is known that calcite grains are prone to crushing during driving resulting in variable strengths (Murff, 1987; Sterianos, 1988). It is suggested that calcite crushing may be responsible for the lower *DPI* values reported by Mohammadi *et al.* (2008) at equivalent D_r values. Practitioners therefore need to take careful consideration of the mineralogy of sands before using correlations suggested in the literature.

3. Conclusions

A correlation was proposed between dynamic cone penetrometer penetration rates and relative density for sands. The correlation was based on testing reported in literature on thirteen (13) different sands from different geographic and geological settings. The standard error in relative density predictions was found to be 11%. Using the same database, a second correlation was proposed that incorporates the median particle size as a measure of particle size effects. The standard error in relative density predictions for this second correlation was found to be 9%.

One data set was found to be statistically inconsistent with the larger database. For this data set, penetration rates were consistently lower at equivalent relative densities. This is likely a consequence of the presence of calcite grains, which are known to be crushable. This data set was therefore excluded from the regression analysis. Local conditions should always be considered before adopting a proposed correlation in engineering design.

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