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Side Resistance of Drilled Shafts Socketed into Rocks for Serviceability and Ultimate Limit States

Yit-Jin Chen*, Cheng-Chieh Hsiao, Anjerick Topacio

Department of Civil Engineering, Chung Yuan Christian University, Taoyuan, Taiwan

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Abstract

This study evaluates the analysis models of side resistance in rock sections by utilizing a wide variety of load test data. Available analytical models including the empirical adhesion factor versus the rock's uniaxial compressive strength and its root are analyzed and compared statistically to determine the optimum relationships. The interpretation criteria for the L_1 and L_2 methods are used to analyze the load test results for serviceability and ultimate limit states, respectively. The analysis results show that the relationship model with the empirical adhesion factor versus the root of the rock's uniaxial compressive strength exhibits better correlation than the one with the rock's uniaxial compressive strength. Moreover, the general coordinate axes regression equation demonstrates better reliability than the semi-logarithmic and full logarithmic axes equations for both limit states. Based on these analyses, specific design recommendations for the side resistance of drilled shafts socketed into rocks are developed and provided with the appropriate statistics to verify their reliability.

Keywords: drilled shaft, socketed into rock, side resistance, statistical analysis

1. Introduction

Limited land for building structures frequently lead to the construction of high buildings to save land occupancy. The structures of such buildings are heavy. To stabilize these structures, a deep foundation is often used to transfer the load of the superstructure to the underlying bearing layer. Occasionally, a certain length of the pile foundation is embedded into the rock layer to increase the effects of stabilizing the superstructure.

Among pile foundations, drilled shafts (also called cast-in-place piles, drilled piers, or bored piles) are frequently used as deep foundation because they produce less noise and vibration during construction and meet the required pile diameter and depth. In addition, drilled shafts can provide sufficient lateral support to resist the force of the superstructure from earthquakes and wind loads.

When a pile is subjected to an axial load, the load is transmitted along the length of the pile toward the hard soil or rock layer, as shown in Fig. 1. Pile capacity includes side and tip resistances for resisting axial load. Side resistance plays an important role when a pile is socketed into rocks.

In the analysis of side resistance, the analysis concept of the shaft in cohesive soil and rocks is the same. In cohesive soil, the total stress analysis method is frequently used to evaluate unit side resistance (f_s). The f_s value can be computed on the basis of an empirical coefficient (a), which is the adhesion factor between the soil and the shaft, and the average soil undrained shear

* Corresponding author. E-mail address: yjc@cycu.edu.tw
Tel.: +886-3-2654227; Fax: +886-3-2654299

strength (S_u) over the shaft length. Moreover, the α value is related to S_u, and the initial a- S_u relationship of the drilled shafts was developed by Stas and Kulhawy [1], as shown in Fig. 2. However, the S_u values in their analysis were obtained from random test types. The S_u value can be determined from various test types, but the results present an evident difference. Therefore, Chen and Kulhawy [2, 3] later adopted a unique test type for S_u from the consolidated isotropically undrained triaxial compression (*CIUC*) test, which is denoted as $S_u(CIUC)$, the reference plane for a consistent test. The improved a_{CIUC}-$S_u(CIUC)$ relation is illustrated in Fig. 3. The data distribution of the improved a_{CIUC}-$S_u(CIUC)$ correlation is superior to that of the previous result shown in Fig. 2. These concepts have been expanded to the analysis of side resistance for driven precast concrete piles [4, 5].

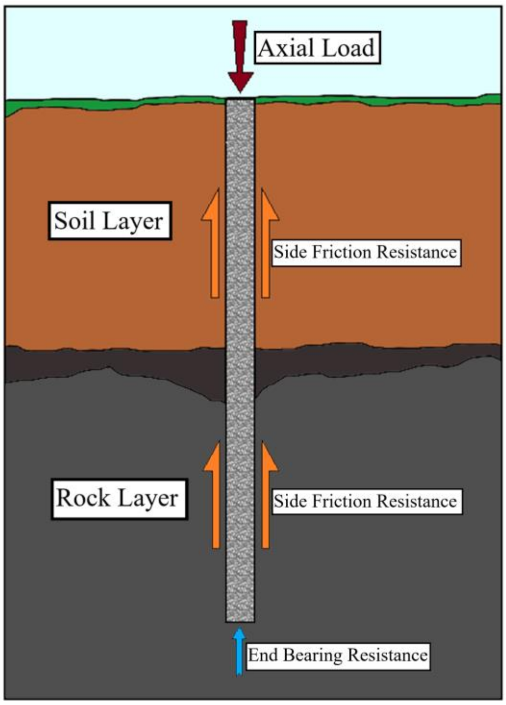


Fig. 1 Axial load resisted by a pile foundation

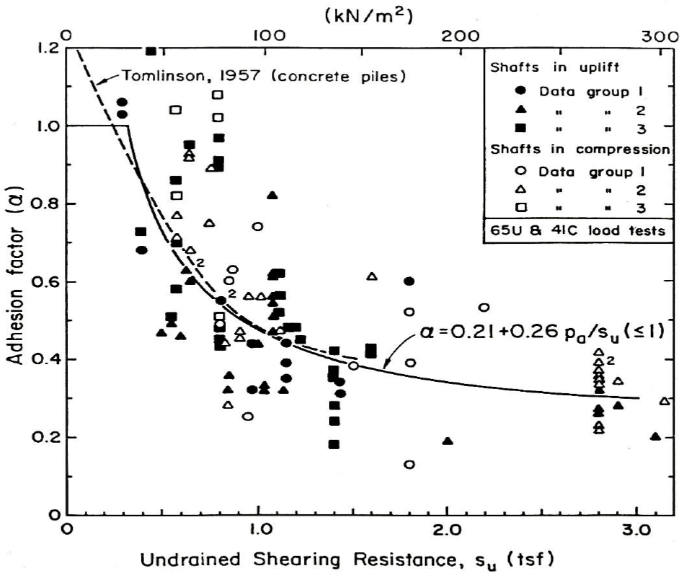


Fig. 2 Early a-S_u relation [1]

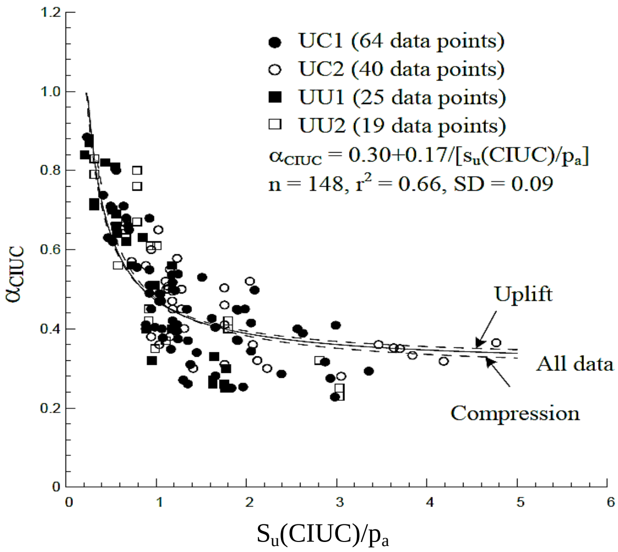


Fig. 3 Improved a_{CIUC}-$S_u(CIUC)$ relation [2,3]

The analysis model of side resistance for drilled shafts socketed into rocks is similar to the conventional total stress analysis in cohesive soil. However, the uniaxial compressive strength (q_u) is adopted in rocks instead of the S_u in cohesive soil. The f_s value expressed by using q_u or its rootz ($\sqrt{q_u}$) can be expressed as:

$$f_s = \alpha \cdot q_u \tag{1}$$

$$f_s = \alpha \cdot \sqrt{q_u} \tag{2}$$

Accordingly, numerous studies have been conducted and have resulted in various relationships in determining the side resistance value of drilled shafts. Kulhawy and Goodman [6] recommended an α value of 0.15 and found that the value of q_u should be less than 5 MPa. They used Eq. (1) to determine side resistance. Moreover, several researchers have utilized Eq. (2) to determine side resistance during analyses. Hooley and Brooks [7] studied the friction force of piles in overcompacted clay, soft rock, and weathered rock. They recommended a q_u value between 0.25 and 3.0 MPa and an α value of 0.15. The American Association of State Highway and Transportation Officials [8] suggested that the q_u value should be less than 40 MPa and the α value should be between 0.03 and 0.04. Horvath et al. [9] suggested that the q_u value should be less than 40 MPa, and the α value should be between 0.2 and 0.3. Ku et al. [10] conducted related research on the western soft rock of Taiwan and recommended an α value of 0.16-0.21 but did not recommend any value for q_u. Lastly, Yang et al. [11] found that the α value of piles socketed into rocks in Northern Taiwan is between 0.1 and 0.5, and the relation α versus $\sqrt{q_u}$ is shown in Fig. 4.

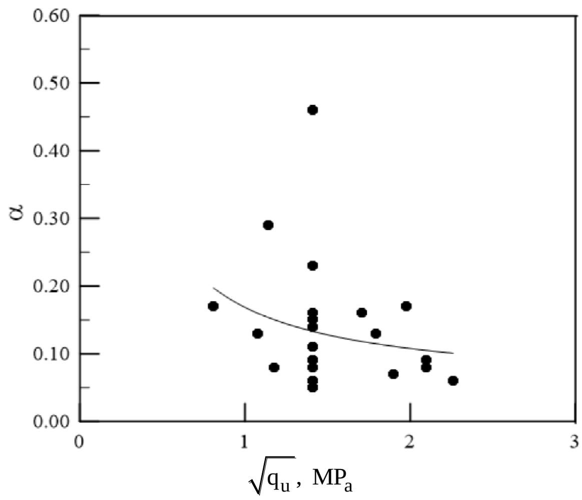


Fig. 4 α-$\sqrt{q_u}$ relationship based on northern Taiwan's load tests [11]

The aforementioned descriptions indicate that the current relations are based on a few load test data, and the range of the values of α is extremely broad and scattered. Thus, the current study was conducted to reassess side resistance for the serviceability limit state (SLS) and ultimate limit state (ULS) of drilled shafts socketed into rocks. Moreover, the various influencing factors were analyzed to provide a reliable design recommendation.

2. Database for Analysis

To evaluate the side resistance behavior of drilled shaft foundations socketed into rock sections, this study collected data from Taiwan, Turkey, the USA, Italy, and Singapore [12]. A total of 44 load tests embedded into rocks were obtained, including 28 sandstones, 3 mudstones, 3 limes, 3 soft sandstones, 3 hard shales, 2 tuffs, and 3 amphibolite. In addition, 81 sets of pile load data instruments were used from these load tests. Therefore, one load test may consist of several instruments for different rock sections. The average *a* and q_u values were adopted for the analysis of each load test. The collected pile information was accompanied by soil/rock layer information, pile foundation information, load–displacement curve, and load distribution curve along the pile length. Table 1 provides the details for the geometries, geotechnical parameters, and interpreted results of these load test data. Table 2 lists the statistical summary of these data [12].

Table 1 Geometries, geotechnical parameters, and interpreted results of load test data

Shaft No.	Depth, D	Diameter, B	Test depth from GL	q_u	$f_s(L_1)$[1]	$f_s(L_2)$[2]
	(m)	(m)	(m)	(MPa)	(MPa)	(MPa)
TP1	37.6	0.95	28.0~36.0	12.77	0.268	0.63
TP2	42.6	0.95	34.2~41.0	10.01	0.176	0.53
TP3	20.0	1.2	4.0~19.0	0.60	0.063	0.16
TP4	66.0	1.5	61.5~66.0	4.17	0.160	0.59
TP5	25.5	1.5	21.5~25.5	0.20	0.088	0.24
TP6	48.0	1.5	40.0~48.0	1.21	0.095	0.31
TP7	48.0	1.5	40.0~48.0	0.80	0.080	0.25
TP8	53.0	1.5	49.5~53.0	1.03	0.110	0.52
TP9	30.0	1.2	26.4~30.0	2.26	0.070	0.24
TP10	53.5	2.0	37.2~53.3	2.46	0.060	0.22
TP11	54.5	2.0	38.2~54.5	0.34	0.069	0.17
TP12	24.0	0.8	16.7~24.0	0.70	0.018	0.11
TP13	48.0	1.5	47.7~52.0	0.65	0.090	0.13
TP14	47.7	1.2	41.7~47.7	0.16	0.115	0.14
TP15	59.0	1.2	55.8~59.0	3.00	0.110	0.29
TP16	29.0	1.2	24.9~29.0	0.13	0.060	0.16
TP17	45.0	1.2	35.0~42.5	3.47	0.062	0.20
TP18	38.0	1.0	35.0~37.4	13.00	0.150	0.37
TP19	60.4	1.5	58.4~59.8	13.70	0.300	0.58
TP20	48.0	1.5	44.5~48.0	13.64	0.277	1.15
TP21	46.0	0.41	43.4~45.3	2.54	0.160	0.53
TP22	10.0	1.2	2.5~10.0	1.30	0.053	0.21
TP23	9.1	1.2	3.5~9.1	1.60	0.050	0.22
TP24	8.0	1.2	4.5~8.0	1.00	0.050	0.20
TP25	25.0	1.0	15.5~25.5	4.26	0.135	0.53
TP26	17.0	1.8	3.0~16.4	1.70	0.064	0.24
TP27	36.0	1.0	32.9~35.4	1.03	0.092	0.18
TP28	27.5	1.2	25.5~27.0	1.51	0.075	0.47
TP29	22.8	0.8	12.3~22.2	0.52	0.110	0.35
TP30	20.4	0.8	15.5~19.8	1.86	0.111	0.30
TP31	26.4	1.0	16.8~26.8	0.32	0.082	0.23
TP32	8.7	0.7	5.6~8.8	5.00	0.227	0.50
TP33	11.0	0.7	5.6~11.0	5.00	-	0.40
TP34	18.5	1.2	11.0~18.5	0.90	0.100	0.15
TP35	39.0	1.2	26.0~37.0	3.00	0.046	0.20
TP36	13.5	1.2	11.0~13.5	6.00	0.148	0.42
TP37	7.3	0.7	2.1~7.3	6.82	0.133	0.46
TP38	13.5	1.35	4 .0~10.0	7.00	0.080	0.34
TP39	11.5	1.5	3.5~9.6	7.77	0.088	0.40
TP40	59.0	1.2	54.6~58	0.26	0.050	0.26
TP41	73.0	1.5	67.0~73.0	0.30	0.053	0.15
TP42	76.0	1.3	71.0~76.0	0.45	0.012	0.22
TP43	40.7	2.2	28.5~39.5	0.37	0.026	0.04
TP44	15.0	1.2	2.0~14.5	0.93	0.053	0.14

[1] $f_s(L_1)$ is the unit friction interpreted from L_1 Method
[2] $f_s(L_2)$ is the unit friction interpreted from L_2 Method

3. Analysis Method

Two methods were used in this study to obtain the side resistance of the drilled shaft foundation. First, the value was directly obtained from the t-z curve, which defines the shear stress–vertical displacement response of the soil at each particular depth. Second, the load–displacement curve and the load distribution curve throughout the pile length were utilized. By considering these test results, the interpretation of Kulhawy and Hirany (called the L_1-L_2 interpretation) [13] was adopted to construe unit side resistance under various limit states.

Table 2 Statistics of load test data for analysis

Interpretation method	n	Statistical Analysis	Pile Geometry			q_u (MPa)	α	f_s (MPa)
			Pile length D (m)	Pile diameter B (m)	D/B			
L_1	44	Range	7.3-76.0	0.41-2.2	6.7-112.2	0.13-13.7	0.011-0.719	0.012-0.50
		Mean	33.10	1.2	28.13	3.372	0.098	0.104
		SD	17.53	0.39	18.35	3.92	0.14	0.078
		COV	0.53	0.33	0.65	1.16	1.42	0.75
L_2	44	Range	7.3-76.0	0.41-2.2	6.7-112.2	0.13-13.7	0.03-1.23	0.04-1.19
		Mean	33.10	1.2	28.13	3.372	0.277	0.33
		SD	17.53	0.39	18.35	3.92	0.31	0.21
		COV	0.53	0.33	0.53	1.16	1.12	0.64

This L_1-L_2 interpretation is a graphical method that utilizes the load–displacement curve. L_1 is defined as the endpoint of the initial linear segment. As illustrated in Fig. 5, the load and displacement are represented by Q_{L1} and ρ_{L1} respectively. L_2 is the starting point of the final line segment. The load and displacement are represented by Q_{L2} and ρ_{L2} respectively. An interpretation example based on one of the pile report data is shown in Fig. 6. Chen and Fang [14] studied the L_1 and L_2 interpretation by using many load test data and established the interrelationships among L_1, L_2, and several typical interpretation criteria. Their analysis showed that $L_1 = 0.5L_2$, on average. This finding indicates a factor of safety of 2 if L_1 is used for the design. Moreover, L_1 should be used in SLS and L_2 should be used in ULS. Tang et al. [15] recently conducted statistical analyses to evaluate model factors in a reliability-based design for drilled shafts under axial loading with SLS and ULS.

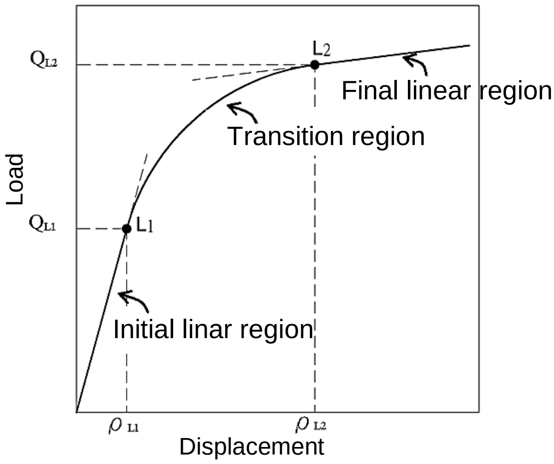


Fig. 5 Regions of load–displacement curve

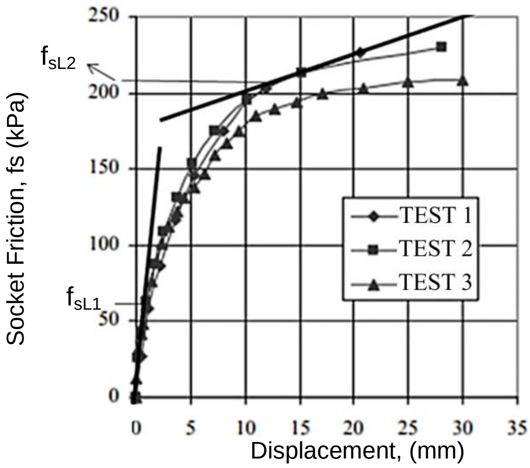


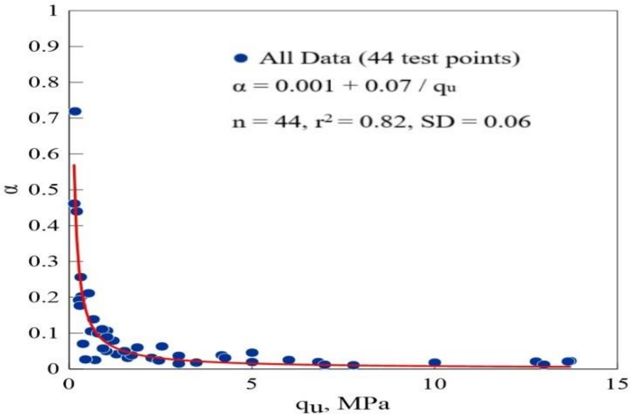
Fig. 6 L_1-L_2 interpretation of the t-z curve example [12]

4. Analysis Results

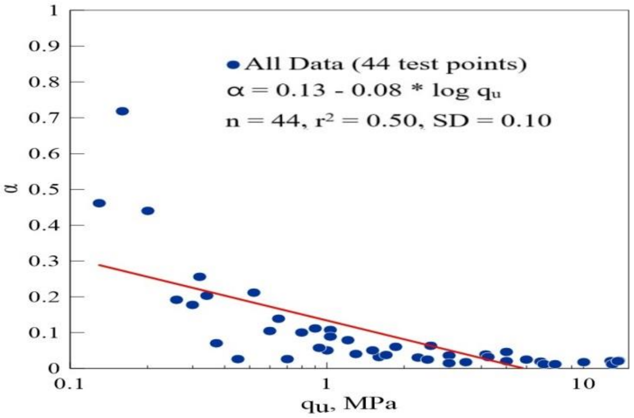
4.1. Correlation of α versus q_u

Eq. (1) was used to evaluate the pile load test data for α, and the results of the L_1 and L_2 interpretations are presented in Figs. 7 and 8, respectively, including the average results of the data obtained from 44 single pile reports. Unit side resistance was determined using the load–displacement curve or the t–z curve.

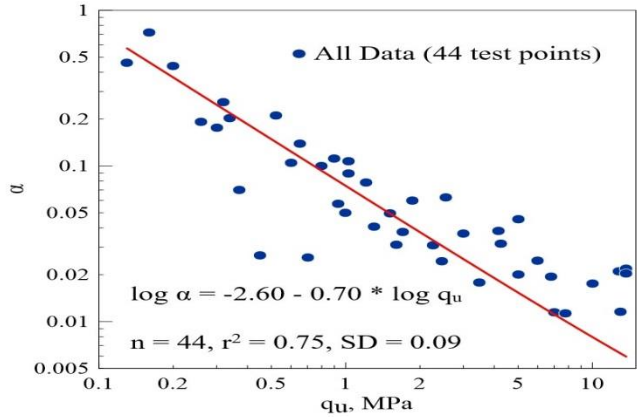
The data in Figs. 7 and 8 were then plotted into three coordinate axes, namely (a) general coordinate, (b) semi-logarithmic, and (c) full logarithmic axes, to determine the optimum trend for each interpretation. The statistical analysis is provided in Table 3 to compare the three equations. The statistical results of the coefficient of determination (r^2), standard deviation (SD), and coefficient of variation (COV) are also listed in the figures and tables.



(a) general coordinate

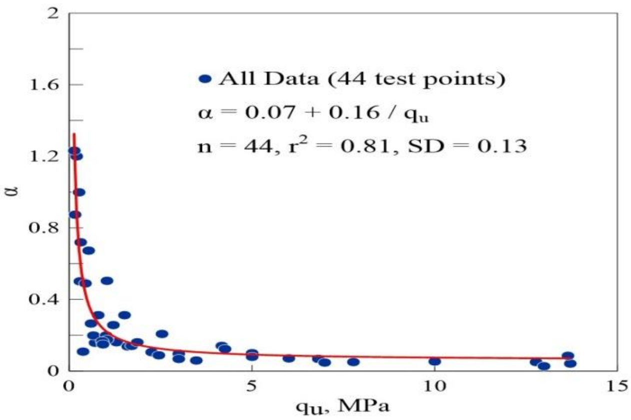


(b) semi-logarithmic coordinate

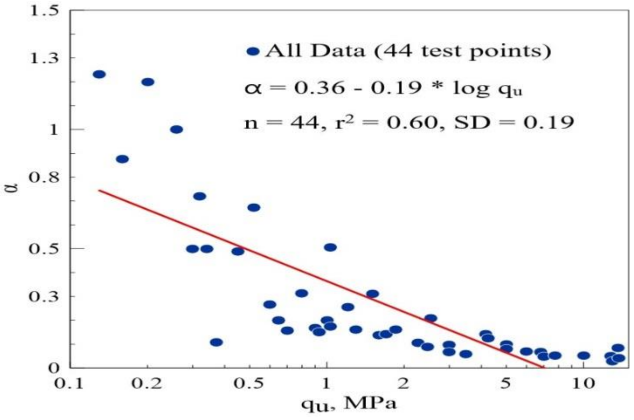


(c) full-logarithmic coordinate

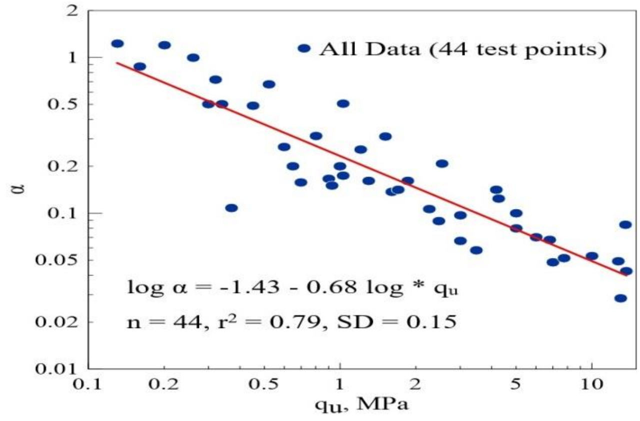
Fig. 7 a-q_u relationships for L_1 interpretation



(a) general coordinate



(b) semi-logarithmic coordinate



(c) full-logarithmic coordinate

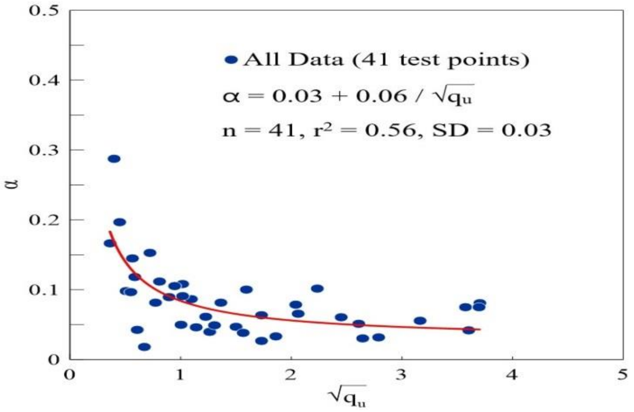
Fig. 8 a-q_u relationships for L_2 interpretation

Table 3 Statistical results for a-q_u relationships

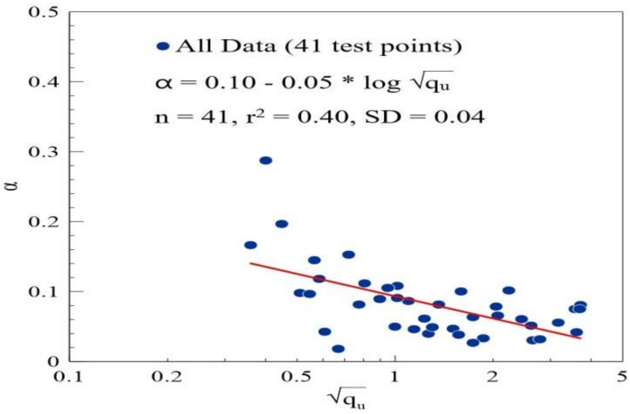
Interpretation method	Coordinate form	Regression equation	n	r^2	SD	COV
L_1	General coordinate	$\alpha = 0.01 + 0.07 / q_u$	44	0.82	0.06	0.59
	Semi-logarithmic	$\alpha = 0.13 - 0.08 \cdot \log(q_u)$		0.50	0.10	1.00
	Full logarithmic	$\log(\alpha) = -2.60 - 0.70 \cdot \log(q_u)$		0.75	0.09	0.87
L_2	General coordinate	$\alpha = 0.07 + 0.16 / q_u$	44	0.81	0.13	0.45
	Semi-logarithmic	$\alpha = 0.36 - 0.19 \cdot \log(q_u)$		0.60	0.19	0.66
	Full logarithmic	$\log(\alpha) = -1.43 - 0.68 \cdot \log(q_u)$		0.79	0.15	0.51

The results of the statistical analyses indicated that the three coordinate axes used in the study caused differences in terms of reliability with each interpretation used. As shown by the results, the general coordinate regression equation has the lowest COV for the L_1 and L_2 interpretations. Therefore, the general coordinate regression equation exhibits higher reliability than the other equations.

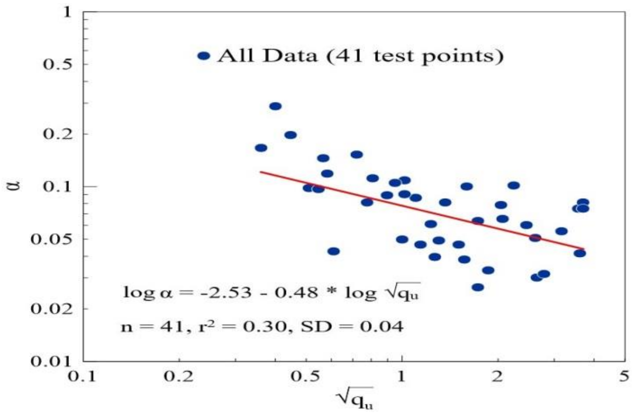
4.2. Correlation of α versus $\sqrt{q_u}$



(a) general coordinate



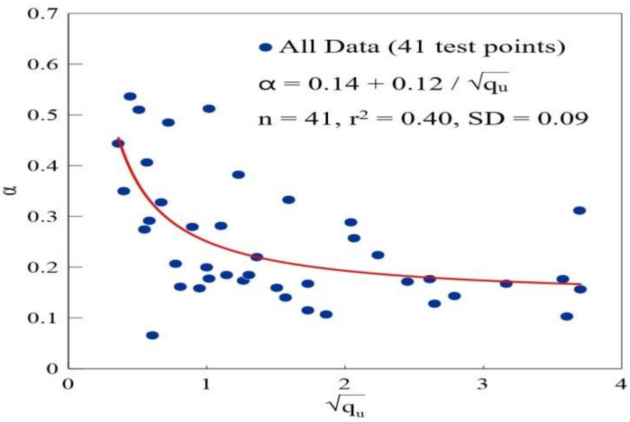
(b) semi-logarithmic coordinate



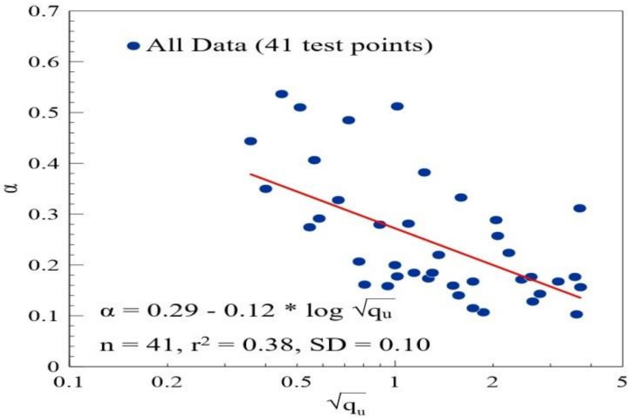
(c) full-logarithmic coordinate

Fig. 9 $\alpha - \sqrt{q_u}$ relationships for L_1 interpretation

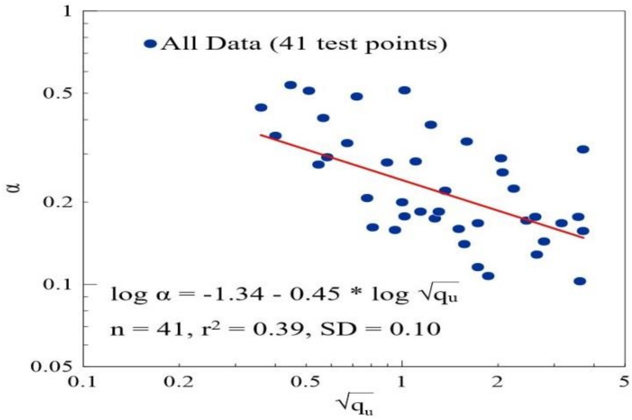
The analysis presented in this section is commonly used in determining the side resistance of drilled shafts socketed into rock sections. The difference is that the uniaxial compressive strength was analyzed through its root. The results showed that several discrete data points are scattered, resulted in an inconsistent plot. These data were obtained from piles socketed into mudstone (n = 3) because foundations embedded into mudstone tend to have a greater tip capacity than friction. Thus, these data were omitted in this section to obtain reasonable results. The new data were then plotted into (a) general coordinate, (b) semi-logarithmic, and (c) full logarithmic axes, as shown in Figs. 9 and 10 for the L_1 and L_2 interpretations respectively. The data were plotted in the three coordinate axes in order to determine the optimum trend for each interpretation. Statistical analysis is provided in Table 4 to compare the two interpretations used in the study.



(a) general coordinate



(b) semi-logarithmic coordinate



(c) full-logarithmic coordinate

Fig. 10 $\alpha - \sqrt{q_u}$ relationships for L_2 interpretation

Table 4 Statistical results for $\alpha - \sqrt{q_u}$ relationships

Interpretation method	Coordinate form	Regression equation	n	r^2	SD	COV
L_1	General coordinate	$\alpha = 0.03 + 0.06 / \sqrt{q_u}$	41	0.56	0.03	0.41
	Semi-logarithmic	$\alpha = 0.10 - 0.05 \cdot \log(\sqrt{q_u})$		0.40	0.04	0.48
	Full logarithmic	$\log(\alpha) = -2.53 - 0.48 \cdot \log(\sqrt{q_u})$		0.30	0.04	0.48
L_2	General coordinate	$\alpha = 0.14 + 0.12 / \sqrt{q_u}$	41	0.40	0.09	0.36
	Semi-logarithmic	$\alpha = 0.29 - 0.12 \cdot \log(\sqrt{q_u})$		0.38	0.10	0.37
	Full logarithmic	$\log(\alpha) = -1.34 - 0.45 \cdot \log(\sqrt{q_u})$		0.39	0.10	0.37

Similarly, the general coordinate regression equation has the lowest COV for the L_1 and L_2 interpretations. Therefore, the general coordinate regression equation exhibits higher reliability than those of the semi-logarithmic and full logarithmic coordinates.

4 .3. *Comparison of α versus q_u and $\sqrt{q_u}$*

From the preceding analysis results, the regression equation developed in the general coordinate axes should be used when analyzing drilled shafts socketed into rocks. Moreover, in accordance with the COV values computed in the study, the

$\alpha-\sqrt{q_u}$ relationship yielded better correlation than that of $\alpha - q_u$. Table 5 provides the comparison of the COV values of the L_1 and L_2 interpretations of the $\alpha - q_u$ and $\alpha-\sqrt{q_u}$ relationships. The $\alpha-\sqrt{q_u}$ relationship resulted in a lower COV than that of the $\alpha – q_u$ relationship, providing accurate results for SLS and ULS.

Fig. 4 indicates that the current proposed relation between a and $\sqrt{q_u}$, and the range of α values is extremely broad and scattered. With the completion of the study, data correlation through analysis was improved, which increased the reliability of its application to SLS and ULS.

Table 5 Statistical results for α-$\sqrt{q_u}$ relationships

Interpretation method	Relationship	Regression equation	n	r^2	SD	COV
L_1	$\alpha-q_u$	$\alpha=0.01+0.07/q_u$	44	0.82	0.06	0.59
	$\alpha-\sqrt{q_u}$	$\alpha=0.03+0.06/\sqrt{q_u}$	41	0.56	0.03	0.41
L_2	$\alpha-q_u$	$\alpha=0.07+0.16/q_u$	44	0.81	0.13	0.45
	$\alpha-\sqrt{q_u}$	$\alpha=0.14+0.12/\sqrt{q_u}$	41	0.40	0.09	0.36

5. Conclusions

This study utilized numerous load test data to evaluate the side resistance of drilled shafts socketed into rocks. Upon analysis of the test results, the following conclusions were drawn.

1. This study developed $\alpha – q_u$ and $\alpha-\sqrt{q_u}$ relationships plotted into three coordinate axes. The three coordinate axes were then compared, and the analysis results showed that the general coordinate axes regression equation exhibited better reliability than the semi-logarithmic and full logarithmic axes equations.

2. The study proved that using the $\alpha-\sqrt{q_u}$ relationship is reliable in the analysis of drilled shafts socketed into rocks for the L_1 and L_2 interpretations because of its lower COV value than that of the $\alpha – q_u$ relationship. The relations recommended in this study also yielded higher reliability than previous ones.

3. To determine SLS, the L_1 interpretation of the $\alpha-\sqrt{q_u}$ relationship developed in the study using the regression equation, $\alpha=0.03+0.06/\sqrt{q_u}$, is recommended for the developed equation, r^2 = 0.56, SD = 0.03, and COV = 0.41.

4. To determine ULS, the L_2 interpretation of the $\alpha-\sqrt{q_u}$ relationship developed in the study using the regression equation, $\alpha=0.14+0.12/\sqrt{q_u}$, is recommended for the developed equation, r^2 = 0.40, SD = 0.09, and COV = 0.36.

Acknowledgments

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Conflicts of Interest

The authors declare no conflict of interest.

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