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Efficacy of Direct SPT-Based Pile Design Methods in Residual Soils of Southern Africa

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ABSTRACT

Direct SPT-based pile design methods are very popular these days despite the fact that many of such methods are based on small databases of pile load tests. Due to the dependence of soil behaviour on geological setting and site specific conditions, it is possible that some of the methods do not produce good prediction of pile capacity. Accordingly this paper presents the evaluation of two SPT-based pile design methods in residual soils against a pile load test database from the Southern African region. The methods include the (i) Franki-SA method reported in Byrne et al. (1995) and (ii) Decourt Method (1995). The pile load tests consist of 26 cases of bored piles in residual soil with each case accompanied by SPT measurements. The SPT measurements were used to calculate the predicted capacity in accordance with the procedure for each of the two methods while the pile load tests were used to determine the measured capacity. The findings of the evaluation indicate that the Decourt method is more reliable and accurate than the SA method. The poor performance of the SA methods suggests further studies to develop specific calculation factors for base and shaft capacities in residual soils.

Keywords: SPT-based pile methods, Load Bearing Capacity, Pile Load Test, Chin extrapolation method, Terzhagi's 10% criteria, Rank Index.

INTRODUCTION

Pile foundations are commonly used to support heavy structures, where shallow foundations are not suitable. These foundations can withstand substantial tensile and lateral forces, deriving their load-bearing capacity from shaft and base resistance. The Standard Penetration Test (SPT) is a widely used and cost-effective field test for soil investigation, providing crucial data pile design. Notably, the SPT N-value is extensively utilized in designing structural foundations, especially for assessing pile bearing capacity (Meyerhof, 1976; Shioi and Fukui, 1982; Decourt, 1995; Robert, 1997).

The interaction between piles and the surrounding soil presents a complex geotechnical challenge. Understanding this interaction is essential for ensuring the safety and performance of pile foundations. However, challenges persist in accurately predicting how piles will behave in specific soil conditions, particularly in contexts like residual soils, which exhibit heterogeneous and weathered properties. This knowledge gap underscores the need for efficient design methods and verification through pile load testing (Fellenius, 2018).The purpose of this paper is to assess the efficiency SA-SPT based pile design method in residual soils in comparison with the well-established Dercourt method.

The pile load test dataset was obtained from the database reported in Dithinde et al. (2011). The Franki-SA and Decourt methods are commonly used for estimating pile capacities but rely on limited databases that may not fully represent Southern Africa's unique conditions. In today's safety-focused engineering industry, it is important not only to ensure the safety of design methods but also to quantify their accuracy. This study aligns with the approach advocated by Sandgren and Cameron (2002), aiming to assess the uncertainty of SPT empirical methods by comparing predicted pile capacities with actual measurements. By shedding light on the safety and economic viability of these design methods for pile foundations in Southern Africa, this research contributes to enhancing engineering practices in the region.

MATERIALS AND METHODS

Compilation of pile load test database

The database contains essential data from full-scale pile load tests, soil profiles, and field tests, crucial for detailed load and resistance analysis. Pile load tests data was collected from various sources, mainly piling companies in South Africa, Botswana, Lesotho, Zambia, eSwatini, and Tanzania. Twenty-six cases were specifically selected for the study. The database includes three pile types:

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i. Expanded base (Franki) piles
ii. Auger piles
iii. Continuous Flight Auger (CFA) piles.

Table 1 summarizes key information from the compiled cases, including pile descriptions, types, shaft and base diameters, and lengths.

Frank-SA method

The shaft and base pile capacities were computed by using the corrected N values in conjunction with factors obtained from Tables 2 and 3. There are different factors for shaft and base capacities depending on the type of pile and the soil conditions, etc.).

Table 1. Pile cases descriptions

Case No.	Pile type	Shaft dia. (mm)	Base dia.(mm)	Length (m)	SPT N-value	
					Base	Shaft
1	Auger	600	600	11.5	Ref.	80
2	Auger	600	600	6.5	Ref.	15
3	Franki	600	800	6.5	60	15
4	Auger	610	610	9	100	20
5	Auger	610	610	7	100	20
6	CFA	750	750	13	100	20
7	Auger	450	450	9	Ref.	Ref.
8	CFA	350	350	5	Ref.	20
9	CFA	500	500	6	Ref.	20
10	CFA	600	600	6	20	10
11	CFA	450	450	6	100	20
12	CFA	300	300	6	Ref.	20
13	CFA	600	600	9.6	Ref.	20
14	CFA	400	400	8.7	100	20
15	CFA	350	350	8.7	60	20
16	CFA	410	410	11	100	20
17	Auger	615	615	12	32	28
18	Auger	615	615	12	32	28
19	Auger	610	610	7	90	70
20	Auger	610	610	5	90	70
21	Auger	500	500	7.8	Ref.	17
22	Franki	450	600	15.5	40	13
23	Auger	750	750	10.2	Ref.	35
24	Auger	450	450	8	100	17
25	Auger	450	450	8	100	17
26	Auger	450	450	8	Ref.	12

Table 2. Factors for calculating ultimate shaft capacity

Test \ Pile	Auger	Auger U/S	CFA	Oscill.	Precast	Tube	Franki Wet Shaft	Franki Ram Shaft	Forum Wet Shaft	Forum Ram Shaft
Piles in Non-cohesive Soils										
CPT q_c	5	5	5	5	8	8	8	12	5	8
SPT ‘N’	2.5	2.5	2.5	2.5	4	4	4	6	2.5	4
Max (kPa)	125	80	125	125	150	150	150	200	125	150
Piles in Cohesive Soils										
CPT q_c	10	10	10	10	15	15	15	30	10	15
SPT ‘N’	2.5	2.5	2.5	2.5	3.0	3.0	3.0	4.5	2.5	3.5
α	0.4	0.4	0.4	0.4	0.6	0.6	0.4	0.6	0.4	0.5
Max (kPa)	150	80	125	125	150	150	150	200	125	150

Table 3. Factors for calculating base capacity

Test \ Pile	Auger	Auger U/S	CFA	Oscill.	Precast	Tube	Franki Wet Shaft	Franki Ram Shaft	Forum Wet Shaft	Forum Ram Shaft
Piles in non-cohesive soils										
CPT q_c	$0.5q_c$	$0.5q_c$	$0.5q_c$	$0.5q_c$	$1.0q_c$	$1.0q_c$	$1.2q_c$	$1.2q_c$	$1.0q_c$	$1.0q_c$
SPT 'N'	300	300	300	300	400	400	500	500	400	400
Max (kPa)	8000	8000	8000	8000	20000	15000	15000	15000	15000	15000
Piles in cohesive soils										
CPT q_c	$0.45q_c$	$0.45q_c$	$0.45q_c$	$0.45q_c$	$0.45q_c$	$0.45q_c$	$0.60q_c$	$0.60q_c$	$0.50q_c$	$0.50q_c$
SPT 'N'	50	50	50	50	50	50	60	60	50	50
α	9	9	9	9	9	9	9 - 20	9 - 20	9 - 12	9 - 12
Max (kPa)	4500	4500	4500	4500	4500	4500	6000	6000	5000	5000

Table 4. "α" Values

Pile type	α			β		
	Clay	Sand	Residual soils	Clay	Sand	Residual soils
Driven	1	1	1	1	1	1
Bored piles (in general)	0.85	0.5	0.6	0.85	0.5	0.6
Bored piles (with mud)	0.85	0.5	0.6	0.9	0.5	0.75
CFA continuous flight auger	0.3	0.3	0.3	1	1	1
Minipiles, without pressure grouting	0.85	0.5	0.6	1.5	1.5	1.5
Pressure grouted minipiles	1	1	1	0.3	0.3	0.3

The base and shaft resistance are calculated as per Eq. 1 and Eq. 2 respectively.

$$Q_b = (N_1)_{60}F_b \leq q_{max} \quad [1]$$

$$q_s = (N_1)_{60}F_s \leq q_{max} \quad [2]$$

Where q_b is the base resistance, qs is the shaft resistance, $(N_1)_b$ is the SPT N-value for the base, (N_1)s is the SPT N-value for the shaft, F_b is the pile base resistance factor (Table 4), Fs is the pile shaft resistance factor (Table 5) and q_{max} indicates the maximum allowable ile capacity for the pile design situation.

The ultimate pile base and shaft capacities were calculated as (Eq. 3 and Eq. 4 respectively):

$$Q_b = q_b A_b \quad [3]$$

$$Q_s = q_s A_s \quad [4]$$

Where Q_b represents base capacity, A_b is the cross-sectional area of the pile base, Q_b is: base capacity and A_s the surface area of the pile shaft.

Decourt method

The ultimate pile capacity using the Decourt Method was determined by following the method's key Eqs 5 -8 in conjunction with coefficient specific to soil types and pile types, as shown in the provided Table 4 and 5.

For the base:

$$q_b = k_b N_b \quad [5]$$

Where qb is the base resistance, kb is a coefficient specific to the type of soil and installation method, Nb is the corrected SPT value around the pile base.

For the shaft:

$$q_s = \alpha(2.8N_s + 10) \quad [6]$$

Where, q_s is the shaft resistance, α accounts for the type of pile being used, Ns is the corrected SPT value around the pile shaft.

The ultimate pile capacity (Q_u) was then calculated as follows: $Q_u = q_b A_b + q_s A_s$ [7]

Table 5. "k " Values

Soil type	k (kPa)
Clays	120
Clayey silts (residual soils)	200
Sandy silts (residual soils)	250
Sands	400

Determination of measured pile capacity pile

The collected pile load test data were further processed by plotting load versus settlement to produce load-deflection curves. The load-deflection curves were then used to determine the ultimate pile capacity or measured capacity (Q_m). However, majority of the test piles were working piles and therefore not tested to failure and requires extrapolation procedure to determine the ultimate capacity e.g. (e.g. Chin, 1970 and 1971; Fleming 1992; Decourt, 1999). On account of its popularity, Chin extrapolation method was adopted for this study.

Evaluation of performance of methods studied

The performance of the methods were accessed by comparing their predicted capacity (Q_p) to the measured capacity (Q_m). The comparison was ahieved through (i) model uncertainty (*M*) statistics and (ii) best fit (Q_{fit} and the associated coefficient of determination (R^2). The model uncertainty or model factor (M) was determined from Eq. 8.

$$M = \frac{Q_m}{Q_p} \quad [8]$$

Where: Qm = pile capacity" interpreted from a load test, to represent the measured capacity; Qp = pile capacity generally predicted using Franki and Decourt method.

In addition to the measure of centrality and dispersion, the mean (*mM*) and standard deviation (sM) of the model factor were considered as indicators of the accuracy and precision of the predication method. An accurate and precise method gives *mM* = 1 and *sM* = 0 respectively, which means that for each pile case, the predicted pile capacity equals to the measured capacity (an ideal case). However, due to uncertainties of prediction models, the results of an ideal case cannot be attained in practice. Therefore in reality, the method is better when mM is close to 1 and sM is close to 0. In general when *mM* > 1, the predicted capacity is less than the interpreted capacity, which is conservative and safe whereas when *mM* < 1, the predicted capacity is greater than the interpreted capacity, which is not conservative and unsafe.

The 'best fit' was based on the equation of the best fit line of predicted versus measured capacity with the corresponding coefficient of determination (R^2). On the basis of regression analysis, the general equation of the best fit line is given by Eq. 9.

$$Q_{fit} = bQ_p \quad [9]$$

Where Q_{fit} is the least squares average of the measured capacity corresponding to a given predicted capacity values; b is a regression constant denoting the slope of the line; and Q_p is the predicted capacity.

Associated with each regression equation is the coefficient of determination (R^2). This is a statistical measure of goodness of fit between the predicted and measured values. More specifically, R^2 measures the proportion of the total variance in the dependent variable explained by the independent variable. For the purposes of this paper, R^2 was taken as a measure of the degree of agreement between the measured and predicted capacity.

RESULTS AND DISCUSSION

Predicted versus measured pile capacities

Tables 6 present the results of predicted and measured pile capacities and Table 7 presents associated M-statistics for the both Franki and Decourt methods. Further analysis of Table 7 indicated that the Decourt method has a mean that suggests the predicted pile capacities are close to the measured pile capacities. In contrast, the Franki method has a mean that indicates the predicted capacities are significantly higher than the measured capacities. Additionally, the Decourt method has a lower standard deviation, indicating less scatter in the predictions. In contrast, the Franki method has a higher standard deviation, suggesting more variability in the predictions. The COVs are comparable even though the Decourt method has relatively a lower value. Overall, these results suggest that the Decourt method is more accurate and reliable for predicting pile capacity in residual soils.

Table 7. Summary statistics for the model factor

Method	N	Mean	Std. Dev.	COV
Decourt	26	1.01	0.50	0.50
Franki	26	2.38	1.41	0.59

Evaluation of performance through best fit

Figures 3 and 4 present scatter plots of Q_m Vs Q_p for Decourt and SA method respectively. The best fit parameters (i.e. b and R^2) are shown in Table 8. The Decourt method shows a better fit and stronger relationship between predicted and measured capacities, with "b" of 1.44 and R^2 of 0.71, indicating that 71% of the variability in measured capacity is explained by the predicted capacity. In contrast, the Franki-SA method has a lower (b = 0.97) and R^2 of 0.20, meaning only 20% of the variability in measured capacity is explained by the predicted capacity, indicating a weaker relationship. Based on the evaluation results, the Decourt method is again better than SA method. The relative accuracy of the Decourt method has been reported by other researchers. In this regard, based on three rank index criterion results Henrina et al 2024 found that the best and efficient direct SPT method is the one proposed by Decourt. The relatively poor performance of the SA- Method is attributed to the fact that it does not have specific factors for calculating base and shaft capacities in residual soils as is the case with the Decourt Method. Therefore further studies for determination of SPT factors in residual soils for the SA method are required.

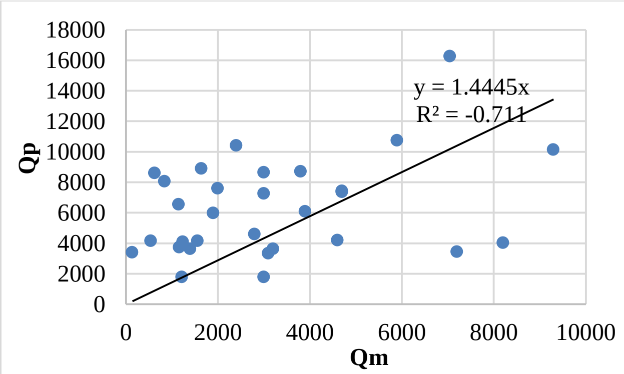

Figure 3. Scatter plot of Q_m Vs Q_p for Decourt method

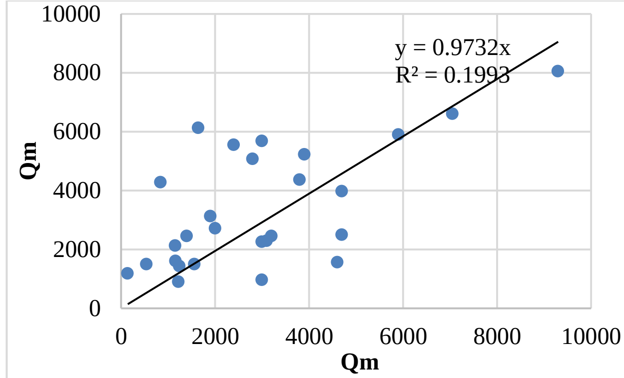

Figure 4. Scatter plot of Q_m Vs Q_p for SA SPT method

Table 8. Best Fit Parameters

Method	b	R^2
Franki	0.97	0.20
Decourt	1.445	0.71

Table 6. Predicted and Measured capacities

Case	Measured Capacity	Predicted Capacities	
		Franki	Decourt
1	4700	3989	4779
2	3000	1138	3150
3	3000	1108	3053
4	2850	1514	3431
5	1920	1331	3285
6	4700	2636	5632
7	3100	1889	2603
8	820	438	1008
9	800	914	2223
10	780	537	1323
11	1230	781	1833
12	1200	437	886
13	3200	1531	3373
14	1390	818	1609
15	875	683	1277
16	1600	1039	1882
17	3100	2099	3131
18	3100	2099	3131
19	1595	2287	3928
20	540	818	2391
21	4970	4028	8325
22	1950	2388	2872
23	3320	3208	5976
24	1600	834	1886
25	1900	1212	3397
26	2230	1078	3307

CONCLUSIONS

In conclusion, the evaluation of the Decourt and Franki methods for predicting pile capacity in residual soils in Southern Africa has revealed that the Decourt method provides better fit between the predicted and measured capacities. Furthermore, the SA method depicts high variability with mM = 2.36 and sM = 1.41 compared to the Decourt method with mM =1.01 and sM = 0.5. Accordingly the uncertainty shown by the SA method is too high for the method to be adopted for practical design of piles in residual soil.

The poor performance of the SA method against the Data base is attributed to absence of specific base and shaft calculation factors for residual soils compared to Decourt method. Therefore further studies are required to develop specific SPT factors for design of piles in residual soils of Sothern Africa.

DECLARATIONS

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Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Author's contribution

Mahongo Dithinde contributed pile load test database which he has previously used to characterize model uncertainties for theoretical pile design methods. Tshepo Maislo under the guidance of Dithinde evaluated the SA SPT-based pile design method against the database for piles in residual soils. She further compared the performance of the SA- Method with that of the well-established Decourt Method.

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Consent to publish
Not applicable.

Competing interests
The authors declare no competing interests in this research and publication.

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