Estimating Side Resistance of Bored Pile in Residual Soils

Mutiasani Dianmarti Kusuma[1] and Eng-Choon Leong[2]

[1]*Formerly School of Civil & Environmental Engineering, Nanyang Technological University, Singapore*

[2] *School of Civil & Environmental Engineering, Nanyang Technological University, Singapore*

E-mail: cecleong@ntu.edu.sg

ABSTRACT: Bored piles are extensively used as foundation in Singapore residual soils. However, traditional design of bored piles is based on properties of clays, sands, or rocks. In addition, bored piles are design to rely on base resistance (Q_b) despite the fact that side resistance's (Q_s) contribution towards axial capacity is higher at the working load. Using instrumented pile load test results from Bukit Timah Granite and Jurong Formation residual soils, correlations for unit side resistance (f_s) with SPT-N and soil properties were developed. The estimates of side resistance (Q_{s_est}) from the developed correlations were compared with Q_{s_est} from recommendations by other researchers which have been adopted in practice. Based on the comparison, the design of bored piles installed in Singapore residual soils can be optimized using the developed correlations.

1. INTRODUCTION

Bored piles are extensively used in Singapore residual soils for their high axial capacity and ease of length adjustment (Chang and Goh 1988). Because of the low noise level during construction, bored piles are preferred over driven piles in high population density areas.

However, bored piles are traditionally designed based on properties of clays, sands, or rocks. Pile design based on properties of residual soils is not well developed due to the dearth of research conducted for residual soils. In addition, at the working load level, contribution of Q_s is much higher than Q_b (Chang and Broms 1991).

In order to provide a better estimate of Q_s for the design of bored piles in Singapore residual soils, instrumented bored pile load test results reported for three sites in Bukit Timah Granite and six sites in Jurong Formation residual soils were evaluated in this paper. Using the evaluated test results, useful correlations for unit side resistance (f_s) with in-situ test results (SPT-N), undrained shear strength (s_u) and effective overburden pressure (σ') were developed to estimate the side resistance. The results showed that using correlations that were specifically developed for residual soils gave better estimate of side resistance.

2. SINGAPORE RESIDUAL SOILS

Residual soils are soil-like materials formed by in situ weathering and rock decomposition that have not been transported from the original location. With respect to the parent rock types, residual soils are classified into igneous, sedimentary and metamorphic (Blight 1997).

Singapore geology comprises three major formations, which are igneous rocks of Bukit Timah Granite, sedimentary rocks of Jurong Formation and semi-hardened Old Alluvium (Figure 1). Each of the formation occupies approximately one third of Singapore's main island. Jurong Formation and Bukit Timah Granite residual soils constitute two thirds of Singapore's total area.

Bukit Timah Granite residual soils vary from silty sand to clayey silt to sandy or silty clay with consistency of medium stiff to very stiff. The soils gradually become stiffer with depth (Chang and Broms 1991). The thickness of the residual soil layer is typically 10-35 m (Poh, et al. 1985). Below the residual soils, are granitic rocks whose weathering grades decrease with depth (Leong, et al. 2002). Jurong Formation comprises sandstone, mudstone, shale, tuff, conglomerate and limestone. Residual soils found in Jurong Formation can be described as clayey silt or silty clay, due to its clay content between 10-50% (Leong, et al. 2002). The consistency of the residual soils is generally stiff to hard.

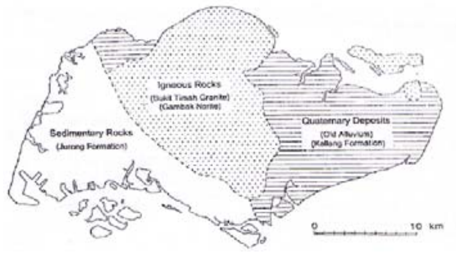

Figure 1 Simplified geological map of Singapore (Adapted from Leong et al., 2002)

3. PILE LOAD CAPACITY

Pile load capacity in compression comprises two components: side (Q_s) and base resistances (Q_b). Full mobilization of Q_b requires large displacement of 5 to 10% of the pile diameter (Woodward et al. 1972, Aurora and Reese 1977). In contrast, to achieve full mobilization of Q_s relatively small displacement of 5 to 10 mm is required (O'Neill and Reese 1972). At the working load, contribution of Q_s towards overall pile compression capacity is therefore much higher than Q_b.

4. INSTRUMENTED PILE LOAD TEST

In Singapore, instrumented pile load test is becoming more common. Instrumented pile load test enables derivation of load-displacement curve and load distribution curve, from which Q_s and Q_b can be assessed independently. To measure the distribution of Q_s along the pile, strain gauges are usually installed at different levels on the longitudinal steel reinforcement along the pile. Given modulus of pile section, load distribution along the pile can be assessed assuming that the same axial strain is developed in both the concrete and the steel.

Between two strain gauge levels, the load at the top of a pile section (P_1) is transferred to the surrounding soil (Q_s) and to the bottom of the section (P_2). Using strain gauge measurements, P_2 can be computed. Side resistance (Q_s), which is developed due to interface friction between pile and soil, is computed from Equation (1).

$$Q_s = P_1 - P_2 \tag{1}$$

where Q_s = side resistance (kN).

5. METHODOLOGY

Instrumented bored pile load test results reported for three sites in Bukit Timah Granite (BT-A, BT-B and BT-C) and four sites in Jurong Formation (JF-C, JT-D, JT-E and JT-F) residual soils were evaluated. At the three sites in Bukit Timah Granite residual soils, seven instrumented pile load tests were conducted. At the four sites in the Jurong Formation residual soils, five instrumented pile load tests were conducted. The instrumented pile load test results were separated into calibration and evaluation data. The calibration data consists of five instrumented pile load tests at BT-A and BT-B sites. Using the calibration data, correlations for unit side resistance f_s with SPT-N, undrained shear strength s_u and effective overburden stress σ' were developed in Section 6.

Using the developed correlations, the estimated side resistance (Q_{s_est}) was evaluated for the evaluation data which were not used to develop the correlations in Section 7. The evaluation data consists of seven instrumented pile load tests at BT-C, JF-C, JF-D, JF-E and JF-F sites. Correlations for f_s by other researchers were also used to compute Q_{s_est} and compared with the measured side resistance Q_{sm}. The ratios of Q_{s_est}/Q_{sm} given by the developed correlations were compared to ratios given by other researchers' correlations. From the results of the comparison, it was determined whether any improvement on the developed correlations was required. If no further improvement was required, the developed correlations were used to compute the ratio of Q_{s_est}/Q_{sm} for the evaluation data.

6. DEVELOPMENT OF f_s CORRELATIONS FOR BUKIT TIMAH GRANITE SITES

Based on the method of estimating f_s, correlations to estimate f_s were categorized into three groups. These are correlations for f_s with in-situ test result (SPT-N), α- and β-methods.

Load tests on five instrumented piles installed in two sites of Bukit Timah Granite residual soils, BT-A and BT-B, were used as the calibration data. The information for the instrumented piles are summarized in Table 1.

6.1 CORRELATION FOR f_s WITH SPT-N

Correlations of f_s with SPT-N proposed by other researchers are summarised in Table 2. Figure 1 shows that the data reported for sites BT-A and BT-B fall within the region bounded by two hyperbolic curves. The equations shown for the two curves were based on the hyperbolic form of correlation suggested by Chang and Goh (1988) for Jurong Formation.

The following equation based on an average of the two curves shown in Figure 2 can be used to estimate f_s for Bukit Timah Granite residual soils:

$$f_s = \frac{1.9N}{N+30} p_a \qquad ; N \le 100 \qquad (2)$$

where p_a = 100 kPa. Equation (2) is different in form from the equation proposed by Chang and Goh (1988) as p_a is introduced to make Equation (2) dimensionally consistent.

The side resistance (Q_{s_est}) was computed using Equation (2) and the equations in Table 2 by other researchers. For the Meyehof (1976) equation, f_s = 2N was used. For CP4, K_s was set at 2.5. Comparison of estimated side resistance (Q_{s_est}) with the measured side resistance (Q_{sm}) is summarised in Table 3 for the five instrumented piles installed in BT-A and BT-B sites.

Table 3 shows that existing equations to estimate Q_{s_est} from SPT N are not suitable for Singapore residual soils. However Q_{s_est} from Equation (2) gives on average slightly higher value than those measured. It is possible to reduce the coefficient 1.9 in Equation (2) by 10-15% to give more conservative values of Q_{s_est}.

Table 1 Summary of pile information at test sites BT-A and BT-B

Pile (Dia, m)	Depth (m)	Soil Description	N	f_s (kPa)
BT-A1 (0.6)	0-4.7	firm sandy silt	7	7.9
	4.7-7.7	very stiff sandy silt	18	38.3
	7.7-10.7	very stiff sandy silt	21	46.1
	10.7-13.7	very stiff sandy silt	19	49.1
	13.7-16.7	very stiff sandy silt	18	52.0
	16.7-19.7	very stiff sandy silt	20	54.0
	19.7-22.7	very stiff sandy silt	30	60.8
	22.7-25.7	very stiff sandy silt	35	69.7
	25.7-28.7	very stiff sandy silt	32	71.6
	28.7-31.7	very stiff sandy silt	45	74.6
BT-A2 (0.6)	3.8-8.4	firm to very stiff sandy silt	13	32.4
	8.4-15.5	very stiff sandy silt	19	59.8
	15.5-18.5	very stiff sandy silt	20	62.8
	18.5-21.5	very stiff sandy silt	30	64.8
	21.5-24.5	very stiff sandy silt	35	64.8
	24.5-27.5	very stiff sandy silt	32	68.7
	27.5-30.5	very stiff sandy silt	45	72.6
BT-B1 (0.7)	4.4-7.4	soft to firm sandy silt	4	28.5
	7.4-10.4	stiff sandy silt	8	38.3
	10.4-13.4	stiff to very stiff sandy silt	10	57.9
	13.4-16.4	stiff to very stiff sandy silt	18	84.4
	16.4-19.4	stiff to very stiff sandy silt	22	108.9
	19.4-22.4	very stiff sandy silt	25	114.8
	22.4-25.4	very stiff sandy silt	29	129.5
	25.4-28.4	very stiff sandy silt	36	135.4
	28.4-31.4	very stiff to hard sandy silt	39	141.3
	31.4-34.4	hard sandy silt	51	146.2
	34.4-36.9	hard sandy silt	57	158.9
	36.9-38.9	hard sandy silt	54	173.6
BT-B2 (0.8)	4.2-7.2	stiff silt / stiff sandy silt	13	41.2
	7.2-10.2	stiff sandy silt	15	65.7
	10.2-13.2	stiff sandy silt	13	69.7
	13.2-16.2	stiff sandy silt	14	82.4
	16.2-19.2	stiff sandy silt	18	88.3
	19.2-22.2	stiff sandy silt	22	109.9
	22.2-25.2	stiff sandy silt	20	127.5
	25.2-28.2	stiff to very stiff sandy silt	19	131.5
	28.2-31.2	very stiff sandy silt	30	139.3
	31.2-34.2	very stiff to hard sandy silt	29	144.2
	34.2-37.2	hard sandy silt	71	151.1
	37.2-39.2	hard sandy silt	83	173.6
BT-B3 (0.6)	5.9-8.9	firm to very stiff sandy silt	8	45.2
	8.9-11.9	very stiff sandy silt	16	60.8
	11.9-14.9	very stiff sandy silt	20	64.8

Table 2 Correlations for f_s in kPa with SPT-N

Reference	Correlation	Remarks
Findlay (1984)	$f_s = N$	-
Meyerhof (1976)	$f_s = N$	small displacement piles
	$f_s = 2N$	large displacement piles
CP 4 (2003)	$f_s = K_sN$	$K_s = 1.5 - 2.5$ $f_s \leq 150$kPa
Balakrishnan, et al. (1999)	$f_s = 2.3N$	N <150
Chang and Goh (1988)	$f_s = \frac{112N}{N+30}$	$f_s \leq 90$kPa

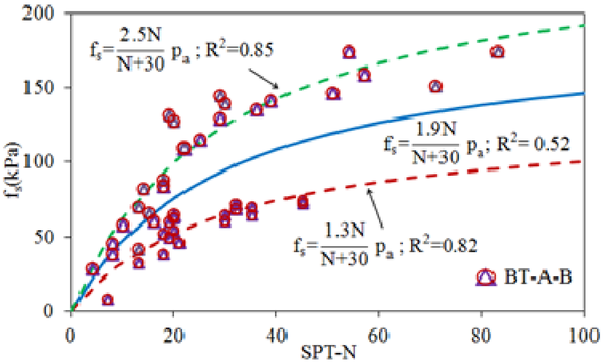

Figure 2 Correlation between f_s and SPT-N for instrumented piles at BT-A and BT-B sites

Table 3 Ratios of Q_{s_est}/Q_{sm} for BT-A and BT-B sites

Pile	Ratio of Q_{s_est}/Q_{sm}					
	Eq. (4)	Findlay (1984)	Meyerhof (1976)	CP4 (2003)	Balakrish-nan et al. (1999)	Chang and Goh (1988)
BT-A1	1.58	0.47	0.94	1.18	1.08	0.93
BT-A2	1.42	0.43	0.86	1.08	0.99	0.84
BT-B1	0.78	0.26	0.53	0.66	0.61	0.46
BT-B2	0.75	0.25	0.50	0.63	0.58	0.44
BT-B3	1.07	0.26	0.52	0.64	0.59	0.63
Average Q_{s_est}/Q_{sm}	**1.12**	**0.34**	**0.67**	**0.84**	**0.77**	**0.66**
S.D.*	**0.37**	**0.11**	**0.21**	**0.27**	**0.24**	**0.22**

*S.D. – Standard deviation

6.2 CORRELATION FOR f_s WITH s_u (α-METHOD)

The approach to estimate f_s using undrained shear strength (s_u) is known as α-method. Based on the α-method, f_s is defined as

$$f_s = \alpha s_u \tag{3}$$

where α = adhesion factor. Suggested equations by other researchers relating α with s_u are summarised in Table 4.

Table 4 Recommended correlations for α with s_u

Reference	Correlation	Remarks
O'Neill and Reese (1999)	$\alpha = 0.55$ $\alpha = 0.45$	$s_u \leq 150$ kPa $s_u \geq 250$ kPa
Chen and Kulhawy (1994)	$\alpha = 0.52\text{-}0.51 \log\left(\frac{s_u}{p_a}\right)$	$p_a = 100$ kPa
API (1974)	$\alpha = 1\text{-}0.5\frac{s_u\text{-}25 \text{ kPa}}{50 \text{ kPa}}$	25 kPa<s_u< 75 kPa

Using back-calculated adhesion factor (α_{BT}) and s_u at sites BT-A and BT-B, a correlation between α_{BT} and s_u was developed following the logarithmic correlation recommended by Chen and Kulhawy (1994). Due to the limited information on s_u reported for the two sites, s_u = 5N was adopted in this project (Stroud 1974). Figure 3 shows α_{BT} values for the five piles installed in Bukit Timah Granite residual soils. The correlation for α_{BT} with s_u was obtained as

$$\alpha_{BT} = 0.7 - 0.7\log\left(\frac{s_u}{p_a}\right) \quad \alpha_{BT} \leq 1.0 \tag{4a}$$

where p_a =100kPa. However, α_{BT} can be expressed in terms of s_u from Equation (2):

$$\alpha_{BT} = \frac{190}{s_u + 150} \quad \alpha_{BT} \leq 1.0 \tag{4b}$$

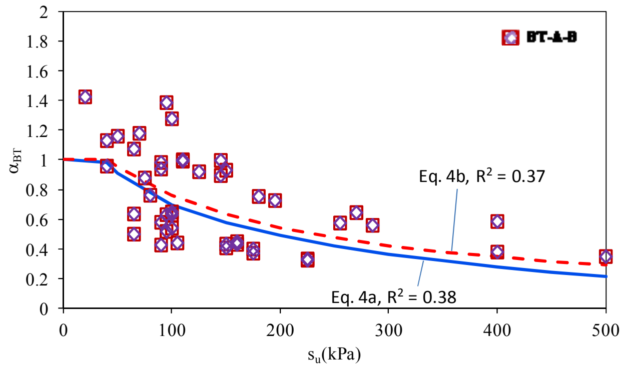

Figure 3 Correlation between α_{BT} and s_u for Bukit Timah Granite residual soils

The difference between Equations (4a) and (4b) is small as shown in Figure 3 with the coefficient of correlation R^2 for Equation (4a) slightly better than that for Equation (4b). Hence, estimated side resistance (Q_{s_est}) was computed using Equation (4a) and equations by other researchers. Table 5 shows that the existing equations to estimate Q_{s_est} from s_u are not suitable for Singapore residual soils.

6.3 CORRELATION FOR f_s WITH σ' (β-METHOD)

The approach to estimate f_s by using effective overburden pressure (σ') is also known as β-method whereby f_s is defined as

$$f_s = \beta\sigma' \tag{5}$$

where β = side resistance coefficient.

For the design of bored piles installed in sands, O'Neill and Reese (1999) recommended:

$$\beta = 1.5 - 0.245\sqrt{z} \qquad 0.25 \leq \beta \leq 1.20 \tag{6}$$

where z = mid-depth of soil layer (m) and 1.5 m $\leq$ z $\leq$ 26 m.

Table 5 Ratios of Q_{s_est}/Q_{sm} for sites BT-A and BT-B

Pile	Ratio of Q_{s_est}/Q_{sm}				
	Eq. (4a)	O'Neill and Reese (1999)	Chen and Kulhawy (1994)	Dennis and Olson (1983)	API (1974)
BT-A-1	1.38	1.22	1.03	0.92	1.15
BT-A-2	1.30	1.15	0.97	0.86	1.10
BT-B-1	0.70	0.66	0.53	0.55	0.68
BT-B-2	0.67	0.68	0.51	0.54	0.68
BT-B-3	1.00	0.71	0.74	0.56	0.73
Average Q_{s_est}/Q_{sm}	**1.01**	**0.88**	**0.75**	**0.69**	**0.87**

Since σ' is a function of bulk unit weight (γ) and ground water table (GWT), information about γ and GWT is necessary. However, γ was only reported for the first few meters and GWT position was not reported. Therefore, computations of f_s were performed using an average γ and an assumed GWT position at the ground surface.

Figure 4 shows the relationship between β_{BT} and z. Adopting the form of the correlation suggested by O'Neill and Reese (1999), the correlation between β_{BT} with z for the Bukit Timah Granite residual soil sites, BT-A and BT-B, is

$$\beta = 0.8 - 0.065\sqrt{\frac{z}{m}} \qquad \beta \geq 0.25 \tag{7}$$

where m = 1m, introduced to make Equation (7) dimensionally consistent.

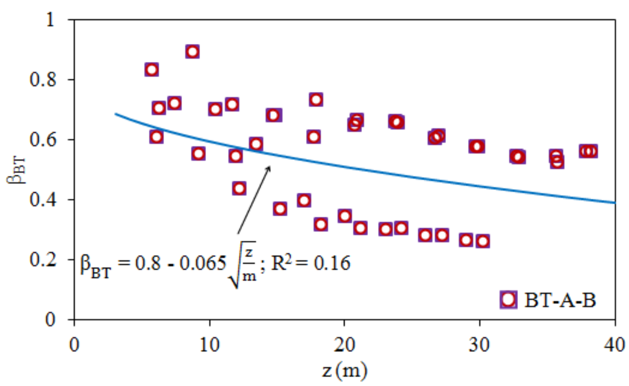

Figure 4 Correlation between β_{BT} and z for Bukit Timah Granite residual soils.

Estimated side resistance (Q_{s_est}) was computed using Equation (7) and the results were compared with measured side resistance (Q_{sm}) in Table 6. Table 6 shows that the correlation given by O'Neill and Reese (1999) is reasonable for Singapore residual soils. The proposed equation, Equation (7), gives comparable estimated side resistance.

7. EVALUATION OF f_s CORRELATIONS FOR BUKIT TIMAH AND JURONG FORMATION SITES

The developed correlations for f_s with SPT-N, α- and β-method were evaluated using data reported for piles installed in sites BT-C, JF-C, JF-D, JF-E and JF-F which were not used in the development of the f_s correlations. The pile information are summarised in Table 7.

Table 6 Ratios of Q_{s_est}/Q_{sm} for sites BT-A and BT-B

Pile	Proposed β_{BT} Eq. (7)	O'Neill and Reese (1999)
BT-A-1	1.41	1.29
BT-A-2	1.33	1.14
BT-B-1	0.82	0.62
BT-B-2	0.78	0.70
BT-B-3	0.89	0.91
Average Q_{s_est}/Q_{sm}	**1.05**	**0.93**

Table 7 Pile information for evaluation data

Site	Pile	Diameter (m)	Depth (m)	Measured side resistance (kN)
BT-C	BT-C1	0.8	10.2-40.2	7766.4
	BT-C2	0.7	5.0-23.0	3280.4
JF-C	JF-C1	0.6	3.1-15.6	3308.1
JF-D	JF-D1	0.3	1.5-21.3	416.1
	JF-D2	0.3	6.1-18.0	1054.0
JF-E	JF-E1	1.5	5.4-8.4	1109.5
JF-F	JF-F1	0.6	2.2-23.0	1703.1

7.1 EVALUATION OF CORRELATION FOR f_s WITH SPT-N

The ratio of Q_{s_est}/Q_{sm} for the evaluation data are summarised in Table 8. On closer examination of the Q_{s_est}/Q_{sm} ratios, site BT-C gave lower Q_{s_est}/Q_{sm} ratios compared to that shown in Table 3 for sites BT-A and BT-B suggesting that residual soil properties are variable. However, since closest estimate of Q_{sm} is given by Equation (2), it can be concluded that a better estimate of Q_{sm} in a particular formation can be obtained if a correlation specifically developed for that formation is used.

For the piles installed in Jurong Formation, Equation (2) also gives the closest estimate of Q_{sm} for piles JF-F1 and JF-D1, second closest for pile JF-C1, and third closest for piles JF-D2 and JF-E1 compared with the other five equations. Overall, Equation (2) still performed very well although it was developed from pile load test results in Bukit Timah Granite residual soils.

Table 8 Ratios of Q_{s_est}/Q_{sm} from f_s correlations with SPT-N for evaluation data

Pile	Ratio of Q_{s_est}/Q_{sm}					
	Eq. (2)	Findlay (1984)	Meyerhof (1976)	CP 4 (2003)	Balakrishnan, et al. (1999)	Chang and Goh (1988)
BT-C1	0.57	0.14	0.28	0.35	0.33	0.33
BT-C2	0.58	0.14	0.29	0.36	0.33	0.34
JF-C1	0.78	0.50	0.63	0.78	1.15	0.46
JF-F1	1.05	0.49	0.71	0.89	1.12	0.62
JF-D1	0.99	0.68	0.82	1.02	1.56	0.59
JF-D2	0.72	0.39	0.64	0.80	0.90	0.43
JF-E1	1.58	0.71	1.43	1.78	1.64	0.93
Average Q_{s_est}/Q_{sm}	0.90	0.44	0.69	0.85	1.00	0.53
S.D.	0.35	0.23	0.39	0.48	0.53	0.21

7.2 EVALUATION OF α-METHOD

The ratio of Q_{s_est}/Q_{sm} for the evaluation data are summarised in Table 9. Similar to the correlation of f_s with SPT-N, the Q_{s_est}/Q_{sm} ratios given by the α-method for site BT-C gave lower Q_{s_est}/Q_{sm} ratios compared to that shown in Table 5 for sites BT-A and BT-B. However, Equation (4a) gives the closest estimate of Q_{sm} compared with the other three methods.

For the piles installed in Jurong Formation, Equation (4a) also gives the closest estimate of Q_{sm} for piles JF-D1 and JF-E1, second closest for piles JF-D2 and JF-F1, and third closest for pile JF-C1 compared with the other three equations. Overall, Equation (4a) performed very well although it was developed from pile load test results in Bukit Timah Granite residual soils.

Table 9 Ratios of Q_{s_est}/Q_{sm} from α-method for evaluation data

Pile	**Ratio of Q_{s_est}/Q_{sm}**			
	Eq. (4a)	**O'Neill and Reese (1999)**	**Chen and Kulhawy (1994)**	**API (1974)**
BT-C1	0.53	0.39	0.39	0.42
BT-C2	0.54	0.40	0.41	0.42
JF-C1	0.58	1.13	0.45	1.26
JF-F1	1.38	1.61	1.04	1.78
JF-D1	0.72	1.53	0.56	1.70
JF-D2	0.60	2.23	0.46	0.98
JF-E1	0.91	1.19	0.69	1.33

7.3 EVALUATION OF β-METHOD FOR EVALUATION DATA

The ratios of Q_{s_est}/Q_{sm} in Table 10 were obtained considering 1.5m $\leq z \leq$ 26m, i.e., the range of mid-depth that is valid for O'Neill and Reese (1999) equation. Equation (7) gave ratios of Q_{s_est}/Q_{sm} that is closer to unity compared to O'Neill and Reese (1999) for five out of the seven instrumented pile load test.

Table 10 Ratios of Q_{s_est}/Q_{sm} from β-method for evaluation data

Pile	**Ratio of Q_{s_est}/Q_{sm}**	
	Eq. (7)	**O'Neill and Reese (1999)**
BT-C-1	1.05	0.43
BT-C-2	1.20	0.57
JF-C-1	0.39	0.36
JF-F-1	1.72	1.39
JF-D-1	1.05	1.11
JF-D-2	0.59	0.74
JF-E-1	1.08	1.47

8. CONCLUSION

Residual soil properties are variable and site-dependent. Using correlation for f_s that is specifically developed for residual soils, better estimate of side resistance for bored piles installed in residual soils can be obtained. The correlations developed in this paper are applicable to estimate side resistance of bored piles installed in Bukit Timah Granite and Jurong Formation residual soils.

The correlation of f_s with SPT-N using Equation (2) gives, on average, a closer estimate of side resistance for Bukit Timah Granite and Jurong Formation residual soils compared to other equations. Using s_u = 5N, the estimates of Q_{sm} given by the α-method [Equation (4a)] give a similar trend as that given by Equation (2). Therefore the assumption of s_u = 5N gives good estimate of s_u from SPT-N for Singapore residual soils. However, since s_u is derived from SPT-N for the α-method, the use of the more direct correlation between f_s and SPT-N is recommended. The β-method given by Equation (7) gives good estimate of side resistance for bored piles in Bukit Timah Granite and Jurong Formation residual soils compared with the O'Neill and Reese (1999) equation.

9. ACKNOWLEDGMENT

The first author wishes to acknowledge the funding support for this project from Nanyang Technological University under the Undergraduate Research Experience on Campus (URECA) programme.

The authors would also like to thank Mr. Wee Hui Hui of APS Asia PDA Enterprise Pte Ltd. for providing all the instrumented pile load test data used in this project.

10. REFERENCES

API (1974). American Petroleum Institute. Recommended practice for planning, designing and constructing fixed offshore platforms (5th ed.). Dallas, Texas.

Aurora, R. R., & Reese, L. C. (1977). Field tests of drilled shafts in clay-shales. Proceedings of 9th International Conference on Soil Mechanics and Foundation Engineering, Tokyo Vol. 2, pp 371-376.

Balakrishnan, E. G., Balasubramaniam, A. S., & Phien-wej, N. (1999). Load deformation analysis of bored piles in residual weathered formation. Journal of Geotechnical and Geoenvironmental Engineering, 125(2), 122-131.

Blight, G. E. (1997). Mechanics of residual soils : a guide to the formation, classification and geotechnical properties of residual soils, with advice for geotechnical design / edited by G.E. Blight: Rotterdam : Balkema, 1997.

Chang, M. F., & Broms, B. B. (1991). Design of bored piles in residual soils based on field-performance data. Canadian Geotechnical Journal, 28(2), 200-209.

Chang, M. F., & Goh, A. T. C. (1988). Behaviour of bored piles in residual soils and weathered rocks of Singapore. Research Report, School of Civil & Environmental Engineering, Nanyang Technological University, Singapore, 272 pp.

Chen, Y. J., & Kulhawy, F. H. (1994). Case history evaluation of the behavior of drilled shafts under axial and lateral loading / prepared by Cornell University, Geotechnical Engineering Group ; Palo Alto, Calif. : Electric Power Research Institute, 1994.

CP 4. (2003). Code of practice for foundations. Spring Singapore, 2003.

Dennis, N. D., & Olson, R. E. (1983). “Axial capacity of steel pipe piles in clay.” Proceedings of Geotechnical Practice in Offshore Engineering, 27-29 April 1983, Austin, Texas.

Findlay, J. D. (1984). “Discussion: piling and ground treatment.” Piling and Ground Treatment. Institution of Civil Engineers, Thomas Telford, London, pp. 189-190.

Leong, E. C., Rahardjo, H., & Tang, S. K. (2002). “Characterisation and engineering properties of Singapore residual soils.” Proceedings of International Workshop on Characterisation and Engineering Properties of Natural Soils, Vol. 2, pp. 1279-1304.

Meyerhof, G. G. (1976). “Bearing capacity and settlement of pile foundations.” American Society of Civil Engineers, Journal of the Geotechnical Engineering Division, 102(3), 195-228.

O'Neill, M. W., & Reese, L. C. (1972). “Behaviour of bored piles in Beaumont clay.” ASCE Journal of the Soil Mechanics and Foundations Division, 98(SM2), 195-213.

O'Neill, M. W., & Reese, L. C. (1999). Drilled shafts : construction procedures and design methods,U.S. Dept. of Transportation, Federal Highway Administration, Office of Infrastructure, Washington, D.C.

Poh, K. B., Chuah, H. L., & Tan, S. B. (1985). “Residual granite soil of Singapore.” Proceedings of 8th Southeast Asian Geotechnical Conference, Kuala Lumpur.

Stroud, M. A. (1974). “The Standard Penetration Test in insensitive clays and soft rocks.” Proceedings of 1st European Symposium on Penetration Testing (ESOPT), Stockholm.

Woodward, R. J., Gandner, W. S., & Greer, D. M. (1972). Drilled pier foundations. New York: Mc Graw-Hill.