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Interpreting DPSH penetration values in sand soils

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Site investigations to classify the underlying soil for geotechnical purposes often rely on in-situ penetrometer tests. Two common tests used in southern Africa are the Standard Penetration Test (SPT) and Dynamic Probe Super Heavy (DPSH) test. Although the specific work per blow is essentially the same in both tests, the resulting penetration values are not equivalent. The DPSH tends to be more variable than the SPT and has higher blow counts. A comparison of SPT and DPSH penetration values at a series of strata below sites has been undertaken. From this, new relative density descriptor boundaries, based on DPSH penetration values, are suggested for sand soils.

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INTRODUCTION

The Standard Penetration Test (SPT) and Dynamic Probe Super Heavy (DPSH) test are two common in-situ penetrometer tests employed in geotechnical site investigations in southern Africa. Although both tests have the same specific work per blow (Table 1), the SPT is carried out in an open hole and the DPSH is driven continuously into the soil. Despite this difference, the two tests are often assumed equivalent (Byrne & Berry 2008). MacRobert *et al* (2011) found this not to be the case and proposed an empirical correlation between the two tests. Since the publication of that paper, questions regarding the observed variability within the reported data and differences from other data sets have been raised (Harrison & A'Bear 2011; Shahien & Farouk 2013). Furthermore, additional data sets have become available to the current author. The aim of this paper is to shed light on this variability and propose new descriptor boundaries to classify the relative density of sand soils using DPSH penetration values.

INTERPRETATION OF PENETROMETER RESULTS

In-situ penetrometer tests are either "dynamic" or nominally "static", that is the probe is either hammered or pushed into the soil. Dynamic tests, such as the SPT and DPSH tests, have been criticised for their poor repeatability, due in particular to hammer energy inefficiencies and rod friction in the case of the DPSH (Broms & Flodin 1988). In southern African practice, the SPT blow count is counted over 300 mm and referred to as an N value; likewise, the DPSH blow count is counted over 300 mm and is referred to as an N_{30SB} value. Reliance on this single qualitative parameter to determine requisite engineering design parameters has also been questioned (Mayne *et al* 2009). Consequently, static tests such as the cone penetration test (CPT) are increasingly being advocated due to higher accuracy and repeatability (Shukla 2015). Traditional CPT equipment measures both tip resistance and sleeve friction, with modern equipment measuring pore pressure and shear wave velocity (Robertson 2009). Engineering parameters can therefore be determined from a greater pool of measurements.

Despite the serious deficiencies of dynamic tests, they are still popular. This is particularly because they are cheap and have a long history of use (Broms & Flodin 1988). Virtually every geotechnical engineering design parameter has been correlated with SPT penetration values, although many of these correlations do not give any indication of statistical scatter (Mayne *et al* 2009). Robertson and Cabal

Table 1 Dynamic probe classifications

Test designation	DPSH	SPT
Hammer mass (kg)	63.5	63.5
Hammer fall (m)	0.76	0.76
Probe	51 mm diameter 90° cone	51 mm diameter split spoon sampler
Specific work per blow (kJ/m^2)	240	240

Keywords: site investigations, in-situ testing, penetrometers, soil classification, statistical analysis

Table 2 Relative density N descriptor boundaries for sand soils (after Terzaghi & Peck 1948)

SPT resistance value (N)	Relative density
0 – 4	Very loose
4 – 10	Loose
10 – 30	Medium dense
30 – 50	Dense
Over 50	Very dense

(2012) conclude that SPT penetration values are suited to determining relative density of predominantly sand profiles, but only moderately so. This is typically done by comparing N values to the descriptor boundaries proposed in Table 2 (Terzaghi & Peck 1948).

Variability in penetration values arises from lateral variation in the soil profile and different testing procedures. It is difficult to separate these two sources of variability. Serota and Lowther (1973) determined that the coefficient of variation (COV), defined by Equation 1, for N values in a calibration chamber is between 12 and 10% for automatic trip hammers.

$$COV = \frac{s}{\bar{x}} \quad (1)$$

where $\bar{x}$ is the sample mean and s is the sample standard deviation.

Phoon and Kulhawy (1999), considering published site investigation data, suggested that the average COV in sand was 54% and ranged between 19% and 62%. The larger variability in the later study reflects lateral variation in site soil profiles and various hammer mechanisms, whereas the variability in the former study predominantly reflects variation within the testing procedure. No studies on variability in the DPSH are apparent in literature; however, similar variability to that reported for the SPT is likely.

Table 3 Descriptive geology of each site

Site	Description	Water table	Average relative density
Bellville South Africa	Transported fine- to medium-grained locally calcareous sand.	No water strikes	Medium-dense
Chloorkop South Africa	Clayey silty sand with fine gravel becoming more abundant with depth. Reworked residual granite.	No water strikes	Medium-dense
Dunkeld South Africa	Clayey silty coarse sand with traces of sub-angular quartz gravel. Reworked residual granite.	No water strikes	Very loose
Glenhazel South Africa	Silty sand with fine gravel at depth. Fill, hillwash and reworked residual granite.	No water strikes	Loose
Matutuíne Mozambique†	Medium and fine sand.	No water strikes	Medium-dense
Namakwa South Africa†	Non-plastic screen-separated sand.	No water strikes	Dense
Mt Edgecombe South Africa†	Slightly clayey transported sand.	On average below 21.5 m‡	Medium-dense
Parktown South Africa	Profile of mixed origin, predominantly silt and sand.	No water strikes	Loose
Milnerton South Africa	Transported loose to medium slightly silty-fine sand.	On average below 0.6 m	Medium-dense
Chicalla Angola	Fine to medium-grained sand with abundant shell fragments.	On average below 14.7 m	Loose
Umdloti South Africa	Slightly moist to moist, fine to medium through coarse-grained sand.	On average below 7.3 m	Medium-dense
Gope Botswana	Transported sand cover with a thin variable layer of poorly developed calcified pedogenic material.	No water strikes	Medium-dense
Matola Mozambique	Silty sand dune deposit.	On average below 21.0 m	Dense

† Due to the extensive nature of these sites, a single site profile was not developed. Instead, tests in close proximity were compared.
‡ One probe over a depth of 1 m was in saturated soil.

Table 4 Summary of penetration testing data from each site

Site	Initial depth (m)	Average refusal depth (m)	Maximum refusal depth (m)	SPT (N) Summary statistics		DPSH (N_{30SB}) Summary statistics	
				Number of profiles†	Average COV (COV range)	Number of profiles	Average COV (COV range)
Bellville,South Africa	1.2	4.2	5.1	1	-	2	25% (50 – 6%)
Chloorkop, South Africa	0.9	5.6	8.1	3	33% (55 – 15%)	2	19% (54 – 6%)
Dunkeld, South Africa	1.2	4.5	5.1	1	-	2	52% (100 – 25%)
Glenhazel, South Africa	0.9	2.0	4.2	1	-	3	41% (91 – 15%)
Namakwa, South Africa	2.1	11.7	26.7	2 (2)	-	8 (2)	33% (127 – 5%)
Matutuíne, Mozambique	0.9	3.1	6.6	4 (2)	29% (76 – 6%)	19 (2)	68% (96 – 4%)
Mt Edgecombe, South Africa	1.5	9.2	15.3	15 (6)	17% (64 – 1%)	18 (6)	19% (90 – 2%)
Parktown, South Africa	0.9	4.1	6.3	8	105% (164 – 78%)	19	139% (222 – 88%)
Milnerton, South Africa	0.9	3.0	3.9	2	14% (35 – 2%)	2	26% (56 – 1%)
Chicalla, Angola	1.2	7.2	10.8	3	31% (47 – 12%)	8	27% (56 – 4%)
Umdloti, South Africa	1.2	3.7	6.3	3	42% (88 – 8%)	10	37% (96 – 6%)
Gope, Botswana	1.2	6.5	9.3	5	23% (46 – 3%)	11	43% (84 – 28%)
Matola Mozambique	1.5	9.6	13.8	17	26% (33 – 19%)	17	22% (41 – 7%)

† Values in parentheses indicate number of subsites considered (see note in Table 3)

CORRELATION BETWEEN N AND N_{30SB}

Test sites

To investigate the correlation between N and N_{30SB}, data from 13 site investigations were analysed. Data was collected from various engineering and contracting companies, with probing carried out according to best practice in southern Africa (MacRobert *et al* 2010). Consequently, relationships developed may not be applicable for different hammer efficiencies and where probing practices differ. Table 3 shows that all profiles probed consisted of sand soils, with Table 4 giving details of the probing undertaken at each site. Most sites were small and borehole logs indicated similar soil profiles, and so all N and N_{30SB} profiles for such sites could be compared. For sites where probing was over a large area, N and N_{30SB} profiles were separated into subsites with similar soil profiles based on borehole logs.

Soil profiles below sites (or subsites) were divided into 1 m thick strata centred at the depths where N values were determined. An example of these strata for the Matola site is given in Figure 1. The average and standard deviation of all N values within a stratum were then determined. For sites with only one N profile, the standard deviation was calculated assuming a COV of 25%. The corresponding range of N_{30SB} values was determined as the average and standard deviation of all N_{30SB} values within each 1 m thick stratum. This resulted in a series of strata for which average N and N_{30SB} values and associated standard deviations were known.

For each of these strata the COV values of the N and N_{30SB} values were calculated. Table 4 summarises the range of COV values for all strata at each site and gives the average. The average values are generally towards the lower range of the limits (19% to 62%) reported by Phoon and Kulhawy (1999). This suggests that there was limited lateral variation in the soil profiles. One site that exhibited significantly greater variability was the Parktown site. This site was characterised by material of mixed origin that included coal, ash and refuse which contributed to the large variation observed. Disregarding this site as anomalous, the average COV for N_{30SB} was 32% and for N was 25%. Although the average COV values for the N_{30SB} and N are similar, it is clear from the ranges of COV values for the two tests that N_{30SB} showed greater variability.

Statistical methodology

In light of the variability in penetration values, individual values were not compared. Rather, the range of N values were compared to the corresponding range of N_{30SB} values within a stratum across a site. Consequently energy corrections, such as proposed by Skempton (1986), were not applied, as these are more appropriate when considering individual N values. Assuming N values to be normally distributed, the probabilities of each stratum being classified into each of the five relative density ranges (Table 2) were calculated. Each stratum was then assigned a relative density based on which relative density resulted in the highest probability.

Equivalent N_{30SB} relative density boundaries (Table 6) were calculated using the empirical correlation proposed by MacRobert *et al* (2011) from N boundaries in Table 2. Assuming N_{30SB} values to be normally distributed, the probabilities of each stratum being classified into each of these relative density ranges were calculated. Each stratum was then assigned a relative density based on which relative density resulted in the highest probability. A comparison was then made between the relative density assigned by N values and N_{30SB} values. The N_{30SB} boundaries were subsequently optimised, using the entire data set, to maximise the number of strata assigned the same relative density by both tests.

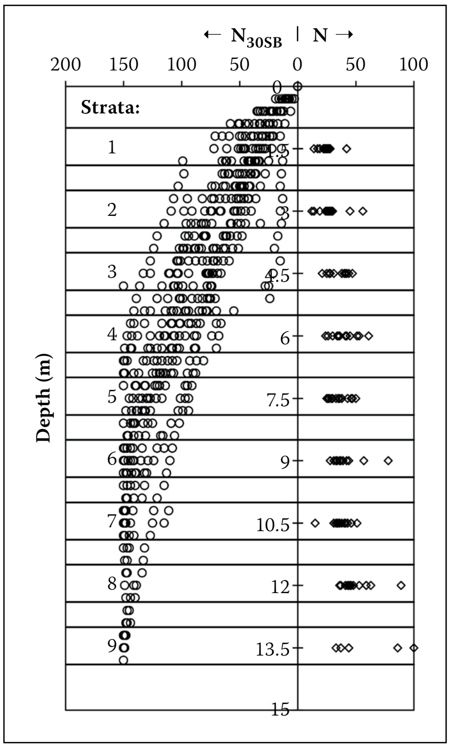

Figure 1 Matola strata

RESULTS

Prior to considering the entire data set, results for the Matola site are discussed. For each of the strata (Figure 1) average and standard deviation of N and N_{30SB} values are given in Table 5. The calculated

Table 5 Matola site statistical output

Strata	N				Terzaghi and Peck (1948) boundaries† Probability associated with relative density					N_{30SB}				MacRobert *et al* (2011) boundaries‡ Probability associated with relative density				Optimised boundaries‡ Probability associated with relative density			
	$\bar{x}$	s	COV (%)	n	Very loose	Loose	Med-dense	Dense	Very dense	$\bar{x}$	s	COV (%)	n	Very loose	Loose	Med-dense	Dense	Very loose	Loose	Med-dense	Dense
1	25	8	32	15	0.004	0.026	**0.704**	0.265	0.001	41	17	41	39	0.013	0.021	**0.834**	0.132	0.023	0.033	**0.933**	0.011
2	27	11	41	17	0.018	0.043	**0.546**	0.374	0.018	64	24	38	39	0.006	0.007	0.422	**0.566**	0.009	0.010	**0.729**	0.252
3	35	8	23	15	0.000	0.001	0.265	**0.704**	0.030	86	28	33	39	0.002	0.002	0.173	**0.823**	0.002	0.003	0.410	**0.585**
4	39	10	26	17	0.000	0.002	0.182	**0.680**	0.136	107	23	21	39	0.000	0.000	0.020	**0.979**	0.000	0.000	0.120	**0.880**
5	36	8	22	15	0.000	0.001	0.226	**0.733**	0.040	124	17	14	31	0.000	0.000	0.000	**1.000**	0.000	0.000	0.005	**0.995**
6	39	12	31	17	0.002	0.006	0.219	**0.594**	0.180	138	13	9	24	0.000	0.000	0.000	**1.000**	0.000	0.000	0.000	**1.000**
7	37	8	22	16	0.000	0.000	0.190	**0.757**	0.052	140	13	9	12	0.000	0.000	0.000	**1.000**	0.000	0.000	0.000	**1.000**
8	50	13	26	15	0.000	0.001	0.061	0.438	**0.500**	143	5	3	6	0.000	0.000	0.000	**1.000**	0.000	0.000	0.000	**1.000**
9	57	28	49	6	0.029	0.017	0.121	0.234	**0.599**	149	1	1	3	0.000	0.000	0.000	**1.000**	0.000	0.000	0.000	**1.000**

†see Table 2 ‡see Table 6

probability for each relative density, for each stratum, based on N values is given. Each stratum's assigned relative density and associated probability are indicated by bold type. Results from calculations performed on N_{30SB} values are presented in a similar fashion. Based on the MacRobert *et al* (2011) boundaries, 6 stratum are assigned the same relative density by both tests, 1 is assigned a higher relative density by N_{30SB} values and 2 are assigned a lower relative density by N_{30SB} values. With the optimised boundaries, 7 stratum are assigned the same relative density by both tests and 2 are assigned a lower relative density by N_{30SB} values. Considering the two strata assigned lower relative densities by N_{30SB} values, the probabilities that these strata would be assigned the same lower relative density by N values are significant (> 0.05). This suggests that the optimised boundaries are adequate for categorising strata.

Figure 2 illustrates the average N and N_{30SB} values for each stratum and for each site. In general, N_{30SB} values are greater than respective N values. This is due to N_{30SB} values increasing with depth at a greater rate than N values. Harrison and A'Bear (2011) attributed this to rods bowing during probing, causing jamming and sidewall collapse. This suggests that a correlation varying with depth may be appropriate. However, no such relationship was apparent when analysing the data. It is evident that the equation proposed by MacRobert *et al* (2011) is not sufficiently accurate to obtain equivalent N values from N_{30SB} values. From the scatter in the graph, it is evidently impossible to define a single equation to obtain equivalent N from N_{30SB}. However, it is possible to assign a relative density to a stratum with some confidence.

Table 6 Relative density N_{30SB} descriptor boundaries for sand soils

Relative density	N_{30SB} boundaries by MacRobert *et al* (2011)	Optimised N_{30SB} boundaries
Very loose	0 – 3	0 – 7
Loose	3 – 10	7 – 14
Medium-dense	10 – 60	14 – 80
Dense	> 60	> 80

With the MacRobert *et al* (2011) descriptor boundaries, 49% of the strata were assigned the same relative density by both tests, 29% were assigned a lower relative density by N_{30SB} values (i.e. a conservative estimate), and 22% were assigned a higher relative density by N_{30SB} values. With the optimised descriptor boundaries, 57% of the strata were assigned the same relative density by both tests, 31% were assigned a lower relative density by N_{30SB} values (i.e. a conservative estimate), and 12% were assigned a higher relative density by N_{30SB} values.

Calculated probabilities associated with defining a stratum's relative density by N values and N_{30SB} values (optimised descriptor boundaries) are considered in Figure 3. Figure 3(a) considers strata assigned the same relative density by both tests. As expected, the confidence with which these strata are assigned a relative density is high in both tests. However, individual probabilities are not comparable, as points do not lie along a line of equality. Figure 3(b) shows strata assigned a lower relative density by N_{30SB} values than by N values. Ordinates are the probabilities that the N values would give the same lower relative density. In this case, the average probability that N values would give the same lower relative density is 0.15. Whilst this probability is small, it is greater than 0.05, suggesting there is nevertheless a significant chance that the strata are correctly defined by N_{30SB} values. Figure 3(c) shows strata assigned a higher relative density by N_{30SB} values than by N values. Ordinates are the probabilities that the N value would give the same higher relative density. In this case, the average probability that N values would give a similar higher relative density is 0.07, so there is a much lower chance that the strata are correctly defined by N_{30SB} values. Referring to Figure 2 it is evident that most of the strata assigned a higher relative density based on N_{30SB} are from the Chicalla site. As pointed out by MacRobert *et al* (2011), the ground profile at this site contained numerous shell fragments which may have resulted in the higher N_{30SB} values. This highlights the need for a local knowledge of geology when interpreting N_{30SB} values. Points marked with a red asterisk in

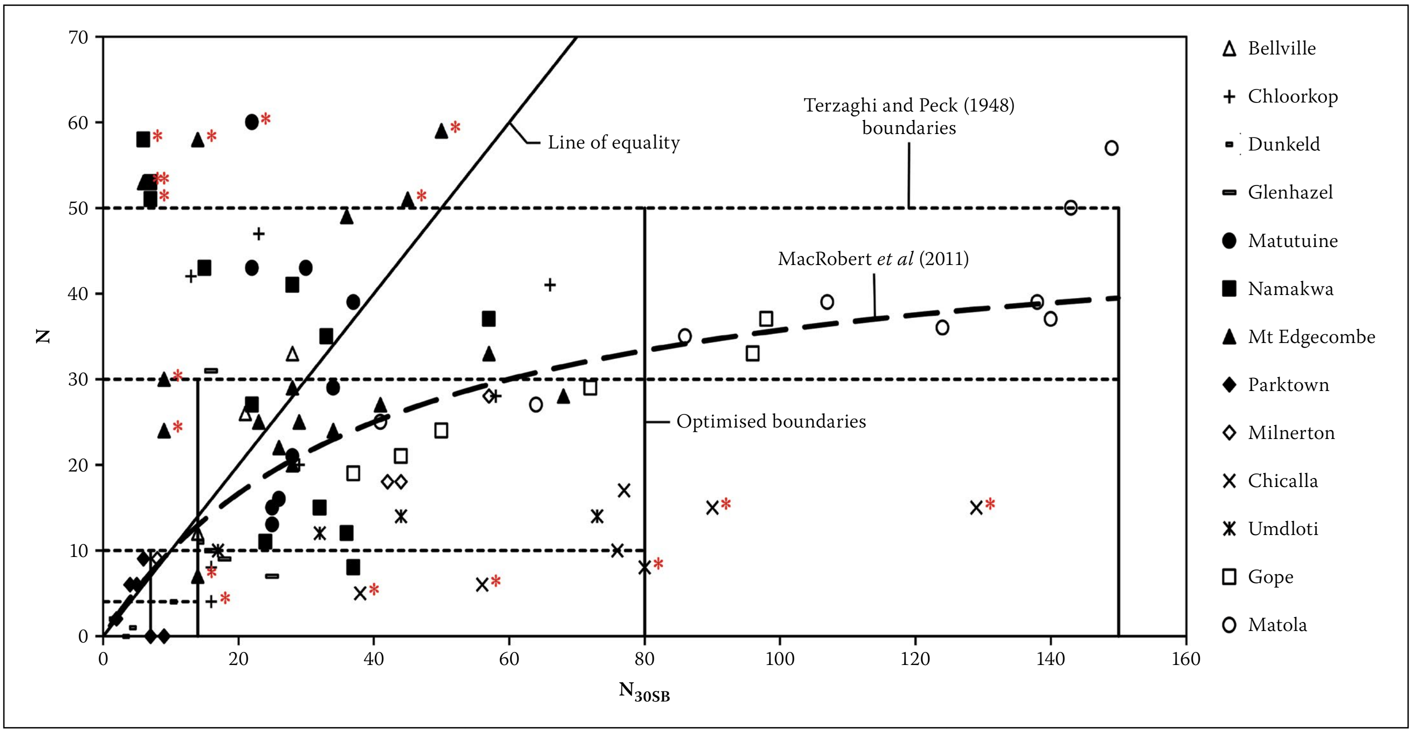

Figure 2 Correlation between N and N_{30SB} values

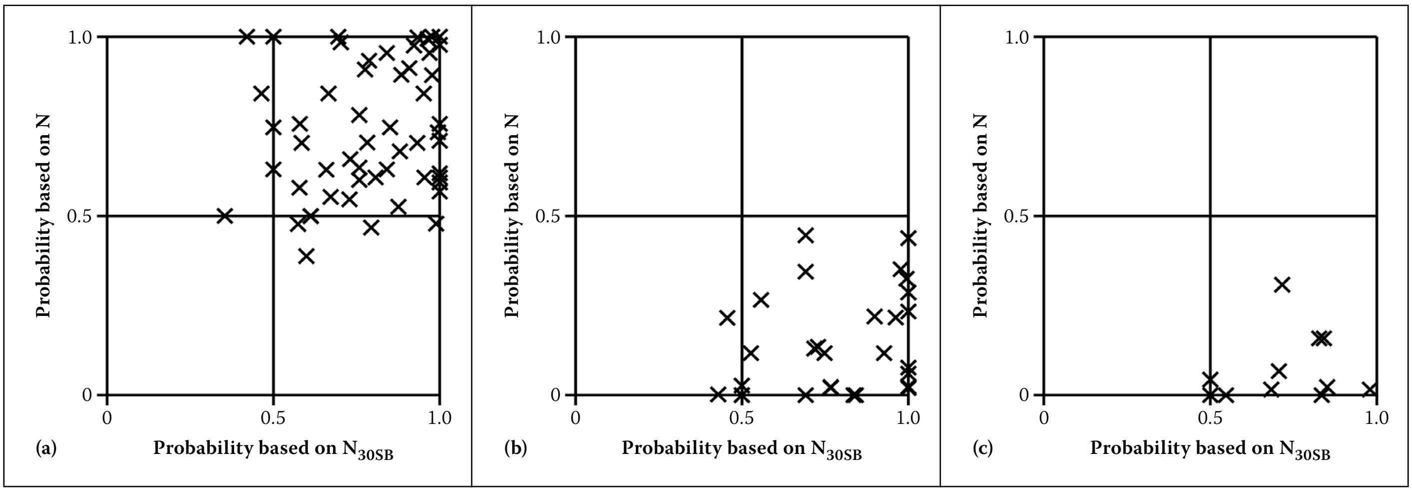

Figure 3 Probability associated with assigning the same relative density to a stratum by N and N_{30SB} for: (a) similar cases, (b) conservative cases and (c) unconservative cases

Figure 2 indicate strata where the probability N would give the same relative density, as N_{30SB} is less than 0.05. These points make up 12% of the data set.

CONCLUSIONS

A statistical analysis of 13 site investigations, in which 65 SPT and 121 DPSH profiles were determined, was undertaken. This was used to propose new N_{30SB} relative density descriptor boundaries for sand soils. Considering the inherent variability of penetration values obtained from penetrometers, it is clear that defining a single equation to determine equivalent N values from N_{30SB} values is futile. The practice of using N_{30SB} values to obtain anything more than an estimate of relative density is therefore unwarranted.

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